

# Experimental Study on the Mechanical Properties of Loess-Based Grout Materials

Long Zhao<sup>1</sup>, Shuaihua Ye<sup>\*,2,3</sup>, Liangliang Xin<sup>2,3</sup>, Yilei Shi<sup>1</sup>

<sup>1</sup>Gansu CSCEC Municipal Engineering Investigation And Design Institute Co., Ltd., Lanzhou, Gansu 730000, China.

<sup>2</sup>Key Laboratory of Disaster Mitigation in Civil Engineering of Gansu Province, Lanzhou University of Technology, Lanzhou 730050, China;

<sup>3</sup>Western Center of Disaster Mitigation in Civil Engineering, Ministry of Education, Lanzhou University of Technology, Lanzhou, 730050, China.

<sup>a</sup> 120083299@qq.com, <sup>b</sup> yeshuaihua@163.com

<sup>c</sup> liangliangxin2022@163.com, <sup>d</sup> 1321781334@qq.com

**Abstract:** In order to develop a controllable low-strength loess-based grout material, loess is used as the primary material with cement and additives as supplements. By employing the controlled variable method and orthogonal experimental design, various samples were prepared with cement content and curing age as variables. The study investigates their impact on the unconfined compressive strength, shear strength, and compression coefficient of loess-based grout materials. Experimental results indicate that within the 4% to 12% cement content range, the relationship between cement content and curing age, and the unconfined compressive strength of loess-based cement grout materials, follows linear and quadratic parabolic patterns, respectively. The research findings have reference significance for the application of loess-based grout materials in embankment slope engineering.

**Keywords:** Loess-based grout material; Mechanical properties; Experimental study

## 1. Introduction

With the introduction of the national "Dual Carbon" strategy, the development of green and low-carbon building materials has increasingly drawn the attention of researchers [1-2]. Some scholars have improved loess by mixing it with other inorganic non-metallic materials [3-4], construction waste, sand, and adding certain additives to meet engineering requirements, providing a feasible and efficient method [5]. Scholars both domestically and abroad have designed and developed novel self-compacting flowable fill materials, such as pre-mixed flowable solidified soil, controllable low-strength materials, and loess-based grout materials. This new type of filling material has a simple preparation process, is easy to construct, and generally exhibits characteristics such as self-compaction, high bearing capacity, and low permeability after hardening [6-8].

Loess-based grout materials possess unique engineering characteristics and find extensive applications in various fields. Among these, the primary applications of flowable fill materials include backfilling in trenches, structural backfilling, road base layers, void filling, and pipe bedding [9]. Baldovino J A et al [10] conducted compressive and split tensile strength tests on fine-grained soil treated with lime for varying durations, revealing a significant improvement in compressive and split tensile strength after lime treatment. Xie Xiao et al [11] conducted shear tests under different lime content conditions, investigating the impact of lime content on the shear strength of loess. Zhao Tianyu et al [12] selected the loess from Longdong and Longxi as the experimental subjects, conducting experimental research on the mechanical properties of roadbed fill materials with lime-modified loess. The experimental results indicate a significant enhancement in the mechanical performance of lime-modified loess when the cement content is in the range of 4% to 6%. Zhang Yuchuan et al [13] considered the improvement effects of fly ash and lime on loess under long-term conditions, comprehensively determining the impact law of shear strength on cured soil considering various influencing factors.

Despite extensive research on loess-based grout materials, the mechanical performance mechanisms of modified loess regarding cement content and curing age remain unclear, and there is no quantitative understanding between mechanical indicators. Few experiments have been conducted on flowable fill materials in the collapsible loess region of China. Developing a new type of backfill material that is easy to construct, has high fluidity, and exhibits good compaction effects is of great significance for the development of engineering construction in the northwest loess region of China.

## 2. Development of Loess-Based Grout Material

### 2.1 Basic Materials of Loess-Based Grout Material

#### 2.1.1 Loess

The loess is sourced from a construction project in Pengjiaping, Lanzhou City, and its basic physical properties are shown in Table 1.

Table 1 Physical properties of test soil

Natural Moisture Content (%)	Air-dried Moisture Content (%)	Liquid Limit	Plastic Limit	Plasticity Index	Liquidity Index
16.5	0.8	28.3	19.5	10.2	0.09

#### 2.1.2 Cement

Ordinary Portland Silicate Cement, labeled as P.042.5, with composition as shown in Table 2.

Table 2 Composition of cement

Chemical Composition	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	MgO	SO <sub>3</sub>	Other
Percentage Content(%)	18.23	6.15	66.25	3.27	0.12	2.85	3.13

#### 2.1.3 Admixtures

In this experiment, naphthalene sulfonate formaldehyde condensate, sodium sulfate, sodium dithionite, and ethylene glycol will be used as admixtures.

### 2.2 Preparation and Curing of Specimens

#### 2.2.1 Design of Different Parameter Mix Ratios

(1) Cement ratio: The dosage range for this experiment is set between 4% and 12%, with cement content at 4%, 6%, 8%, 10%, and 12% of the loess mass. (2) Slump index: Fluidity is a key criterion for loess-based grout materials, and this experiment controls the slump index at the moisture content when the slump is 180mm during the development of loess-based cement grout materials [14]. (3) Curing age: The curing age is set at 7 days, 14 days, 28 days, and 60 days. (4) Mixing time: The mixing time is set at 10 minutes.

### 2.3 Preparation and Curing of Specimens

#### 2.3.1 Process of Specimen Preparation

According to reference [15], the unconfined compressive strength test uses cubic specimens with dimensions of 70.7mm×70.7mm×70.7mm, while the shear and compression tests use ring-knife specimens with dimensions of Φ61.8×20mm.

(1) According to the experimental plan, calculate the required amounts of loess, water, and cement for the specimens. After weighing each component, mix them thoroughly. (2) Pre-mix the loess and cement in the mixer for 2-3 minutes to ensure thorough mixing, then add the required water and continue mixing for 10 minutes. After mixing is complete, mold the specimens. (3) Brush mineral oil inside the test mold, then fill the loess-based cement grout material slurry into the mold

in two steps. After filling, vibrate the mold on the vibrating table for 20 seconds to compact the slurry. (4) For direct shear and compression tests, insert the ring-knife into the cubic test mold, and remove the ring-knife specimen. (5) Use a knife to scrape off and smooth excess material, and cover the surface with a layer of plastic wrap.

### 2.3.2 Curing of Specimens

The specimens are cured in a curing box, with a controlled temperature of  $20 \pm 2^\circ\text{C}$  and humidity of over 95%, for varying curing periods.

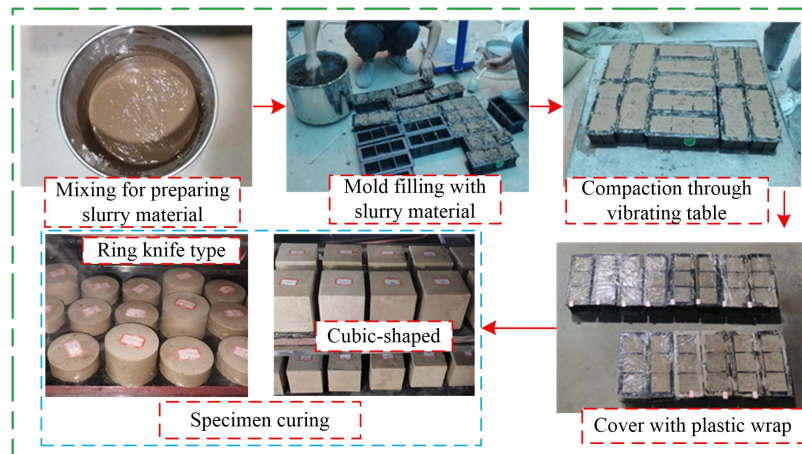


Fig.1 Sample preparation process diagram

## 3. Analysis and Evaluation of Engineering Mechanical Properties

### 3.1 Engineering Mechanical Properties

#### 3.1.1 Unconfined Compressive Strength

(1) The fitting curve of cement content and unconfined compressive strength is shown in Figure 2.

Unconfined compressive strength, shear strength, and compression coefficient are important indicators for evaluating soil performance. Specimens with cement content ratios of 4%, 6%, 8%, 10%, and 12% are prepared, with curing ages of 7 days, 14 days, 28 days, and 60 days. The influence of cement content and curing age on unconfined compressive strength, shear strength, and compression coefficient is explored. Evaluation of engineering mechanical indicators for loess-based cement grout material.

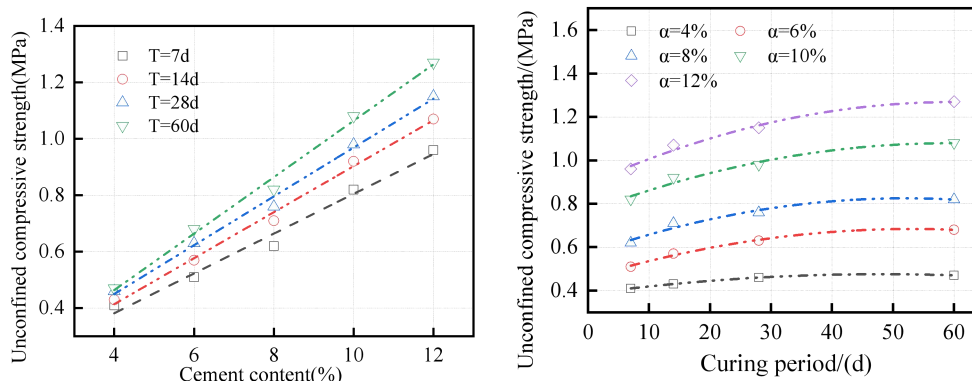


Fig.2 Relationship between cement content and unconfined compressive strength

Fig.3 Relationship between curing age and unconfined compressive strength

According to Figure 2, with the increase in cement content, the products generated by cement hydration reactions increase. The spatial colloidal action of loess-based cement grout material

becomes more significant, leading to an increase in unconfined compressive strength as the cement content grows from 4% to 12%. As the curing age increases, the unconfined compressive strength also increases. The relationship between unconfined compressive strength and cement content in loess-based cement grout material shows a linear correlation, and the fitting parameters are shown in Table 3.

The relationship between the unconfined compressive strength ( $P_u$ ) and cement content can be fitted using Formula (1):

$$P_u = a\alpha + b \quad (1)$$

Table 3 Fitting parameters of unconfined compressive strength and cement content

Curing Age	T=7d	T=14d	T=28d	T=60d
a	0.071	0.082	0.087	0.100
b	0.100	0.088	0.104	0.064
R2	0.978	0.992	0.993	0.992

(2) The fitting curve of curing age and unconfined compressive strength is shown in Figure 3.

From Figure 3, it is observed that the unconfined compressive strength of loess-based cement grout material increases with the growth of curing age for various cement contents. As the curing age extends from 7 days to 60 days, the unconfined compressive strength of loess-based cement grout material with cement content at 4%, 6%, 8%, 10%, and 12% increases by approximately 13%, 33%, 32%, 31%, and 32%, respectively. With the prolonged curing age, cement continues to undergo hydration reactions, and the cementing effect is enhanced, leading to an improvement in the unconfined compressive strength of loess-based cement grout material.

The relationship between the unconfined compressive strength  $P_u$  and the curing age  $T$  of cemented soil can be fitted with Formula (2), and the fitting coefficients are shown in Table 2.

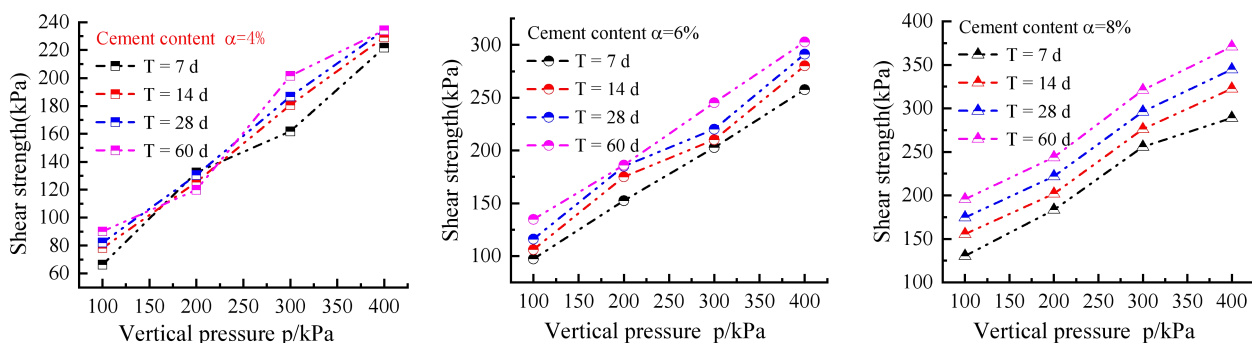
$$P_u = aT^2 + bT + c \quad (2)$$

Table 4 Fitting coefficient between unconfined compressive strength and curing age

Cement Content	4%	6%	8%	10%	12%
a1	-3.9E-5	-8.0E-5	-9.5E-5	-9.04E-5	-1.05E-5
b1	0.0038	0.0085	0.0099	0.0107	0.0126
c1	0.3855	0.4591	0.5681	0.7639	0.8904
R2	0.9998	0.9821	0.8941	0.9209	0.9493

### 3.1.2 Shear Strength

(1) When cement content is the same, the relationship between shear strength and vertical pressure at different curing ages is shown in Figure 4.



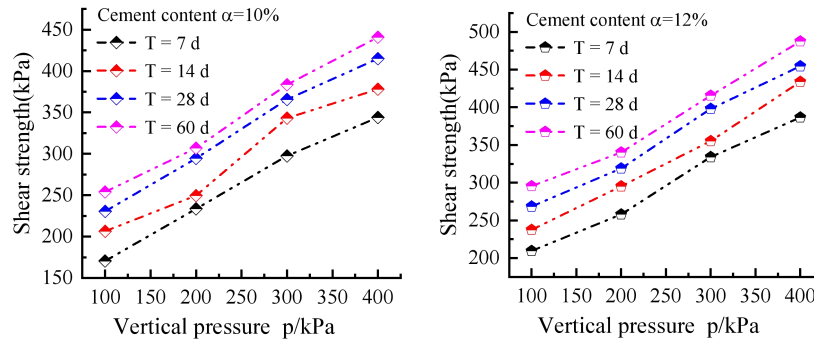


Fig.4 Relationship Between Shear Strength and Vertical Pressure at Different Curing Ages with the Same Cement Content.

According to Figure 4, the shear strength of loess-based cement grout material increases by approximately 12% to 23% with a 14-day curing age compared to a 7-day curing age. The increase is about 5% to 13% with a 28-day curing age compared to a 14-day curing age, and about 7% to 12% with a 60-day curing age compared to a 14-day curing age. Overall, curing age has a positive impact on the increase in shear strength of loess-based cement grout material.

(2) The relationship between cement content and cohesion and internal friction angle is shown in Figures 5 and 6, respectively.

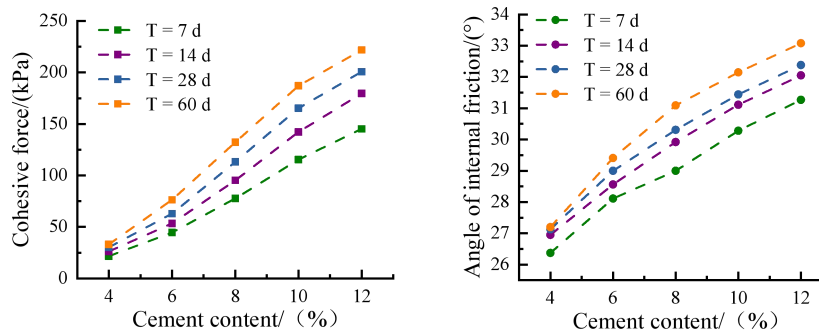


Fig.5 Relationship Between Cement Content and Cohesion

Fig.6 Relationship Between Cement Content and Internal Friction Angle

From Figure 5, it is evident that the cohesion of loess-based cement grout material significantly increases with the increase in cement content. Cohesion within the given range of cement content exhibits a slow growth, followed by an accelerated growth trend. When the cement content is high, the rate of cohesion growth is faster. The reason is that with lower cement content, the cohesion of loess-based cement grout material is smaller, and the products generated by cement hydration reactions are fewer, resulting in less bonding between soil particles and, consequently, lower shear strength. Figure 6 shows that the internal friction angle of loess-based cement grout material generally increases with the increase in cement content.

(3) The relationship curves between curing age and cohesion, as well as internal friction angle, are shown in Figures 7 and 8, respectively.

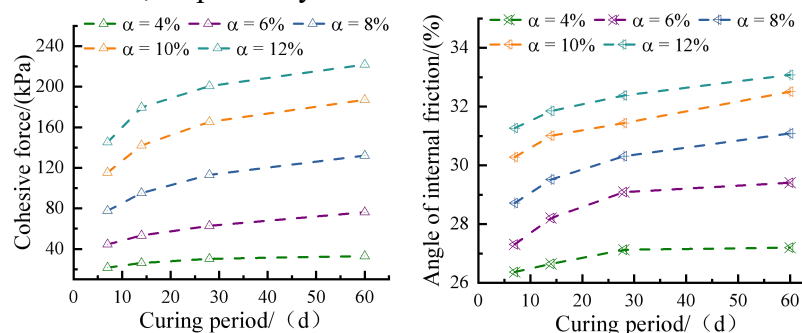


Fig.7 Relationship Between Curing Age and Cohesion

Fig.8 Relationship Between Curing Age and Internal Friction Angle

From Figure 7, it can be observed that the cohesion and internal friction angle of loess-based cement grout material increase to a certain extent with the increase in curing age. As the curing age increases, the growth rate of cohesion significantly improves. When the cement content is relatively high, the time required for cement hydration reactions is longer, and the ion exchange and hardening reactions in loess-based cement grout material become more sufficient, leading to a further increase in strength. Figure 8 shows that with the increase in curing age, both cohesion and internal friction angle of loess-based cement grout material are enhanced to a certain extent. However, compared to the growth in cohesion, the increase in the internal friction angle is noticeably smaller. As the shear strength of loess-based cement grout material is provided by both cohesion and internal friction angle, the increase in shear strength mainly relies on the increase in cohesion, with the contribution of the internal friction angle being relatively minor.

### 3.1.3 Compression Coefficient

The relationship between compression coefficient and cement content is shown in Figure 14, and the relationship between compression coefficient and curing age is shown in Figure 10.

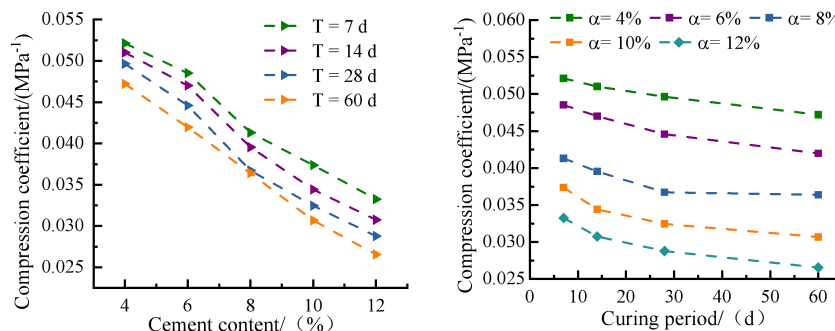


Fig.9 Relationship Between Compressibility and Cement Content

Fig.10 Relationship Between Compressibility and Curing Age

According to Figure 9, the compression coefficient of loess-based cement grout material is less than 0.1 MPa<sup>-1</sup>, indicating that it belongs to low compressibility soil. With an increase in cement content, the compression coefficient decreases. This is because cement strengthens the loess framework, fills the internal pores of the soil, significantly reduces the spacing between soil particles, and increases the interlocking effect between particles. As shown in Figure 10, the compression coefficient decreases with the increase in curing age. This is because with the increase in curing age, the particles in loess-based cement grout material gradually arrange more closely, increasing the contact area between particles and the compactness of the soil. Cement continuously generates hydration products during the curing period, filling the gaps between soil particles, collectively leading to a gradual reduction in the compression coefficient of the soil.

## 4. Conclusion

This paper takes loess as the main material, with cement and additives as auxiliary materials, and conducts experiments on the unconfined compressive strength, shear strength, and compressibility of loess-based cement grout material under different cement parameters and curing ages. The main conclusions are as follows:

(1) When the cement content is in the range of 4% to 12%, the unconfined compressive strength of loess-based cement grout material shows a linear relationship with cement content, and the unconfined compressive strength is in a quadratic relationship with curing age.

(2) The improvement of shear strength in loess-based cement grout material mainly relies on the growth of cohesion, with a relatively small contribution from the internal friction angle. When the cement content is less than 6%, the growth rate of cohesion in loess-based cement grout material is

slow. When the cement content is in the range of 6% to 12%, the growth rate of cohesion in loess-based cement grout material significantly accelerates. Additionally, with the increase in curing age, the cohesion of loess-based cement grout material continues to increase significantly.

(3) Through cement modification, under each cement content, the compression coefficient of loess-based cement grout material is less than 0.1 MPa-1, indicating that it belongs to low compressibility soil.

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