

Evaluation of the Effectiveness of Calcium Lignosulfonate for Loess Stabilization

Peiyao Li*

College of Geosciences and Engineering, North China University of Water Resources and Electric Power, Zhengzhou 450045, China

*E-mail address: x20231020199@stu.ncwu.edu.cn

Abstract

In recent years, lignin-based products have been increasingly investigated for soil improvement. In this study, calcium lignosulfonate (CLS) was adopted to enhance the mechanical behavior of loess. To quantify the effect of CLS on shear strength, specimens were prepared at a water content of 15% with three degrees of compaction (85%, 90%, and 95%). Six CLS dosages (0, 0.25%, 0.5%, 1%, 2%, and 4% by dry soil mass) were considered, and direct shear tests were conducted under normal stresses of 100, 200, 300, and 400 kPa. The results show that CLS addition effectively increased the shear strength of loess, mitigated post-peak softening, and improved the residual shear resistance, accompanied by notable enhancements in the shear strength parameters. A quadratic regression model for the peak shear stress (τ_p) was developed using a Box-Behnken response surface design. The model was highly significant overall, and the relative contribution of the factors followed the order: normal stress > degree of compaction > CLS dosage. Overall, the strength gain induced by CLS was primarily attributed to an increase in cohesion. Under the tested conditions, a low dosage of 0.25% CLS, combined with a higher degree of compaction, is recommended to achieve a more stable improvement in shear strength.

Keywords

Loess, Calcium Lignosulfonate, Shear Strength, Response Surface Methodology.

1. Introduction

Loess is widely distributed worldwide and is characterized by pronounced collapsibility and a tendency for its structure to destabilize upon wetting, which can trigger foundation failures and slope instability. Previous studies have shown that wetting-induced collapse is often accompanied by strength degradation, highlighting the need for stabilization or improvement measures to enhance its engineering suitability [1]. Traditional stabilizers such as lime and cement can effectively increase soil strength; however, their high energy demand and associated carbon emissions have raised growing environmental concerns. In addition, large material dosages and construction disturbance may further increase project costs [2]. In recent years, biomass-derived green stabilizers have attracted increasing attention owing to their potential for resource valorization and practical engineering applicability. Calcium lignosulfonate (CLS), a by-product of the pulping and papermaking industry, exhibits adsorption, dispersion, and cementation capabilities [3]. CLS is considered an eco-friendly and cost-effective stabilizer derived from industrial by-products. Existing studies suggest that it can strengthen interparticle bonding by promoting flocculation and aggregation, ionic bridging, and surface cementation, thereby improving the mechanical performance of fine-grained soils, sands, and cohesive soils [4,5]. Notably, CLS may exhibit a non-linear dosage effect. In cementitious systems, its performance has been linked to adsorption on particle (or binder

particle) surfaces and the modulation of electrostatic repulsion; varying dosages can shift the system between dispersed and flocculated states, leading to the emergence of an “optimal dosage window”. This further indicates that, in loess, the coupled effects of dosage, stress level, and compaction state should be quantified using a systematic experimental design [6]. From an application perspective, CLS has also been used as a sustainable stabilizer for clay improvement. Direct shear tests have demonstrated enhancements in strength parameters, and carbon footprint assessments indicate substantially lower emissions compared with conventional stabilizers such as cement and lime, providing evidence to support low-carbon stabilization strategies for loess regions [7].

Nevertheless, stabilization performance is strongly influenced by stress level and compaction state, and the strength enhancement provided by CLS in loess still requires systematic quantification under controlled conditions. On the one hand, failure mechanisms and the relative contributions to strength vary with normal stress, which may lead to different CLS effects on peak and residual strength; on the other hand, compaction modifies pore structure and interparticle contacts, potentially amplifying or diminishing the cementation-related benefits. Therefore, it is necessary to develop a shear-strength evaluation framework for CLS-stabilized loess based on direct shear testing, considering (i) shear response, (ii) the magnitude of strength gain, and (iii) variations in strength parameters, to support design parameter selection and construction quality control.

Accordingly, this study investigated natural loess and CLS-stabilized loess by conducting direct shear tests at a water content of 15%, using three degrees of compaction (85%, 90%, and 95%) and four normal stress levels (100, 200, 300, and 400 kPa). CLS was added at 0.25%, 0.5%, 1%, 2%, and 4% by dry soil mass. Specimens were prepared by simple mixing to represent an “instant stabilization” scenario that is closer to field practice. By comparing the shear stress–displacement responses and peak shear strengths and by fitting Mohr–Coulomb strength parameters (cohesion c and internal friction angle φ), the study systematically evaluated the magnitude and trends of shear-strength improvement induced by CLS under different dosages and compaction states, providing guidance for dosage selection and engineering application.

2. Materials and Methods

2.1. Materials

The loess used in this study was collected from the loess region of western Henan Province, China. This area exhibits the typical characteristics of northern Chinese loess while also showing certain site-specific features influenced by local environmental conditions. Loess in the Lingbao area is generally classified as moderately to highly collapsible; its structure deteriorates rapidly upon wetting. In addition, the vertical permeability is much higher than the horizontal permeability, which promotes intensive rainfall infiltration and aggravates erosion-induced structural damage in slopes. As a result, the landscape is characterized by dense gullies and strong surface dissection.

The calcium lignosulfonate (CLS) used in this study was supplied by Tianjin Huasheng Chemical Reagent Co., Ltd. It has a relative molecular mass of 528.61, and its aqueous solution exhibits a pH of 4.0–6.0, indicating weak acidity. CLS appears as a light- to dark-yellow powder, is readily soluble in water, and shows good stability (Fig. 1).



Fig.1 Appearance of CLS

2.2. Experimental Methods

(1) Direct shear test

Shear strength is a key indicator for evaluating the mechanical behavior of loess. Direct shear tests were conducted to quantify the improvements in shear strength, cohesion, and internal friction angle before and after stabilization. The loess was oven-dried and passed through a 2 mm sieve. The required amount of loess was then mixed thoroughly with CLS at dosages of 0.25%, 0.5%, 1%, 2%, and 4% (by dry soil mass). Water was subsequently added to achieve a target water content of 15%, and the mixture was sealed and stored for 24 h to allow moisture equilibration. After equilibration, the water content was re-measured using samples taken from three different locations within the mixture, with a maximum allowable deviation of no more than 1%. Once the requirement was satisfied, specimens were prepared using a standard ring cutter at degrees of compaction of 85%, 90%, and 95% based on a maximum dry density of 1.79 g/cm³. Direct shear tests were performed using a ZJ-type strain-controlled direct shear apparatus (four-unit shear box) manufactured by Nanjing Soil Instrument Factory.

(2) Response surface methodology

Response surface methodology (RSM) is an effective approach for optimizing process parameters and evaluating the effects of multiple factors and their interactions. Compared with conventional one-factor-at-a-time and orthogonal experimental approaches, RSM enables continuous analysis across the factor levels. RSM fits the functional relationship between factors and the response by constructing a multivariate quadratic regression model, thereby addressing key limitations of one-factor-at-a-time and orthogonal designs, such as the inability to interpret factor interactions and to provide an explicit regression model linking factors to the response. Common RSM experimental designs include the Box–Behnken design and the central composite design. In this study, CLS dosage, normal stress, and degree of compaction were selected as the three factors in the RSM analysis. The corresponding coded levels and actual values are listed in [Table 1](#).

Table 1. Factors and their coded levels for the Box–Behnken design.

| Factors | notation | units | coded factor levels | | |
|-------------------|----------|-------|---------------------|-----|-----|
| | | | -1 | 0 | 1 |
| Dosage of CLS | A | % | 0.25 | 0.5 | 1 |
| Direct stress | B | kPa | 100 | 200 | 300 |
| Compaction degree | C | % | 85 | 90 | 95 |

3. Results and Analysis

3.1. Analysis of Shear Stress–displacement Responses

The shear stress–displacement curves of the natural loess and CLS-treated specimens indicate that, as the normal stress increases from 100 to 400 kPa, the shear stress level increases monotonically for all mixtures. The curves generally exhibit a typical strain-hardening pattern, characterized by rapid mobilization, attainment of a peak, and transition to a stable residual stage, demonstrating that normal stress markedly enhances interparticle contact and frictional resistance. At normal stresses of 100–300 kPa, the natural loess shows pronounced post-peak softening (Fig. 2): the shear stress reaches a peak at approximately 1–2 mm displacement and then decreases toward a stable value, suggesting that structural breakdown weakens bonding and reduces shear resistance. By contrast, under 400 kPa the response becomes predominantly strain-hardening with negligible post-peak softening, indicating that a higher normal confinement suppresses dilation and rapid structural collapse along the shear plane, resulting in a friction-dominated and more stable load-bearing behavior.

The incorporation of CLS substantially alters both curve shape and strength level. Specimens with 0.25% and 0.5% CLS exhibit markedly higher peak and residual shear stresses than the natural loess under all normal stresses, together with reduced post-peak softening and a more stable residual stage, indicating concurrent improvements in shear capacity and softening resistance (Figs. 3 and 4). The improvement is particularly pronounced at 100 and 200 kPa. For 0.25% CLS, the peak shear strength increases from 32.14 and 47.18 kPa to 67.69 and 95.38 kPa, respectively, corresponding to more than a twofold increase. These results imply that, under low normal stress, CLS effectively cements soil particles and substantially enhances both peak and residual shear resistance, which may help mitigate the severity of loess-related geohazards in practice. In contrast, under a high normal stress of 400 kPa the strength still increases but with a smaller margin, suggesting that shear resistance becomes dominated by friction and densification, and the incremental contribution from CLS-induced cementation is less pronounced.

Notably, the strength gain does not increase monotonically with dosage. When the CLS dosage reaches 1% or higher, the shear stress level tends to decrease (Fig. 5). Under 100–300 kPa, specimens with 2% and 4% CLS exhibit lower peak and stable shear stresses than those with 0.25% and 0.5% CLS, and in some cases they approach or are only slightly higher than the natural loess (Fig. 6 and Fig. 7). This suggests the existence of an optimal dosage range. Beyond this range, excessive organic salt may lead to thicker adsorbed layers and looser aggregates, thereby reducing effective interlocking and frictional contributions and ultimately decreasing shear strength. Considering both peak strength and residual stability, low CLS dosages enable rapid mobilization of higher shear resistance at small displacements and maintain improved residual capacity, demonstrating effective enhancement of loess shear strength and stability. By contrast, higher dosages require stricter control of mixing uniformity and water addition to avoid the adverse effect of “over-dosage-induced strength reduction.”

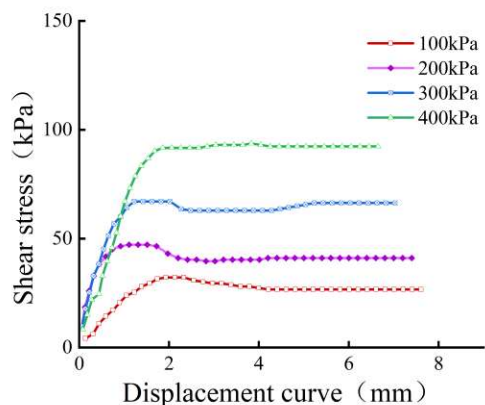


Fig.2 Untreated soil shear stress-strain curve

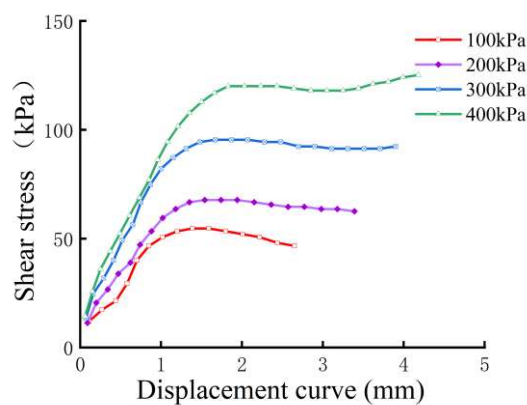


Fig.3 0.25% CLS-treated soil shear stress-strain curve

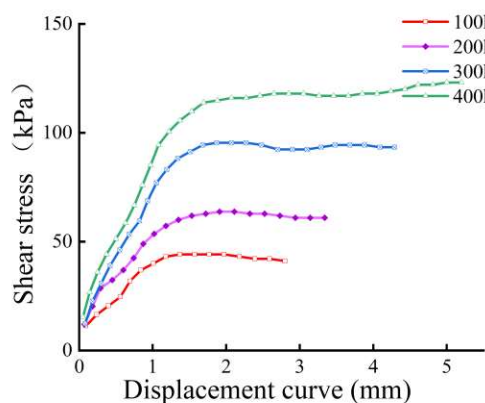


Fig.4 0.5% CLS-treated soil Shear stress-strain curve

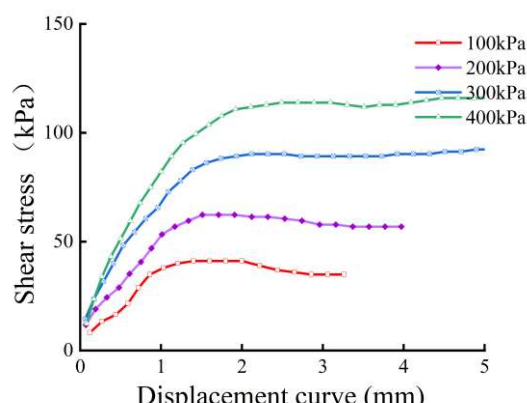


Fig.5 1% CLS-treated soil Shear stress-strain curve

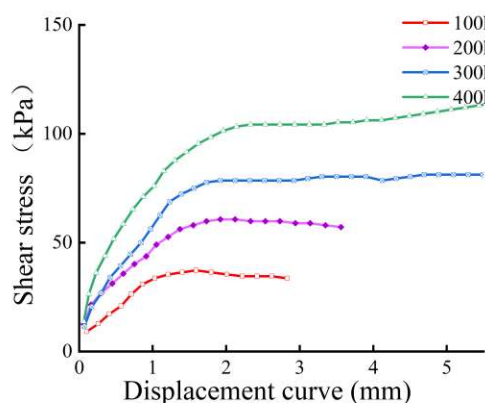


Fig.6 2% CLS-treated soil Shear stress-strain curve

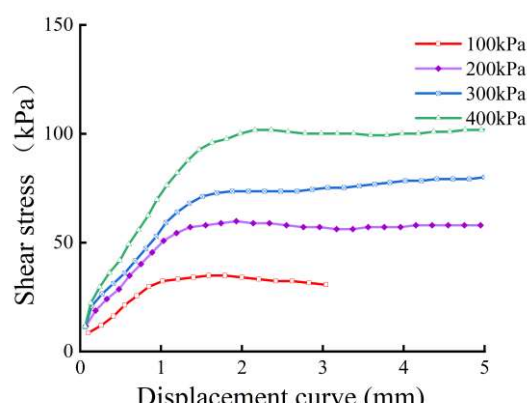


Fig.7 4% CLS-treated soil Shear stress-strain curve

3.2. Analysis of Shear Strength Parameters

As shown in Fig. 8 and Fig. 9, increasing the degree of compaction elevates both the cohesion c and the internal friction angle φ , reflecting the fundamental roles of pore compression, increased interparticle contacts, and densification of the shear plane in governing strength parameters. For the natural loess, c increases from 5.13 to 9.23 kPa and φ increases from approximately 10.58° to 11.44° , indicating relatively modest gains primarily attributable to

densification and enhanced frictional resistance. After CLS addition, both parameters increase; however, the sensitivity differs markedly, with a much larger increase in c than in φ . At 95% compaction, for example, the cohesion of 0.25% CLS yields 20.41 kPa—more than doubling that of the natural loess—while φ increases to approximately 15.23° , corresponding to a 33.13% increase. A similar trend is observed at 85% compaction: c increases from about 5.13 kPa to 12.86 kPa, whereas φ increases only from about 10.58° to approximately 13.46° . These results indicate that CLS stabilization primarily promotes an apparent increase in cohesion through enhanced interparticle cementation, whereas its effect on the friction angle is comparatively weaker.

Further comparison across dosages reveals a clear non-linear dosage effect for both c and φ : low dosages (0.25% and 0.5% CLS) provide the best overall performance, and their advantages become more pronounced at higher compaction. Among all mixtures, 0.25% CLS yields the highest c and φ across the three compaction levels. Specifically, c reaches 12.86, 13.69, and 20.41 kPa at 85%, 90%, and 95% compaction, corresponding to increases of 150.68%, 90.67%, and 121.13%, respectively. The corresponding φ values are 13.46° , 14.68° , and 15.23° , representing increases of 27.22%, 35.05%, and 33.13%, respectively. The 0.5% CLS mixture performs second best, with significant improvements in both cohesion and friction angle. When the dosage increases to 1%–2%, both parameters still increase with compaction, but the magnitude of improvement becomes less pronounced. Notably, for 4% CLS the friction angle under high compaction becomes lower than that under low compaction, suggesting that excessive CLS may induce non-uniform aggregation, limiting effective interlocking and frictional contributions and thereby suppressing the increase in φ . In contrast, c still increases markedly at high compaction, indicating that a denser soil skeleton can partially offset the adverse effects of high dosage and allow cementation-related contributions to be mobilized. Overall, CLS improves loess strength primarily by increasing c , and under the present conditions (15% water content, simple mixing, and no curing), 0.25%–0.5% appears to be the most appropriate dosage range.

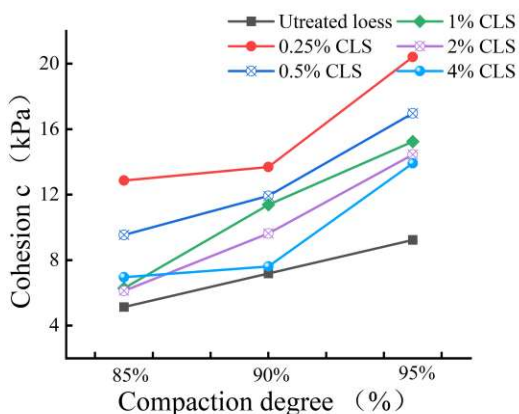


Fig.8 Trend of the cohesion

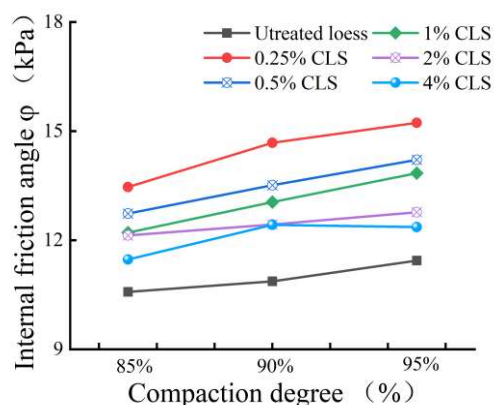


Fig.9 Trend of the angle of internal friction

3.3. Integrated Response Surface Analysis

To further investigate the effects of CLS dosage, normal stress, and degree of compaction on the shear strength of loess, a Box–Behnken response surface design was adopted. A three-factor, three-level scheme was employed to develop a predictive model for the peak shear stress τ_p . The experimental design matrix and corresponding results are summarized in Table 2. A second-order polynomial regression was fitted to predict τ_p , as expressed in Eq. (1), and the analysis of variance (ANOVA) results for model regression are presented in Table 3.

$$\tau_p = 491.76 - 99.84A - 0.18B - 10.40C - 0.004AB + 0.71AC + 0.002BC + 20.37A^2 + 0.0007B^2 + 0.06C^2 \tag{1}$$

The ANOVA results indicate that the peak shear stress model is highly significant (F=114.91, P<0.0001). The coefficient of determination is R²=99.33%, demonstrating excellent agreement between the model predictions and the experimental observations. The model exhibits a low coefficient of variation (CV = 3.68%), well below the commonly accepted threshold of 10%. In addition, R²_{adj}=98.46 and R²_{pre}=92.77%, indicating that the proposed model is stable and has good predictive capability within the investigated domain. According to ANOVA, normal stress (B) exerts the most significant effect, confirming that the peak shear stress is primarily governed by normal confinement. The degree of compaction (C) is the second most influential factor, suggesting that improved compaction enhances interparticle contact and structural densification, thereby increasing shear load-bearing capacity. The CLS dosage (A) is also statistically significant, indicating that CLS provides a measurable gain in peak strength within the studied dosage range, although its contribution is smaller than those of B and C. The interaction terms AB, AC, and BC are not significant at the 0.05 level (P>0.05), indicating weak coupling among the factors and that variations in τ_p are dominated by the individual main effects. Among the quadratic terms, only B² is highly significant, whereas A² and C² are not significant. This finding demonstrates a pronounced non-linear response of peak shear stress to normal stress, i.e., τ_p does not increase strictly linearly with B. In contrast, within the current factor ranges, τ_p varies more approximately linearly with CLS dosage and compaction degree. Model-based optimization suggests that the combination of 0.25% CLS, 300 kPa normal stress, and 90% compaction provides the most cost-effective improvement in the shear strength of loess.

Table 2. Response surface design and results for peak shear stress of soil

| Sample | A/% | B/kPa | C/% | Peak shear stress τ_p /kPa |
|--------|------|-------|-----|---------------------------------|
| 1 | 0.5 | 200 | 90 | 55.3839 |
| 2 | 0.5 | 100 | 95 | 44.102 |
| 3 | 0.5 | 200 | 90 | 54.4368 |
| 4 | 1 | 200 | 95 | 62.2762 |
| 5 | 0.25 | 200 | 85 | 56.4096 |
| 6 | 0.25 | 100 | 90 | 46.6661 |
| 7 | 0.5 | 200 | 90 | 53.2488 |
| 8 | 0.5 | 200 | 90 | 57.6832 |
| 9 | 0.25 | 200 | 95 | 67.6915 |
| 10 | 1 | 100 | 90 | 36.9226 |
| 11 | 0.5 | 300 | 85 | 82.0503 |
| 12 | 0.5 | 100 | 85 | 33.8457 |
| 13 | 0.5 | 200 | 90 | 56.4368 |
| 14 | 1 | 300 | 90 | 81.0247 |
| 15 | 0.25 | 300 | 90 | 89.2297 |
| 16 | 0.5 | 300 | 95 | 95.3835 |
| 17 | 1 | 200 | 85 | 46.0302 |

Table 3. ANOVA of the regression model for peak shear stress of loess

| Source of variance | quadratic sum | mean square | F-value | p-value | Prominence |
|--------------------|---------------|-------------|---------|---------|-----------------|
| Model | 5035.89 | 559.54 | 114.91 | <0.0001 | Significant |
| residual error | 34.09 | 4.87 | / | / | |
| A | 142.33 | 142.33 | 29.23 | 0.0010 | Significant |
| B | 4106.64 | 4106.64 | 843.35 | <0.0001 | Significant |
| C | 332.21 | 332.21 | 68.22 | <0.0001 | Significant |
| AB | 0.0848 | 0.0848 | 0.0174 | 0.8987 | Not significant |
| AC | 7.48 | 7.48 | 1.54 | 0.2551 | Not significant |
| BC | 2.37 | 2.37 | 0.4861 | 0.5082 | Not significant |
| A ² | 25.78 | 25.78 | 5.29 | 0.0549 | Not significant |
| B ² | 199.49 | 199.49 | 40.97 | 0.0004 | Significant |
| C ² | 9.78 | 9.78 | 2.01 | 0.1993 | Not significant |

Note: P<0.05 indicates statistical significance, and P<0.0001 indicates a highly significant difference, R2 =0.9933.

3.4. Particle Size Distribution Analysis

To further verify the effectiveness of 0.25% CLS stabilization, particle size distribution (PSD) tests were performed on the natural loess and CLS-treated loess using a wet-method particle size analyzer. As shown in Fig. 10, the particle sizes of the natural loess are mainly distributed in the range of 10–60 μm. For the 0.5% CLS mixture and the higher-dosage mixtures, the overall PSD shape is nearly identical to that of the natural loess; however, the distribution becomes more uniform. Compared with the natural loess, the proportions of finer particles and coarser fractions increase. For brevity, only the PSD curves for 0.5% and 1% CLS are presented in Fig. 11. In contrast, the 0.25% CLS-treated loess shows a distinct change in PSD, with an additional small peak emerging near 1 μm. This observation suggests that 0.25% CLS can effectively modify the soil fabric by promoting the formation of fine aggregates or redistributed fines, thereby improving the structural skeleton and enhancing shear strength.

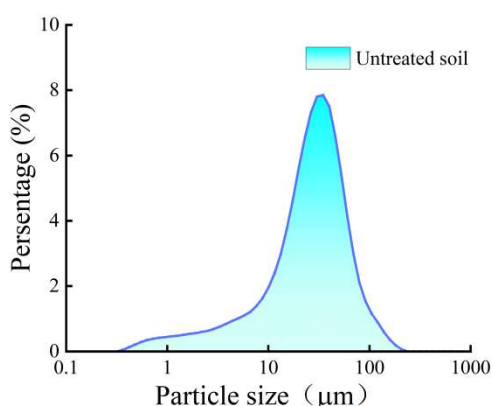


Fig. 10 Grain size curve of untreated soil

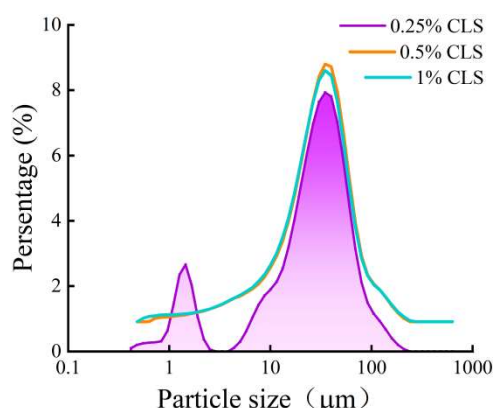


Fig. 11 Grain size curve of CLS-untreated soil

4. Conclusion

This study investigated the shear strength of CLS-stabilized loess through direct shear tests under different CLS dosages and degrees of compaction. Response surface methodology (RSM) and laser particle size analysis were further employed to interpret and validate the experimental findings. The main conclusions are summarized as follows:

(1) CLS improves the shear strength of loess to a noticeable extent, with the most pronounced enhancement observed at a dosage of 0.25%. The addition of CLS shifts the shear stress–displacement response from post-peak softening toward strain-hardening behavior, and this hardening tendency becomes more evident at higher compaction levels. Under low compaction, the relative gain in shear strength is more pronounced.

(2) The strength-parameter results show that CLS has a much greater effect on cohesion c than on the internal friction angle φ , indicating that the dominant strengthening mechanism is an apparent increase in cohesion associated with cementation. The improvements in c and φ are non-linear with respect to dosage: low dosages exhibit superior overall performance, whereas at high dosages ($\geq 2\%$) the increase in φ tends to plateau or even slightly decrease.

(3) The RSM results further confirm that peak strength is primarily governed by normal stress and degree of compaction, while the effect of CLS dosage is comparatively weaker; interactions among the three factors are also weak. The particle size distribution analysis provides microstructural evidence supporting that 0.25% CLS delivers the optimal improvement for loess.

References

- [1] Aro, T., & Fatehi, P. (2017). Production and application of lignosulfonates and sulfonated lignin. *ChemSusChem*, 10(9), 1861–1877. <https://doi.org/10.1002/cssc.201700082>
- [2] Chavali, R. V. P., & Reshmarani, B. (2020). Characterization of expansive soils treated with lignosulfonate. *International Journal of Geo-Engineering*, 11, 17.
- [3] Fernandez, J., Bian, H., Bian, Y., Kim, J., Wang, C., Walther, D., Lee, H., & Chen, Y. (2024). Unraveling the interplay: Impact of lignin type on oil spill remediation by organoclays. *Environmental Technology & Innovation*, 33, 103475. <https://doi.org/10.1016/j.eti.2023.103475>
- [4] Tabarsa, A., Latifi, N., Meehan, C. L., & Majid, M. Z. A. (2018). A laboratory investigation and field evaluation of loess improvement using nanoclay-A sustainable material for construction. *Construction and Building Materials*, 158, 454–463. <https://doi.org/10.1016/j.conbuildmat.2017.09.167>
- [5] Tiwari, N., Satyam, N., & Gupta, A. K. (2021). Strengthening of pavement subgrade soil using lignin. *Transportation Geotechnics*, 27, 100491. <https://doi.org/10.1016/j.trgeo.2020.100491>
- [6] Wang, W., Duan, G., Guan, K., Li, Y., Fu, S., & He, X. (2023). Sustainable, multifunctional, and high-performance cellulose nanofiber-based composites reinforced by metal and metal oxide nanoparticles for water treatment and oil spill remediation: A review. *Materials*, 16(3), 1355. <https://doi.org/10.3390/ma16031355>
- [7] Zhang, X., Zhang, X., Yan, Y., Zhang, X., Ren, J., Xu, Y., Xia, W., & Gong, J. (2024). Preparation of lignosulfonate-based zwitterionic composite materials for efficient adsorption and separation of oil spill. (Preprint).