Experimental study on the compressive strength of unsaturated loess with different contents of grout material and water glass

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Abstract. Unsaturated loess, classified as a distinctive soil type, possesses a compressible large-pore structure, and exhibits a rapid reduction in strength upon exposure to water. This characteristic imposes significant constraints on engineering constructions in loess regions. Introducing grouting materials such as mixing grout and sodium silicate into loess is deemed an effective measure to ameliorate and enhance its engineering properties. This study conducts experiments to investigate the compressive strength of unsaturated loess with varying ratios of grouting material to sodium silicate. Standard-sized specimens are prepared for different test groups (grouting material: 15% - 33%; sodium silicate dry content: 3% - 5%; initial moisture content: 15% - 25%), and their unconfined compressive strength is measured after a curing period of 28 days. The experimental results indicate that the compressive strength of unsaturated loess monotonically increases with the escalating dosage of sodium silicate, rises with higher initial moisture content, and decreases with an increasing amount of grouting material within the specified parameter range. The weight of the impact of the three factors on compressive strength within the experimental parameter range can be ranked as follows: sodium silicate > grouting material > initial moisture content. Through theoretical analysis from both physical and chemical perspectives, this study elucidates the mechanisms by which sodium silicate, grouting material, and soil moisture influence the strength of unsaturated loess. The research findings offer valuable insights for optimizing the performance-based design of unsaturated loess.

Keywords: Loess, Grout material, Water glass, Compressive strength.

1 Introduction

Unsaturated loess, classified as a distinctive soil type, exhibits a compressible large-pore structure and the unique characteristic of rapid strength reduction upon water exposure, contributing to its distinctive collapsibility [1]. This property deteriorates both the physical and engineering characteristics of loess, posing challenges in construction

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and civil engineering in loess regions and leading to frequent engineering and geological hazards [2,3]. In efforts to enhance the engineering performance of loess, various reinforcement measures, including the use of grouting materials and sodium silicate, are commonly employed [4].

Grouting materials, containing cement components, undergo hydration reactions similar to cement slurry. The hydration products of cement filling the soil micropores form a robust cement gel, thereby increasing the soil's compressive strength. The chemical components in grouting materials can react chemically with soil particles, forming cementitious substances [5]. These substances contribute to improved soil cohesion and binding forces, mitigate soil particle movement, and enhance soil stability. Sodium silicate, also known as water glass, is an inorganic binder. Its application in loess primarily involves reacting with ions in the soil to form cementitious substances, thereby increasing soil cohesion and binding forces and improving the overall performance of the soil. Researchers [6] have focused on the construction techniques of sodium silicate in actual engineering, including methods such as immersion and spraying. Simultaneously, studies have delved into factors affecting the reinforcement effectiveness of sodium silicate, such as concentration, temperature, and pH [7].

Grouting materials and sodium silicate are commonly used in combination for soil improvement [8-10]. There have been engineering practices involving the combined application of grouting materials and sodium silicate, accumulating valuable experience in assessing the feasibility and effectiveness of this method. Scholars have explored the impact of the joint action of grouting materials and sodium silicate on the strength and stability of sandy soil through simulating soil properties and engineering environments with different proportions and ratios. Researchers [11] have tested the Vicat, unconfined compressive strength, and ultrasonic pulse velocity of clay after mixing with grouting materials and sodium silicate, analyzing the optimal values for different concentrations. Loess is rich in soluble salts, which leads to its unique combination effect of grouting material and water glass double material reinforcement compared to other soil types. Natural loess has the characteristic of vertical large pore development, which leads to the reinforcement and filling effect of double material on the large pore structure of loess being different from other soil types. Therefore, conducting research on the joint reinforcement of loess with grouting material and water glass double material is of great significance.

This study considers the unique engineering properties of loess, focusing on unsaturated loess as the research subject to investigate its engineering properties under different ratios of grouting materials and sodium silicate. The experiments primarily consider three factors: initial moisture content, grouting material dosage, and sodium silicate dosage, testing their unconfined compressive strength after 28 days. The aim is to understand the variation patterns of unconfined compressive strength of loess under different ratios of grouting materials, sodium silicate, and initial moisture content. The study also attempts to provide a mechanistic explanation for the experimental phenomena, offering valuable insights for the application of the mixed grouting and sodium silicate method in engineering practices in loess regions.

2 Experimental methods

2.1 Test materials

The soil used in this experiment was taken from Xi'an Airport New City, where the loess belongs to the typical late Pleistocene loess (Q_3) of the fourth season. It is famous for its typical collapsible characteristics and is widely distributed in the loess area. After the test soil is retrieved, relevant geotechnical tests are conducted to determine its physical indicators. The measured results are shown in Table 1.

Table 1. Physical parameters of test material

Indicator	Value
w_P(%)	19.1
w_L(%)	31.6
I_P	12.6
r_s (g·cm^{-3})	2.71
Clay particle (%): <5μm	22
Silt particle (%): 5μm~50μm	66
Sand particle (%): >50μm	12

The grouting material is C40 high-strength non-shrinkage grouting material produced by Qingdao Zhuonangda Construction Technology Co., Ltd., and the water glass is instant sodium silicate (M. R=2.85) produced by Henan Yixiang New Materials Co., Ltd.

2.2 Experimental design

Firstly, prepare a plain soil sample with a specific moisture content. According to the geotechnical test standards, the soil retrieved from the field is processed through processes such as air drying, crushing, and passing a 2mm sieve to obtain dry soil that meets the test requirements. Weigh the required dry soil according to the specific dry density of the sample. Before adding water, weigh the required weight of grouting material and water glass for the corresponding experimental group, and mix the dry soil, grouting material, and water glass evenly. Then, according to the moisture content corresponding to the weight of soil particles, specific distilled water is weighed and poured into the mixed dry material, and quickly stirred. This method, compared to the traditional method of adding water to the dry soil first and then adding other admixtures, avoids the agglomeration phenomenon of the later admixtures and is conducive to improving the overall uniformity of the admixtures of the sample.

Then prepare standard size specimens. According to the specific dry density, the soil sample is layered into the standard mold, and each layer is roughened to increase interface contact. Place the prepared soil sample into a curing box, and after 28 days of standard curing, demould to obtain the test block.

Finally, conduct an unconfined compressive strength test on the test block, with the axial strain rate controlled at 1% -3% strain per minute. Raise the lifting equipment for testing. When the axial strain is less than 3%, read every 0.5% strain (or 0.4 mm). When the axial strain is equal to or greater than 3%, read every 1% strain (or 0.8 mm). When the reading of the dynamometer reaches a peak, continue with the 3% -5% strain and stop the test; When there is no peak in the reading, the test should be conducted until the strain reaches 20%. The single unconfined test should be completed within 8-10 minutes.

The moisture content of unsaturated loess is dynamically changing due to the influence of light, radiation, wind speed, and rainfall in the atmospheric environment, as well as the influence of surface rivers and runoff, as well as the seepage movement of water inside the soil. The range of moisture content change in natural environments is approximately 15% -25%. The ranges of water glass content and grouting material content are referred to in reference [9,11]. A total of 8 groups of experiments were conducted, with three horizontal samples set for each group. The parameter group settings are shown in Table 2.

Table 2. Setting of experimental parameter groups

Grout material (%)	Water glass (%)	Initial water content(%)
20	5	20
20	3	15
20	3	25
15	5	20
33	3	20
20	4	20
20	3	20
27	3	20

3 Experimental results

3.1 Relationship between grouting materials and strength

By observing the data in Figure 1, it can be observed that as the amount of grouting material increases, the strength of the soil actually decreases. As the content of grouting material increases from 20% to 33%, the unconfined compressive strength of the soil decreases from 10.74 MPa to 8.03 MPa. This may indicate that excessive grouting material may lead to excessive compaction of the soil, which in turn affects the strength of the soil.

Through linear fitting analysis, the corresponding relationship between the parameters of dry grouting slurry and its strength is obtained:

$$y = -0.2065x + 15.023, R^2 = 0.956 \tag{1}$$

where x is the percentage of grouting material content, y is the unconfined compressive strength (MPa) of the sample after 28 days, and R^2 is the square value of the correlation coefficient, reaching 0.956, indicating that this formula can better reflect the relationship between grouting material content and sample strength.

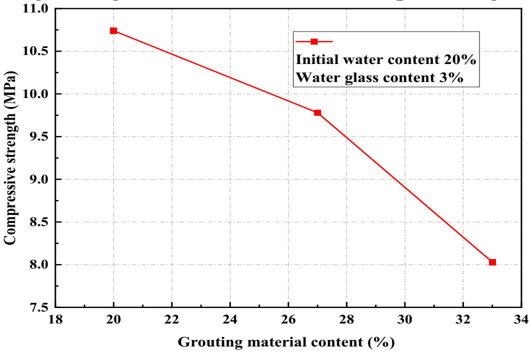

Fig. 1. Relationship between grouting material content and strength.

3.2 Relationship between water glass and strength

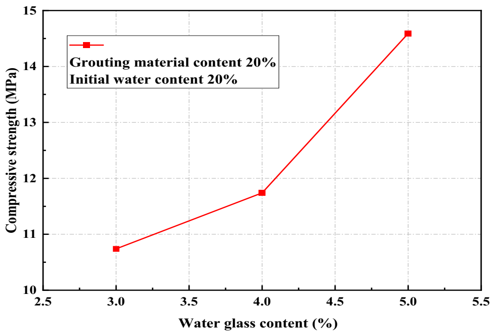

Fig. 2. Relationship between water glass content and strength

By observing Figure 2, it can be observed that as the amount of water glass increases, the strength of the soil also increases. As the content of grouting material increases from 3.0% to 5.0%, the unconfined compressive strength of soil increases from 10.74 MPa to 14.59 MPa, indicating that the addition of water glass has a positive impact on improving soil strength. As a cementitious material, water glass may play a cementitious role in soil, enhancing the overall stability and strength of the soil.

Through linear fitting analysis, the corresponding relationship between water glass content and strength is obtained:

$$y = 1.925x + 4.6567, R^2 = 0.929 \tag{2}$$

where x is the percentage of water glass content, y is the unconfined compressive strength (MPa) of the sample after 28 days, and R^2 is the square value of the correlation coefficient, reaching 0.929, indicating that this formula can better reflect the relationship between water glass content and sample strength.

3.3 Relationship between moisture content and strength

Figure 3 shows the experimental data of the corresponding relationship between the initial moisture content and strength when the grouting material content is 20% and the water glass content is 3%. It can be observed in the figure that as the moisture content increases, the strength of the soil shows an upward trend.

By linear fitting analysis, the corresponding relationship between initial moisture content and strength is obtained:

$$y = 0.266x + 4.8733, R^2 = 0.887 \quad (3)$$

where x is the percentage of initial moisture content, y is the unconfined compressive strength (MPa) of the sample after 28 days, and R^2 is the square value of the correlation coefficient, reaching 0.887, indicating that this formula can better reflect the relationship between initial moisture content and sample strength.

Within the investigated parameter range, the weight of the impact of the three factors on compressive strength can be ranked as follows: sodium silicate > grouting material > initial moisture content.

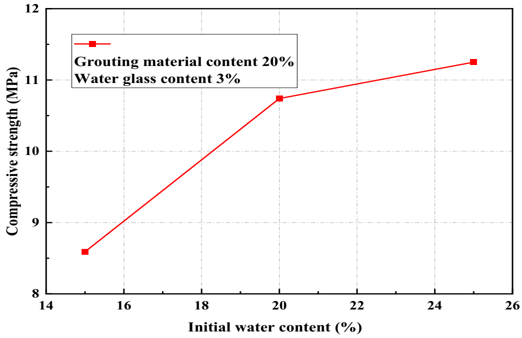

Fig. 3. Relationship between initial moisture content and strength

4 Mechanism discussions

4.1 Mechanisms of Grouting Material on Strength Impact

Regarding the chemical effects of grouting materials on soil, these materials typically include components such as cement and bentonite. These components undergo hydration reactions with the water and minerals in the soil. The resulting hydration products fill the soil pores, enhancing soil density and consistency. Additionally, the gel formation also improves the soil's shear strength and permeability. Lastly, exchange of calcium ions from cement with soil ions alters the soil's ion composition, potentially strengthening the bond between soil particles and enhancing overall soil strength.

In terms of the physical effects of grouting materials on soil, the injection of grouting materials fills the voids in unsaturated soil, reducing the soil's porosity and improving its density. This filling significantly enhances the soil's bearing capacity. However, experimental results indicate that excessive grouting material may lead to overcompaction of the soil, adversely affecting its strength.

4.2 Mechanisms of Sodium Silicate on Strength Impact

In terms of the chemical effects of sodium silicate on soil, the silicates in sodium silicate react with certain components in the soil, forming a silicate gel. This gel possesses strong binding properties, filling the soil pores and increasing soil density and consistency, thereby enhancing overall soil strength. Additionally, sodium silicate reacts with alkaline ions in the soil, forming silicate colloids.

Concerning the physical effects of sodium silicate on soil, the gelation action of sodium silicate improves the particle structure of the soil, forming a binding structure. This binding effect enhances the overall compressive and shear strength of the soil. Additionally, sodium silicate, through filling voids in unsaturated soil, reduces soil porosity and improves soil density.

4.3 Mechanisms of Moisture Content on Strength Impact

From the analysis results in Section 3.3, samples with higher initial moisture content exhibited higher compressive strength, contrary to general soil mechanics principles where soil strength is negatively correlated with moisture content. However, due to the incorporation of sodium silicate and grouting material into the soil, even with the same dry density, compacted soil samples at different initial moisture content states exhibit different pore structures. Higher moisture content soils have a more optimal pore combination, resulting in enhanced mechanical properties after the hydration-induced pore-filling consolidation of sodium silicate and grouting material, showcasing stronger mechanical performance.

5 Limitations

This article provides a preliminary study on the strength indicators of loess reinforced by the combined mixing of grouting materials and water glass, which has certain guiding significance for practical engineering applications. However, considering the complexity of the specifications of grouting materials and water glass materials, the diversity of the climate and temperature conditions in which the loess is located, and the lack of scientific evaluation of the durability of the reinforced loess, it is necessary to focus on studying related issues in the future.

6 Conclusions

The compressive strength of unsaturated loess monotonically increases with the escalating dosage of sodium silicate, rises with higher initial moisture content, and decreases with an increasing amount of grouting material.

Within the investigated parameter range, the weight of the impact of the three factors on compressive strength can be ranked as follows: sodium silicate > grouting material > initial moisture content.

Excessive grouting material may lead to overcompaction of the soil, adversely affecting its strength. Compacted soils with higher moisture content may exhibit more optimal pore combinations, resulting in higher strength after pore-filling consolidation.

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