Experimental study on the engineering characteristics of improved expansive soil with high-water grouting materials

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Abstract: *In light of the issues of slow strength enhancement and complex construction associated with traditional expansive soil improvement methods, high-water grouting materials were chosen to improve expansive soil, and then its engineering characteristics under different amendment dosages and different curing ages were investigated. To this end, a series of studies, including slurry compressive and bending tests, unconfined compressive tests, and triaxial tests, were conducted. Experimental results indicate that the use of high-water grouting materials to improve expansive soil can significantly enhance the early strength of expansive soil and reduce its expansibility. As the content of grouting materials increases, the compressive and flexural strength of the modified expansive soil is significantly improved. As the curing age increases, the expansibility of the improved soil gradually decreases, and the strength continues to increase, basically reaching the optimal value at 7 days of curing and tending to stabilize after 7days of curing, demonstrating good early-strength characteristics. The stress-strain curve of the improved soil exhibits a strain-hardening type, and the shear strength increases significantly with the increase in confining pressure. The research results provide a certain reference value for enhancing the engineering application of expansive soil.*

Keywords: *Expansive soil; Improvement; Engineering characteristics; Unconfined compression test; Triaxial test*

1. Introduction

Expansive soil and its engineering-related issues have long been a technical concern in the field of geotechnical engineering both at home and abroad, and are regarded as the "cancer" in the geotechnical engineering industry. Expansive soil differs significantly from ordinary clay in terms of engineering characteristics. It exhibits expansion and contraction, fracture, and super-consolidation. Its special engineering properties are mainly attributed to the fact that the clay content in the particle composition exceeds 30%, and strong hydrophilic minerals such as montmorillonite and illite are [1]predominant. This type of typical clay mineral has a strong binding capacity with water. It absorbs water, expands, and softens, and shrinks and hardens upon water loss, which is the main reason for expansive soil being considered a disaster-prone soil[2]. The expansion and deformation of expansive soil result in structural cracking, subgrade deformation, slope instability, etc., causing substantial economic losses to engineering projects. Therefore, it is necessary to improve expansive soil.

Currently, the main methods for improving expansive soil include physical improvement[3][4][5], chemical improvement[6][7][8], and non-traditional modification[9][10][11]. Cement improvement can effectively enhance the strength and stability of expansive soil[12]. Composite modified materials such as lime have significant effects in improving the strength of expansive soil and optimizing its microstructure[13]. There are significant differences in the effects of different improvement measures on the mechanical properties of expansive soil, and the comparative analysis of physical mechanisms can provide a basis for the optimization of improvement schemes[14]. The application of traditional improvement methods in engineering is quite mature, but there are relatively few studies on high-water grouting materials in the fields of construction and transportation at home and abroad, especially in the field of soil improvement.

Therefore, this paper takes the typical expansive soil in the Nanyang area as the research object and uses high-water grouting materials to improve the expansive soil. Through a series of mechanical experiments, the engineering characteristics of the improved expansive soil with high-water grouting materials under different dosages and curing ages are discussed to provide a reference for its application in engineering construction.

2. Experiment

2.1 Test materials

The expansive soil was obtained from the side of a highway in a township of a county in Nanyang City, Henan Province. The soil, at a depth of 2.5 m, is yellowish-brown. After air-drying and grinding, the basic physical indicators of the soil samples were measured, as shown in table 1. The free expansion rate of the soil is 58.6%. According to the relevant norms[15], it can be determined that the tested soil sample is weak expansive soil.

The grouting material used in the test was produced by a building materials company in Hebei Province. The grouting material consists of two components, Material A and Material B, collectively referred to as the cementing material. They are used in a weight ratio of 1:1, and the slurry is rapidly stirred and cured.

Table 1 Basic physical indicators of expansive soil

Natural moisture content(%)	Natural dry density(g/cm^3).	Plastic limit (%)	Liquid limit (%)	Optimal moisture content(%).	Maximum dry density (g/cm^3)	Free expansion rate(%)
24.3	1.39	26.7	50.2	19.0	1.698	58.6

2.2 Test method

The soil samples underwent preliminary screening to eliminate impurities, were air-dried, crushed, and then passed through a 2-mm sieve. Subsequently, the treated samples were oven-dried at 108 °C for approximately 24 hours to prepare plain soil specimens. The maximum dry density was controlled at 1.698 g/cm³, and the optimum moisture content was set at 19%. Compression-flexure tests, unconfined compressive strength tests, and triaxial tests were conducted on both plain soil specimens and expansive soil specimens modified with high-water grouting materials. The test scheme is presented in Table 2.

Table 2 Trial protocol

Trial name	Curing age/d	Content of improved material/%
Compressive and flexural tests of the slurry test block	1, 3, 7, 28	10, 20, 30
There is no lateral limit compressive strength.	1, 3, 7	10, 20, 30
Triaxial test	3(confining pressure 100kpa, 200kpa, 300kpa)	10, 20, 30

2.2.1 Compressive and Flexural Test

The preparation and strength testing of high-water grouting materials are carried out in accordance with the "Standard for Basic Performance Test Methods of Building Mortar" (JGJ/T 70-2009). Materials A and B are separately mixed with water and thoroughly stirred. Then, equal amounts of the two mixtures are combined and rapidly stirred for 60 seconds. The resulting mixture is then poured into a 40mm×40mm×160mm triple mold specimen. After natural indoor curing for 2-3 hours, the specimen is demolded and transferred to a constant temperature and humidity curing chamber. The temperature is set at 20°C and the relative humidity at 95%. The specimens are cured until the 1st, 3rd, 7th, and 28th days, at which points the compressive and flexural strengths are measured.

2.2.2 Unconfined Compressive Test

The specimen for the unconfined compressive strength test is a cylinder with a height and diameter of 50 mm. The specimen is prepared by the static pressure method with a compaction degree of 95%. The test equipment employed is the CBR-Ш type unconfined compressive strength tester, and the axial loading rate is regulated at 1 mm/min. In accordance with the "Standard for Geotechnical Test Methods" (GB/T 50123-2019), the water-cement ratio of the high-water grouting material is set to 10%. Ten percent, 20%, and 30% of the high-water grouting material are respectively incorporated into the expansive soil. After specimen preparation, the specimens are sealed with plastic wrap and placed in a constant temperature and humidity chamber at a temperature of (20±2)°C and a relative humidity greater than 95% for 1 day, 3 days, and 7 days respectively.

2.2.3 Triaxial Shear Test

Based on the unconfined compressive test and the free expansion rate test, and in accordance with the field survey data and the analysis of soil sampling depth, the triaxial test protocol was established, as specified in Table 2.The preparation method of the triaxial shear specimen is the same as that of the unconfined compressive test, and the specimen specification is 50mm in diameter and 100mm in height. After specimen preparation, the specimen is cured for 2 days (during which the grouting material reacts). Then, it is taken out, subjected to vacuum saturation in a vacuum cylinder for 2.5 hours, left standing in water for 12 hours, and then the specimen is taken out for counter-pressure saturation on a GDS triaxial instrument. The test instrument is the GDS standard stress path triaxial test system produced by GDS Company in the UK. Consolidated undrained shear is adopted, and the shear rate is 0.1mm/min.

3. Results and Discussion

3.1 Analysis of the compressive and flexural test of high-water grouting materials

Figures 1 and 2 respectively depict the curves that illustrate the variations in the compressive strength and flexural strength of high - water grouting materials at different curing ages. The curve in Figure 1 indicates that the pure grout specimens underwent significant volume compression during the initial compression stage and then stabilized rapidly. Subsequently, the stress - strain relationship exhibits a linear variation, with the stress increasing continuously and the strain growth rate decreasing. When the peak stress is attained, micro-cracks emerge and continuously propagate within the specimen, resulting in a sharp rise in strain and a rapid attenuation of stress until failure occurs. The compressive strength of the specimens is 3.25 MPa at the curing age of 1 day, increases to 5.95 MPa at 3 days with a growth rate of 83.08%, and reaches 7.82 MPa at 7 days. The strength grows rapidly within the 0-7-day period, and the growth rate gradually slows down in the later stage. The compressive strength at 28 days stabilizes at 8.30 MPa. The strength at 7 days exceeds 94% of the 28-day strength, and the subsequent strength increment is only 6.14%, which demonstrates that the hydration and cementation reactions primarily occur in the early curing stage. It can be concluded that the high-water grouting material has remarkable early-strength performance, excellent short-term bearing capacity, stable later strength without strength degradation, and superior overall mechanical properties.

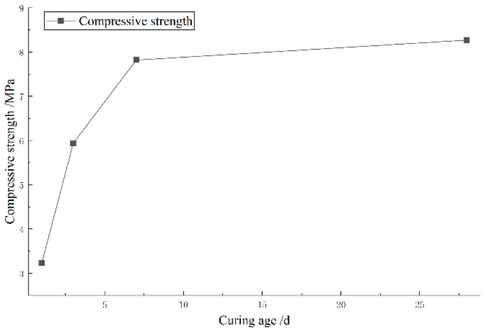


Figure 1 Compressive strength curve of high-water grouting material with curing age

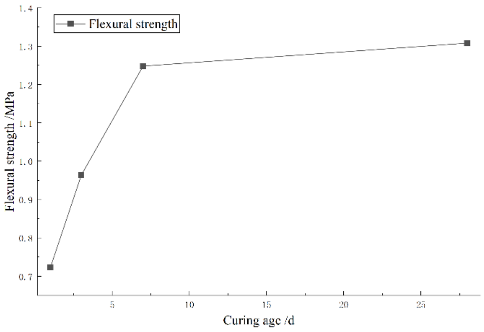


Figure 2 Flexural strength curves of high-water grouting materials with curing age

As observed from the curve in the figure, at the initial flexural loading stage2, the deformation of the high-water grouting material specimens is gentle, and the stress-strain relationship is approximately linear. After reaching the ultimate stress, cracks form rapidly and penetrate the entire cross-section, leading to brittle fracture without obvious plastic deformation. The flexural strength is 0.73 MPa at the curing age of 1 day, rises to 0.96 MPa at 3 days with an increase of 31.51%, and reaches 1.25 MPa at 7 days, an increase of 30.21% compared to that at 3 days. The flexural strength increases rapidly within the 0-7-day period, followed by a gradual decrease in the growth rate in the later stage. The flexural strength at 28 days stabilizes at 1.31 MPa. The 7-day flexural strength accounts for 95.42% of the 28-day strength, with only a 4.8% increment from 7 days to 28 days. This indicates that the hydration and hardening reactions of the material are concentrated in the early stage, with slight strength improvement in the later period, showing an overall variation characteristic of rapid growth in the early stage and gradual stabilization later.

Specimens of high - water grouting materials exhibit a high degree of consistency under compression and flexure.Under compression, the specimens experience initial volumetric compression and stabilization, followed by linear stress growth in the middle stage, and eventually failure induced by crack propagation after reaching the peak stress. Under flexural loading, the material behaves linearly elastic and undergoes brittle fracture without obvious plastic deformation once the ultimate strength is attained. Both compressive and flexural strengths exhibit a consistent evolution pattern of rapid early growth and gradual stabilization in the later stage. A significant strength increase is observed within 1–7 d, and the strength at 7 d exceeds 94% of the 28 d final strength, with only a marginal strength increment thereafter. This indicates that the hydration, cementation and hardening reactions of the material are mainly concentrated in the early curing period. The material possesses excellent early-strength performance, enabling the development of high compressive and flexural bearing capacity within a short curing age, accompanied by stable later strength without obvious degradation, thus demonstrating stable and reliable overall mechanical properties.

3.2 Analysis of unconfined compressive strength

Figures 3 and 4 respectively illustrate the correlations between the unconfined compressive strength of expansive soil modified by high - water grouting materials, the dosage of these materials, and the age. As shown in Figure 3, the high - water grouting material significantly enhances the unconfined compressive strength of the expansive soil. The strength of the improved soil continued to increase with the extension of the curing age. From 1 to 7 days, the intensity increased significantly. After 7 days, the growth rate slowed down, showing the characteristics of rapid hardening in the early stage and slow and stable change in the later stage. At the same age, the strength increased significantly with the increase of material content.30% Dosage 7d The strength is nearly twice that of plain soil. The mechanism lies in the hydration reaction between the active components of the material and the soil particles, forming cementitious products to fill the pores and cementitious particles, forming a stable soil skeleton. The higher the dosage, the more cementitious products, and the higher the density and strength of the soil. The extension of the curing age can continue to promote the development of hydration reaction and further enhance the overall structural strength of the improved expansive soil.

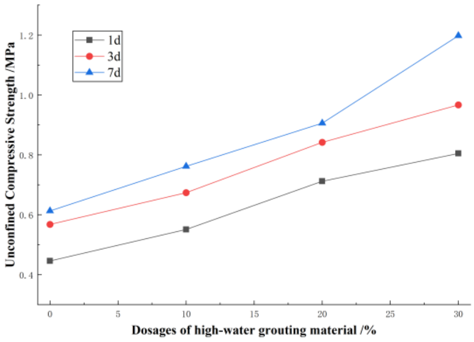


Figure 3 Improved expansive soil unconfined compressive strength curve

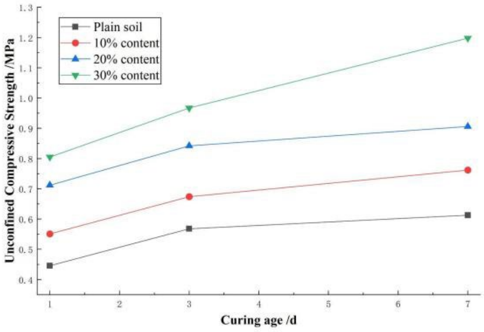


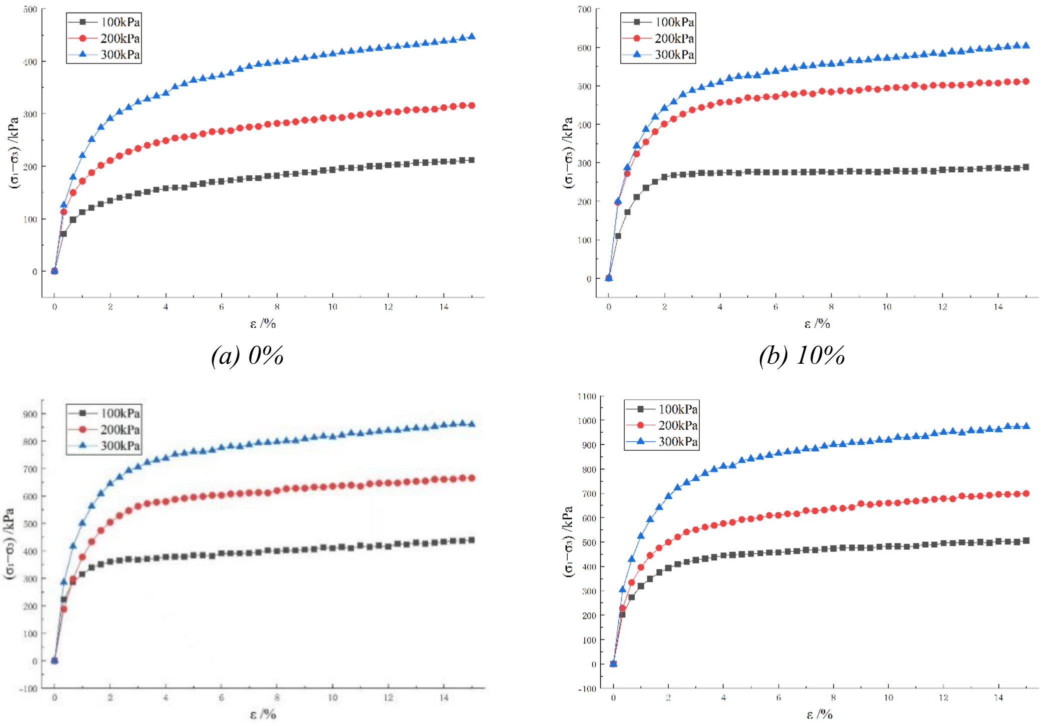
Figure 4 Improved expansive soil unconfined compressive strength curves with age

Figure 4 demonstrates that at each curing age, the unconfined compressive strength of the modified expansive soil continuously increased with the increase in the content of high-water grouting materials, and the strength increase was more pronounced with a higher dosage. An increase in the dosage can lead to the production of more hydrated cementitious products, strengthen the cementation between soil particles, and make the soil skeleton structure more compact. Under the same dosage, the strength of the improved soil gradually increases with the extension of the curing age, following the pattern that the 7d strength is higher than the 3d strength, and the 3d strength is higher than the 1d strength. As the age increases, the hydration reaction continues, and the cementitious products continuously fill the pores of the soil, further enhancing the compactness and overall strength. The 7d compressive strength of the specimen with a 30% mix is nearly twice that of plain soil, and the potential for later stage strength development is remarkable. In summary, the material content and curing age have a significant synergistic effect on the strength of the improved expansive soil, and the improvement effect is better under high content and long age.

3.3 Triaxial test analysis

Figure 5 depicts the stress - strain relationship curves of expansive soil under various soil mix ratios. Under confining pressures of 100 kPa, 200 kPa, and 300 kPa, both the plain soil and the modified expansive soil with different dosages exhibited strain - hardening failure, and no distinct strength softening characteristics were observed.In the initial loading stage, the principal stress difference is approximately linearly correlated with the axial strain, and the initial tangent modulus increases significantly with the increase in material content. Under a confining pressure of 300kPa, the initial modulus of the sample with a 30% dosage is 115% higher than that of the plain soil and 45% higher than that of the sample with a 10% dosage. A high content can generate more hydrated cementitious products, making the soil skeleton denser, and significantly enhancing the stiffness and deformation resistance.

As the axial strain increases, the soil enters the elastoplastic stage, and the stress growth rate decelerates. The higher the confining pressure, the greater the increase in the ultimate principal stress difference. The confining pressure constraint can inhibit lateral deformation and postpone the development of plastic damage. Under the same confining pressure, the ultimate shear strength of the improved soil rises with an increase in the dosage. Under a confining pressure of 300kPa, the ultimate strength of the 30% dosage is nearly 50% higher than that of the 10% dosage. When the strain of each sample reaches 15%, there is still no strength attenuation, indicating good ductility. This demonstrates that the high-water grouting material can simultaneously enhance the strength and deformation performance of expansive soil.



(a) 0%

(b) 10%

(c) 20%

(d) 30%

Figure1 Stress-strain relationship curves of expansive soil under different dosages of plain soil

4. Conclusion

(1) High-water grouting materials can significantly enhance the engineering properties of Nanyang expansive soil, effectively reduce the soil's expansibility, and substantially improve its mechanical strength. The strength of the improved soil develops rapidly with the increase of curing age, basically reaching the optimal strength within 7 days and tending to stabilize in the later stage, demonstrating excellent early strength performance and reliable long-term structural stability.

(2) After the addition of high-water grouting materials, the expansion rate and growth rate of the

improved expansive soil are reduced to varying degrees compared to the plain soil. The reinforcement effect of high-water grouting materials on expansive soil is governed by the coordination of content and age. The laws of improvement in compressive and shear resistance are consistent. The 7-day unconfined compressive strength of the improved soil with 30% content is nearly twice that of the plain soil, and it shows stable strength gain under different confining pressure conditions, which can significantly improve the overall bearing capacity of the expansive soil.

(3) After improvement with high-water grouting materials, the stress-strain curve of expansive soil exhibits a strain-hardening behavior without an obvious softening section. The initial modulus and ultimate shear strength increase significantly with dosage and confining pressure. The ultimate strength of the 30% dosage sample under 300kPa confining pressure is nearly 50% higher than that of the 10% dosage sample, maintaining good ductility while enhancing soil stiffness. The material generates cementitious products through rapid hydration reactions, cementing discrete soil particles, filling soil pores, reconstructing a dense and uniform skeleton structure, and achieving efficient reinforcement and modification of expansive soil at the microscopic level.

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References

[1] Sun De'an, Zhang Junran, Lu Haibo, et al. Soil-water characteristic curve of Nanyang expansive soil in full suction range[J]. Rock and Soil Mechanics, 2013, 34(07): 1839-1846. DOI:10.16285/j.rsm.2013.07.005.

[2] Wang Chenghan, Cha Wenhua, Wang Jingjiu. Review of expansion and contraction mechanism and new treatment methods of expansive soil[J]. Subgrade Engineering, 2020, (02): 6-11. DOI:10.13379/j.issn.1003-8825.2020.02.02.

[3] You Bo, Xu Hongzhong, Dong Jinmei, et al. Triaxial experimental study of basalt fiber reinforced expansive soil[J]. Journal of Disaster Prevention and Mitigation Engineering, 2015, 35(04): 503-507+514.

[4] Wang Huan, Cao Yikang, Ren Junxi, et al. Effect of dry-wet cycle on cracks and strength of improved expansive soil in silt soil[J]. Journal of Building Science and Engineering, 2022, 39(05): 213-221.

[5] LI Jia-ming, TANG Shi-bin, SONG Huai-bo, et al. Engineering properties and microstructure of expansive soil treated with nanographite powder[J]. Journal of Central South University, 2022, 29(02): 499-514.

[6] Fu Ce Ling, Zeng Zhaotian, Mo Hongyan, et al. Experimental study on engineering characteristics of lime modified expansive soil[J]. Journal of Guangxi University (Natural Science Edition), 2019, 44(02): 524-533.

[7] Suo Wentao, Li Xinming, Sun Yuzhou. Strength characteristics and microscopic mechanism of lime-modified Nanyang expansive soil[J]. Subgrade Engineering, 2018, (05): 30-34+64.

[8] Lu Y, Liu S, Zhang Y, et al. Freeze-thaw performance of a cement-treated expansive soil[J]. Cold Regions Science and Technology, 2020, 170: 102926.

[9] Du Jing, Zhou Dong. Experimental study on microbial modified expansive soil[J]. Water Conservancy and Hydropower Technology, 2012, 43(07): 103-105+87.

[10] Ouyang Q, Xiao H, Li Z, et al. Experimental study on the influence of microbial content on engineering characteristics of improved expansive soil[J]. Frontiers in Earth Science, 2022, 10: 863357.

[11] Li Yun-fat, Wang Guiyao, Zhang Yongjie, et al. Experimental study on the effect of planting vetiver roots on expansive soil characteristics[J]. Highway Traffic Science and Technology, 2020, 37(05): 43-52.

[12] Li Zhengyin, Zhang Bin, Zhao Wei, et al. Experimental Study on the Engineering Properties of Cement-Modified Expansive Soil [J]. Comprehensive utilization of fly ash, 2025, 39(05): 97-102.

[13] ZHANG Yuguo, ZHAO Chunhao, ZHANG Zhaobin, et al. Research on the strength characteristics and microscopic mechanism of improved expansive soil with lime-zeolite powder[J]. Silicate Bulletin, 2024, 43(11): 4167-4176.

[14] Chai Shiyu, Zhang Lingkai. Comparative analysis of the influence of different improvement methods on the mechanical properties and physical mechanism of expansive soil[J]. Hydropower and Energy Science, 2023, 41(4): 190-194.

[15] Technical Specifications for Buildings in Expansive Soil Areas: GB50112-2013[S]. Beijing: China Building Industry Press, 2013.