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Experimental Study on the Engineering Characteristics of Expansive Soil Improved by High-Water Grouting Materials

Yuguo Zhang, Jinshuai Kou*, Zhan Jing, Jianfu Zhou

Institute of Civil Engineering and Architecture, Zhongyuan University of Technology, Zhengzhou, Henan, 450007, China
**Corresponding author: 951012394@qq.com*

Abstract: *To address the issues of slow strength improvement and complex construction in traditional methods for improving expansive soils, this paper analyzes the feasibility and effectiveness of using high-water grouting materials to improve expansive soils. The expansive soil from Nanyang City, Henan Province, is used as the subject of this study. A series of tests, including unloaded expansion rate, expansion force, and unconfined compressive strength, were conducted to analyze the swelling characteristics and mechanical properties of expansive soil under different dosages of additives, water-cement ratios, and curing periods. The results indicate that high-water grouting materials significantly improve the early strength of expansive soils and reduce their expansiveness. As the dosage of high-water grouting materials increases and the water-cement ratio decreases, the expansiveness of the improved soil decreases, and compressive strength increases. With the extension of the curing period, the expansiveness of the improved soil gradually decreases, and strength continues to grow, reaching an optimal value at 7 days. The best improvement effect occurs when the water-cement ratio is 1.0 and the dosage is 25%, with the expansion almost eliminated after 7 days of curing and a 360% increase in compressive strength compared to untreated soil.*

Keywords: *Expansive Soil Improvement, High-Water Grouting Material, Expansion Characteristics, Mechanical Properties*

1. Introduction

Expansive soil and its associated engineering problems have long been significant concerns in the field of geotechnical engineering, often referred to as the 'cancer' of geotechnical engineering. Expansive soils differ greatly from general clay soils in terms of engineering properties, exhibiting shrinkage and swelling, fissures, and over-consolidation. The special engineering properties of expansive soils are mainly attributed to the high clay content (greater than 30%), and the dominance of highly hydrophilic minerals such as montmorillonite and illite in their mineral composition[1]. These clay minerals exhibit a strong affinity for water, swelling and softening upon water absorption, and hardening upon desiccation, which are the primary causes of expansive soil's disastrous effects[2]. The shrinkage and swelling of expansive soils lead to structural cracking, roadbed deformation, slope instability, and other issues, resulting in significant economic losses for engineering projects. Therefore,improving expansive soils is crucial. Current primary improvement methods include physical improvement[3][4][5], chemical improvement[6][7][8], and non-traditional improvement techniques[9][10][11]. Although traditional improvement methods have been widely applied in engineering, they often present challenges such as complex construction, slow strength gain, and high costs, which may not meet the demands of some projects. Consequently, researchers continue to search for novel improvement materials to meet the diverse needs of engineering projects.

High-water grouting materials consist of two components, A and B, mixed with water to form a slurry. The slurry of each component can remain uncoagulated for extended periods before mixing, thus exhibiting good pumpability. After thorough mixing, the material quickly sets and hardens, providing good early strength[12]. Component A of the high-water grouting material is made of calcium aluminate cement, retarders, and suspending agents, which prevent the slurry from setting prematurely and help maintain the suspension of solid particles in the mixture. Component B is composed of gypsum, lime, accelerators, and suspending agents. Gypsum and lime are essential for generating large amounts of ettringite, while the accelerator is key to the rapid setting and hardening of

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the slurry mixture, forming early strength[13][14]. Research by Yan Zhiping[15] suggests that high-water grouting materials are well-suited for strengthening and treating soft soil foundations, significantly increasing their unconfined compressive strength. Huang Yucheng et al.[16] demonstrated through experiments that high-water grouting materials increase compressive strength, shear strength, and tensile strength as the curing period extends, with compressive strength being the highest, followed by shear strength, and tensile strength being the lowest, consistent with conclusions drawn by Sun Henghu[17].

Although high-water grouting materials have many unique advantages, research on their applications in construction, transportation, and other fields remains relatively sparse, especially in soil improvement. Therefore, this study focuses on improving expansive soil from Nanyang, Henan, using high-water grouting materials. By conducting a series of expansion and mechanical tests, the study explores the effects of different water-cement ratios, dosages of grouting materials, and curing periods on the expansive characteristics and mechanical properties of the improved expansive soil. The optimal combination of grouting materials is determined to provide valuable references for their application in engineering construction.

2. Experiment

2.1 Experimental Materials

The expansive soil used in the experiment was collected from an abandoned land near a highway in Neixiang County, Nanyang City, at a depth of 2 meters. The soil sample was yellow-brown, with strong viscosity and semi-solid hardness. Laboratory tests were performed on the soil sample, and the results are shown in Table 1. The unloaded expansion rate of the expansive soil is 59.6%. According to the 'Technical Code for Buildings in Expansive Soil Areas' (GB 50112-2013), the soil sample can be classified as weak expansive soil.

Table 1: Basic physical indexes of expansive soil.

Natural water content/%	Natural dry density/ (g/cm^3)	Liquid limit/%	Plastic limit/%	Optimum moisture content/%	Maximum dry density/ (g/cm^3)	Free swelling ratio/%
24.3	1.39	50.2	26.7	19.0	1.698	59.6

The high-water grouting material used in the experiment was produced by a construction material company in Shandong Province. The high-water grouting material consists of two components, A and B, which are mixed in a 1:1 weight ratio to form a slurry. After mixing, the slurry is rapidly stirred to initiate solidification.

2.2 Experimental Methods

The soil samples were first screened, impurities were removed, and the soil was air-dried before being crushed through a 2mm sieve and placed in a drying oven at 108°C for preparation. According to the 'Standard for Soil Testing Methods' (GB/T 50123-2019), the internal mixing method was used. The high-water grouting material was mixed with a water-cement ratio of 1.0, 1.2, and 1.4, and the grouting material was added to the expansive soil at dosages of 10%, 15%, 20%, and 25%. At the same time, untreated soil samples were prepared as controls to compare the improvement effects. The maximum dry density was kept at 1.698 g/cm3, and the optimum moisture content was 19%.

The following tests were conducted on both the untreated soil samples and the improved expansive soil samples with high-water grouting materials: unloaded expansion rate test, expansion force test, and unconfined compressive strength test. The unloaded expansion rate and expansion force tests were conducted using a 20mm height and 61.8mm diameter compaction ring. The WZ-2 expansion instrument and the Nanjing Ningxi Soil Consolidation Instrument were used for testing. The unconfined compressive strength tests were performed on cylindrical samples with 5cm height and diameter, prepared using static pressure. The samples were sealed with preservation film and placed in a constant temperature and humidity box at (20±2)°C and relative humidity >95% for curing at 1d, 3d, 7d, and 28d.

The high-water grouting material test blocks were prepared and tested for strength according to the 'Standard Test Methods for Basic Performance of Building Mortars' (JGJ/T 70—2009). The components A and B were mixed according to water-cement ratios of 1.0, 1.2, and 1.4, and then

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quickly mixed and poured into a three-cell mold of size 40mm×40mm×160mm. After an initial curing time of 1 hour, the samples were demolded and placed in a constant temperature and humidity box for curing at 20°C and relative humidity of 95% until tested for compressive strength at 2h, 1d, 3d, 7d, and 28d.

3. Experimental Results and Analysis

3.1 Compressive Strength Test of High-Water Grouting Material

The variation curve of compressive strength of high-water grouting material with curing age is shown in Fig.1. The compressive strength increases rapidly, showing obvious early strength characteristics. The compressive strength at 2 hours for water-cement ratios of 1.0, 1.2, and 1.4 reaches 43.49%, 39.19%, and 30.82% of the maximum compressive strength, respectively. Thus, a lower water-cement ratio leads to faster early strength development (0-2h). After 1 day, the compressive strength reaches about 70% of its final value, and after 3 days, it reaches about 85%. By 7 days, it reaches 95% of the final strength. In general, the compressive strength development of high-water grouting materials follows a similar pattern for different water-cement ratios: a rapid increase in strength during the early period (0-7d), followed by a decreasing growth rate (growth rate: 2h-1d > 1d-3d > 3d-7d), and after that, the strength curve flattens, with minimal strength increase from 7d to 28d.

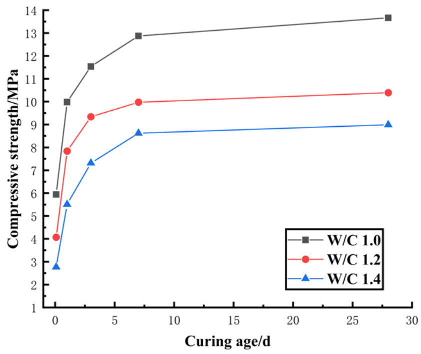

Figure 1: The relationship between compressive strength and curing age of high-water grouting materials.

As shown in Fig.2, as the water-cement ratio increases, the compressive strength of high-water grouting material decreases significantly. When the water-cement ratio increases from 1.0 to 1.2, the compressive strength at each age decreases by 19.1%-31.5%, with an average decrease of 23.7%. When the water-cement ratio increases from 1.2 to 1.4, the compressive strength at each age decreases by 13.5%-31.9%, with an average decrease of 22.1%. For the samples at 2h and 1d, a 0.2 increase in the water-cement ratio causes a decrease in compressive strength by approximately 30% and 25%, respectively. Thus, the compressive strength of high-water grouting material is very sensitive to changes in the water-cement ratio, with even a small change of 0.2 leading to a substantial decrease in strength, particularly during the early stages (2h and 1d).

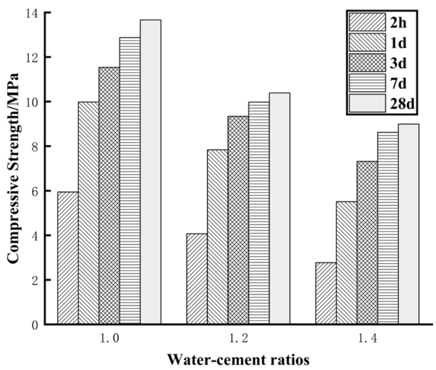

Figure 2: The relationship between compressive strength and water-cement ratios of high-water grouting materials.

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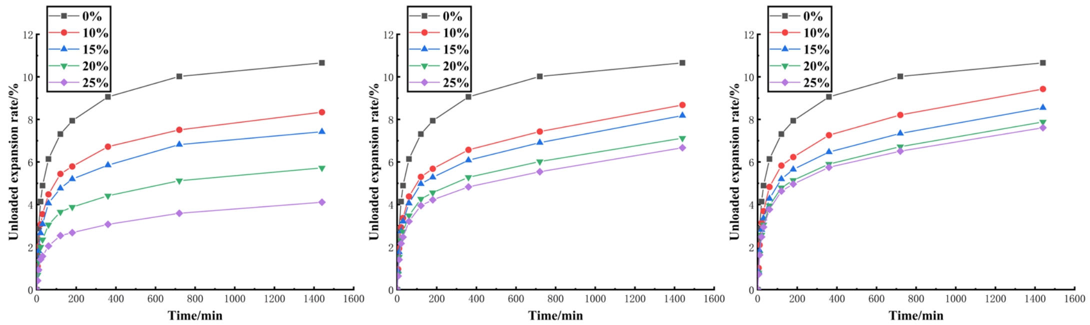
3.2 Unloaded Expansion Rate Test

The samples of high-water grouting material improved expansive soil and untreated soil were subjected to an unloaded expansion rate test at the 7-day curing age. The expansion rate was analyzed for different water-cement ratios and dosages of grouting material. As shown in Fig.3, although the water-cement ratio and dosage of grouting material vary, the expansion rate of all samples follows a similar pattern, which can be divided into three stages: rapid expansion, slow expansion, and stable expansion. In the 0-2h period, the improved expansive soil undergoes rapid expansion, with the unloaded expansion rate reaching approximately 60% of the final expansion rate. From 2 to 12 hours, the expansion rate increases slowly compared to the initial 2 hours. After 12 hours, the expansion rate stabilizes and gradually tends to stabilize. This behavior is due to the relatively low moisture content at the start of the test, making the soil highly sensitive to water absorption. A large amount of water is absorbed by the soil particles, leading to rapid swelling. As the test progresses, the soil particles continue to absorb water, and the internal pores are gradually filled, reducing the expansion potential of the soil, which results in the deceleration of expansion. Additionally, it can be observed that the expansion rate and extent of growth are reduced when high-water grouting material is added.



(a) Water-cement ratios 1.0 *(b) Water-cement ratios 1.2* *(c) Water-cement ratios 1.4*

Figure 3: Time dependent graph of unloaded expansion rate for improved expansive soil.

Fig.4 shows the changes in unloaded expansion rate for samples with different dosages of high-water grouting material. With a fixed curing age and constant water-cement ratio, the unloaded expansion rate of the improved soil decreases as the dosage of grouting material increases. When the water-cement ratio is 1.0, the unloaded expansion rate decreases at a constant rate with increasing dosage. However, for samples with water-cement ratios of 1.2 and 1.4, as the dosage increases, the improvement effect gradually decreases, especially at dosages of 20%-25%, where the rate of decrease in unloaded expansion rate is very small. Moreover, with the increase in curing age, the unloaded expansion rate of the improved soil gradually decreases. By 7 days of curing, the unloaded expansion rate reaches its lowest value, and it does not decrease further with longer curing times. This trend aligns with the development of compressive strength for high-water grouting materials.

When the water-cement ratio is 1.0 and the dosage is 25%, the best improvement effect is achieved. After 7 days of curing, the unloaded expansion rate is reduced to only 0.29%, which is a 97% decrease compared to untreated soil, which had an expansion rate of 10.66%. This improvement is primarily due to the hydration reaction between the high-water grouting material and expansive soil, which produces a series of hydration products, mainly ettringite crystals and gel. These products increase the overall strength of the soil and the bonding between soil particles, restricting the swelling of expansive soil particles. Additionally, as the dosage of high-water grouting material increases, the content of expansive soil particles in the sample decreases, thereby enhancing the water stability of the soil and reducing its unloaded expansion rate.

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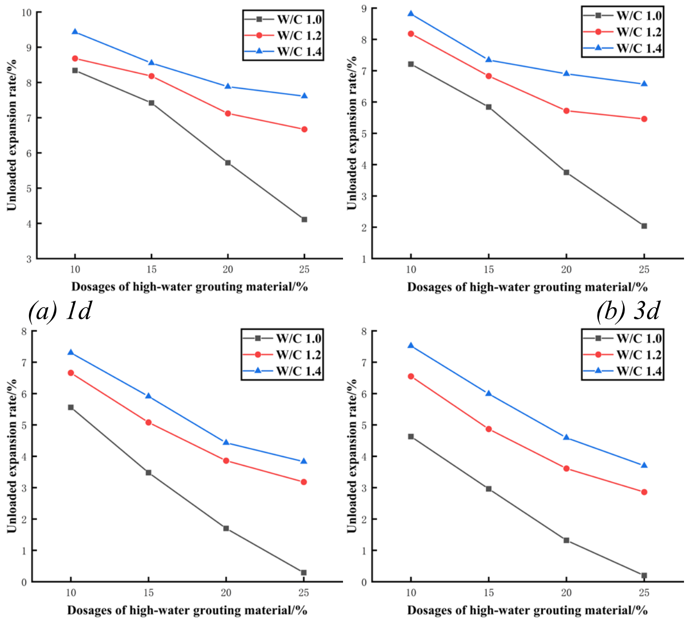


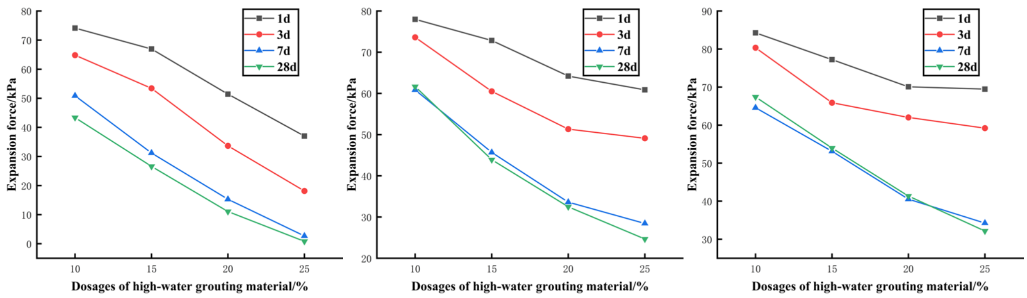
(a) 1d *(b) 3d*

(c) 7d *(d) 28d*

Figure 4: The relationship between unloaded expansion rate and dosage.

3.3 Expansion Force Test

The relationship between expansion force and the dosage of high-water grouting material at different curing ages is shown in Fig.5. It can be observed that when the water-cement ratio of the high-water grouting material is 1.0 and the dosage is 25%, the expansion force is the lowest, and after 7 days of curing, the expansion force is almost eliminated, which is consistent with the results of the unloaded expansion rate test.



(a) Water-cement ratios 1.0 *(b) Water-cement ratios 1.2* *(c) Water-cement ratios 1.4*

Figure 5: The relationship between expansion force and dosage.

The addition of the grouting material can effectively reduce the expansion force of the expansive soil. Furthermore, the longer the curing period, the smaller the expansion force. However, similar to the unloaded expansion rate test, after 7 days of curing, the expansion force decreases very little, and in some cases, a rebound in expansion force is observed, particularly in samples with higher water-cement ratios. This phenomenon can be explained by the fact that high-water grouting material, being a rapid-setting and early-strength material, forms a large number of needle-like ettringite crystals and gel substances during the early chemical reactions. These substances fill the pores between soil particles and bind the particles together, effectively restricting the expansion potential of the soil. As the curing period increases, the hydration reaction completes, and the expansion force no longer decreases significantly. In samples with higher water-cement ratios, the mechanical performance of the material is relatively weaker, leading to a decrease in the overall improvement effect.

3.4 Unconfined Compressive Strength Test

As the stress-strain curves for high-water grouting material improved expansive soils at different curing ages are similar, only the stress-strain curve at the 7-day curing age is presented in Fig.6. From

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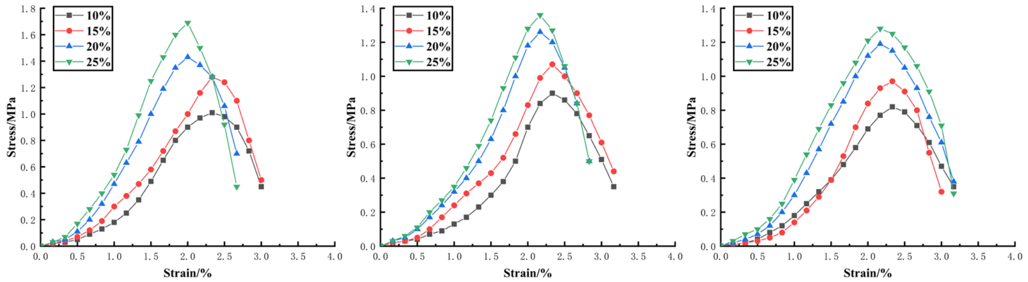
the curve, it can be seen that under constant grouting material dosage, the stress increases steadily with increasing strain, but the rate of stress growth slows down as the ultimate bearing capacity is approached. After reaching the peak stress, the stress rapidly decreases, and the specimen enters the strain-softening stage, which may lead to plastic deformation or brittle failure. As the grouting material dosage increases and the water-cement ratio decreases, the brittle failure phenomenon becomes more prominent. Additionally, as the amount of high-water grouting material increases, the slope of the stress-strain curve becomes steeper, and the peak characteristics become more distinct. The strain corresponding to the ultimate bearing capacity decreases gradually.



(a) Water-cement ratios 1.0 *(b) Water-cement ratios 1.2* *(c) Water-cement ratios 1.4*

Figure 6: Stress-strain curve of improved expansive soil.

The unconfined compressive strength of high-water grouting material improved expansive soils at different dosages is shown in Fig.7. It can be concluded that for all curing ages, when the water-cement ratio is kept constant, the addition of high-water grouting material effectively increases the unconfined compressive strength of the improved expansive soil, and the strength increases with the increase in the grouting material dosage. However, when the water-cement ratio is 1.2 and 1.4, the increase in compressive strength gradually decreases with increasing dosage. In particular, when the dosage is increased from 20% to 25%, the improvement effect is significantly reduced, which is consistent with the findings of previous experimental studies. At the same curing age and dosage, the water-cement ratio has a substantial impact on the unconfined compressive strength of the specimens. For instance, at 7 days of curing and a 25% dosage, the unconfined compressive strength values for water-cement ratio of 1.0, 1.2, and 1.4 are 1.69 MPa, 1.36 MPa, and 1.28 MPa, respectively—representing increases of 360%, 289%, and 272% compared to untreated soil. The strength at a water-cement ratio of 1.0 is 1.32 times that at 1.4. When both the water-cement ratio and dosage are fixed, the unconfined compressive strength of the improved soil increases with curing age under standard curing conditions, reaching the highest value at 7 days, after which the strength remains nearly constant. For example, at a water-cement ratio of 1.0 and 25% dosage, the unconfined compressive strength values at 1, 3, 7, and 28 days are 1.19 MPa, 1.48 MPa, 1.69 MPa, and 1.68 MPa, respectively—corresponding to increases of 253%, 315%, 360%, and 357% compared to untreated soil.

The significant improvement in the compressive strength of expansive soil due to the addition of high-water grouting materials is primarily attributed to the formation of hydration products upon mixing with the soil. These products mainly include ettringite crystals and a small amount of gel-like substances. As curing progresses, the ettringite crystals continue to grow and extend, encapsulating the soil particles within a network of crystalline structures, thereby greatly enhancing the strength of the soil[18]. Additionally, the gel materials envelop and bind soil particles together, forming an integrated structure that further contributes to strength improvement.

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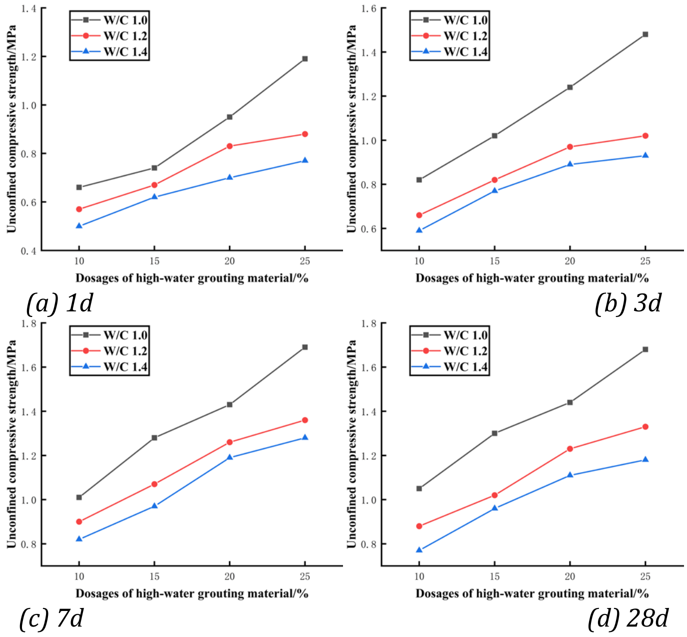

Figure 7: The relationship between unconfined compressive strength and dosage.

4. Conclusion

(1) The uniaxial compression test of high-water grouting material can be divided into three typical stages: the initial compression stage, the elastic deformation stage, and the failure stage. The compressive strength of the material develops rapidly, showing obvious early strength characteristics. The compressive strength at 1d, 3d, and 7d reaches 70%, 85%, and 95% of its final value, respectively. The water-cement ratio has a significant impact on the compressive strength of high-water grouting material. As the water-cement ratio increases, the compressive strength decreases notably, and this effect is more pronounced at early ages (2h and 1d).

(2) After adding high-water grouting material, the expansion rate and growth of the improved expansive soil are reduced compared to untreated soil. The expansion rate of the improved expansive soil follows a similar development pattern, divided into three stages: rapid expansion, slow expansion, and stable expansion. As the water-cement ratio of the grouting material decreases, the dosage increases, and the curing age extends, the unloaded expansion rate and expansion force of the improved soil gradually decrease. The best improvement effect is achieved when the water-cement ratio is 1.0 and the dosage is 25%. After 7 days of curing, the expansion rate and expansion force are almost eliminated.

(3) With the increase in the dosage of high-water grouting material and the decrease in the water-cement ratio, the slope of the stress-strain curve becomes steeper, and the peak characteristics become more pronounced. As the curing age increases, the unconfined compressive strength of the improved expansive soil significantly increases, reaching the maximum value at 7 days of curing. Consistent with the results of the expansion tests, when the water-cement ratio is 1.0 and the dosage is 25%, the best improvement effect is achieved. After 7 days of curing, the unconfined compressive strength reaches 1.69 MPa, which is a 360% increase compared to untreated soil.

(4) The hydration reaction of high-water grouting materials generates ettringite crystals and some gel substances that form a high-strength skeleton, filling the pores between soil particles and binding the particles together. This significantly reduces the expansiveness of the soil and improves its compressive strength. The ettringite crystals are the main structure responsible for enhancing the strength, while the gel substances serve as auxiliary structures.

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