Experimental Assessment Of Mechanical Properties Of Silty Soil Improved By Xanthan Gum

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Abstract: This study investigated the effects of xanthan gum dosage and curing time on the mechanical properties of silty soil through unconfined compression tests. Xanthan gum dosages of 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% were selected, combined with curing times of 0, 4, 7, and 14 days. Results indicated that xanthan gum significantly enhanced soil strength, with unconfined compressive strength increasing continuously with higher dosages and longer curing periods. Concurrently, the failure mode gradually transitioned from plastic flow to brittle failure. Strength exhibited rapid initial increase followed by gradual stabilization with increasing dosage, with an optimal range of 2%–3%. Strength increased logarithmically with curing time, reflecting rapid early development of the cementation network. A mathematical model was established to predict the strength. Model validation demonstrated excellent agreement between calculated and experimental values. This research provides a quantitative tool for optimizing xanthan gum-based soil improvement in engineering applications.

Keywords: Silty soil; Xanthan gum; Stabilization; Unconfined Compressive Strength.

1. Introduction

In geotechnical engineering construction, silty soil is prone to engineering problems such as excessive foundation settlement, uneven deformation, and even instability sliding under load due to its unfavorable engineering characteristics, including high natural moisture content, low strength, and high compressibility [1-3]. Therefore, effectively improving the mechanical properties of silty soil to enhance its bearing capacity and deformation resistance has become a critical issue that requires urgent resolution in the field of geotechnical engineering.

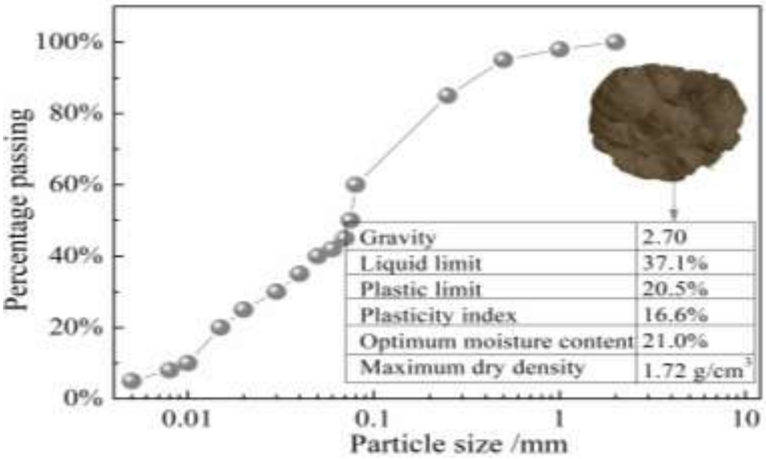
To improve the mechanical performance of such problematic soils, inorganic cementitious agents, most notably cement, lime, and fly ash, have been routinely employed in geotechnical engineering for soil stabilization [4-6]. These conventional additives function through hydration reactions that generate cementitious products such as calcium silicate hydrate, which fill intergranular voids and enhance particle bonding, thereby improving soil strength, stiffness, and water resistance [5,6]. Over decades of engineering practice, cement and lime stabilization techniques have matured into well-established methodologies supported by robust theoretical frameworks, and they remain widely adopted in applications such as road subgrade construction, foundation improvement, and slope reinforcement [7,8]. Nevertheless, the growing emphasis on sustainable development within civil engineering has brought the limitations of these traditional approaches into sharper focus. The production of cement and lime is energy intensive and associated with considerable CO_2 emissions, an environmental burden increasingly at odds with global imperatives for low-carbon development [9]. Moreover, the introduction of highly alkaline stabilizers can elevate the pH of surrounding soil and water, disrupt local ecological equilibria, and adversely affect microbial communities and vegetation [10]. Additional drawbacks, including susceptibility to drying shrinkage cracking and poor compatibility with organic-rich soils, further constrain the applicability of conventional stabilizers under certain site conditions [11]. In response to these challenges, the search for environmentally benign, operationally simple, and mechanically effective alternative stabilizers has emerged as a priority in contemporary geotechnical research. Bio-based materials have garnered growing international interest owing to their renewability, environmental compatibility, and distinctive physicochemical characteristics [12-14]. Among these, biopolymers, a class of macromolecular compounds synthesized by microorganisms or derived from natural biomass, have shown particular promise for soil improvement, capitalizing on their pronounced thickening, gelling, and water-retention capacities [13]. Mechanistically, biopolymers interact with soil particle surfaces via non-covalent forces, including hydrogen bonding, van der Waals interactions, and electrostatic attraction, forming three-dimensional polymeric networks that bridge adjacent particles and concurrently enhance both the mechanical and hydrological behavior of the treated soil [14]. Relative to their inorganic counterparts, biopolymers offer several practical advantages, including lower dosage requirements, simplified application procedures, and a reduced environmental footprint. A range of biopolymers, including gellan gum, guar gum, chitosan, and xanthan gum, have been explored for soil stabilization purposes [15-17]. Xanthan gum, in particular, has attracted considerable attention within the biogeotechnical engineering community due to its unique molecular architecture and robust physicochemical stability, demonstrating notable efficacy in applications spanning erosion control, heavy metal immobilization, and foundation reinforcement [17]. Despite these advances, existing studies have primarily focused on establishing the baseline mechanical response of xanthan gum-stabilized soils [18,19]. Critical knowledge gaps persist regarding the temporal evolution of mechanical properties under varying curing regimes, the coupled influence of polymer dosage and curing duration, and, most notably, the lack of robust quantitative frameworks for predicting strength development. These deficiencies collectively impede the translation of xanthan gum stabilization from laboratory research to reliable field implementation.

In this study, unconfined compression tests were performed on silty soil from Jingzhou, Hubei Province, to evaluate the effects of xanthan gum dosage and curing time on its mechanical behavior. A mathematical model was developed and validated using the experimental data to predict strength evolution. This work aims to provide the theoretical and experimental basis necessary for the practical implementation of this sustainable modification approach.

2. Materials and methods

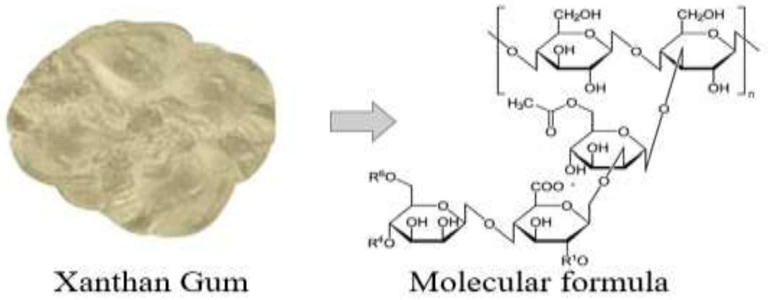
The soil sample used in this study was collected from Jingzhou City, Hubei Province. The collected soil sample was crushed and then oven-dried at a temperature range of 102°C to 105°C for more than 8 hours. After drying, the soil was passed through a 2 mm sieve and reserved for subsequent testing. The physical properties of the soil sample were determined in accordance with the Standard for Geotechnical Testing Method [20], and the results are presented in Figure 1. It is shown from the particle size distribution curve that the particle sizes of the soil sample are mainly concentrated in the range of 0.005 mm to 2 mm, with a relatively high proportion of fine-grained components being observed. The gradation curve is characterized by a continuous distribution pattern, which reflects good continuity in the particle composition of the soil sample. Based on the Atterberg limits and plasticity index, the soil sample can be classified as low-liquid-limit silt. Reliable fundamental parameters for subsequent mechanical property tests are provided by these typical physical and mechanical characteristics of fine-grained soil.

Figure.1 Physical properties of soil sample



Xanthan gum is recognized as a typical anionic microbial polysaccharide, characterized by a highly regular main chain and branched structure, as illustrated in Figure 2. As can be seen from the molecular structure, the main chain of xanthan gum is composed of glucose units linked by β-1,4-glycosidic bonds. A trisaccharide side chain consisting of mannose, glucuronic acid, and mannose is attached to every other glucose unit. The terminal mannose residues in the side chains are often substituted with pyruvate or acetate groups, and some hydroxyl groups may undergo further substitution. Owing to this unique branched configuration and the distribution of anionic functional groups, xanthan gum molecules readily form rigid double-helical structures in aqueous solutions. As a result, the polymer exhibits excellent thickening properties, shear-thinning behavior, and colloidal stability. These characteristics render it a promising material for geotechnical engineering applications [18,19].

Figure.2 Molecular formula of xanthan gum



To investigate the effects of xanthan gum dosage and curing time on the mechanical properties of modified soil, xanthan gum dosages of 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% were selected in this study, and curing times of 0, 4, 7, and 14 days were employed, with the specimen preparation and testing procedures illustrated in Figure 1. A predetermined mass of dry soil was first weighed, and the required mass of xanthan gum was calculated based on the specified dosage, after which the xanthan gum and dry soil were thoroughly mixed until a homogeneous mixture was achieved. Purified water was then added to the soil mixture according to the optimum moisture content, and the mixture was thoroughly blended again to ensure uniformity, followed by sealing with plastic film and allowing it to stand for 12 hours to achieve uniform moisture distribution within the soil. After moisture conditioning, the soil was placed into a static compaction mold with an inner diameter of 39.1 mm, and specimens were prepared using layered compaction in three layers with a compaction degree of 95%, where each layer was compacted to a predetermined height and its surface was scarified before the next layer was placed and compacted. Upon completion of compaction, the specimen was extracted from the mold using a sample extruder, and the prepared specimens, with a diameter of 39.1 mm and a height of 80 mm, were then cured in an environment maintained at a temperature of 25°C±2°C and a relative humidity of 50% until the prescribed curing time was reached. Unconfined compressive strength tests were performed after the curing period, during which each specimen was placed in the testing apparatus and axial loading was applied to obtain the stress-strain response curve under strain-controlled loading at an axial loading rate of 1 mm/min, with three parallel specimens tested for each experimental condition to ensure the reliability of the test data.

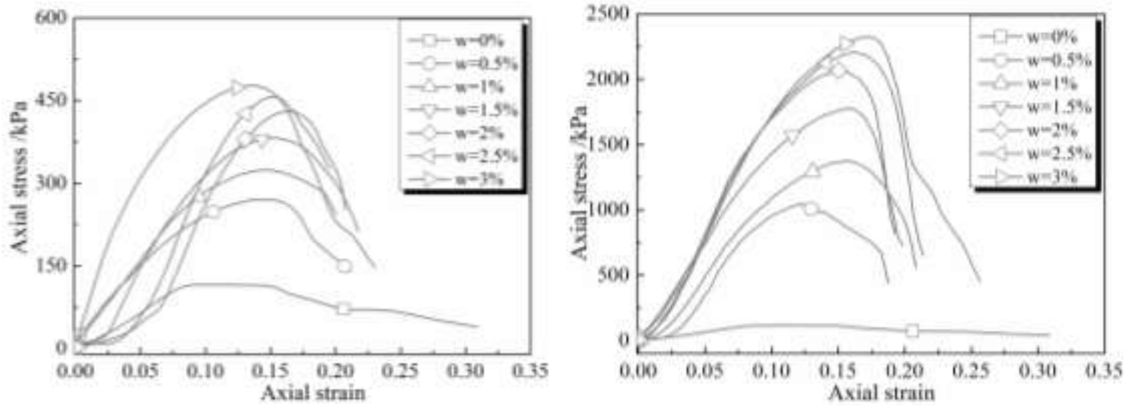
Figure.3 Testing procedure

3. Experimental results

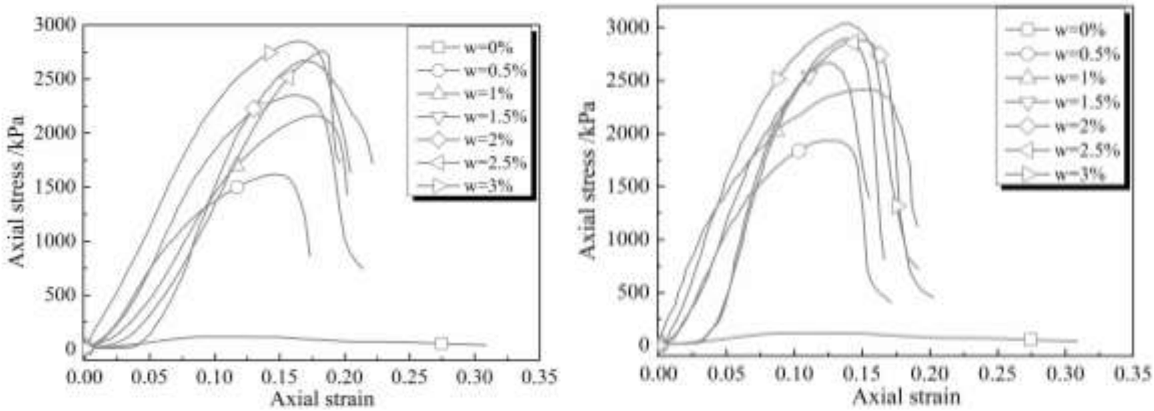
Stress-Stain Responses

The uniaxial compressive stress-strain curves of specimens with different curing times and xanthan gum dosages are presented in Figure 4. All curves are characterized by typical strain-softening behavior, and their features are systematically influenced by gum dosage and curing time. For the reference specimens without xanthan gum (w=0%), low strength and weak strain-softening characteristics were observed at all curing stages. Stress levels remained low even after the axial strain exceeded 0.20. This behavior is attributed to the predominantly plastic flow deformation of soft soil, which is fundamentally caused by the absence of effective interparticle cementation. As xanthan gum dosage was increased, the shape of the stress-strain curves was significantly altered. Both peak stress and peak strain were increased simultaneously. The slope of the rising segment was steepened, and the elastic stage became more pronounced. Meanwhile, the post-peak descending segment gradually became well-defined, indicating a transition toward brittle failure. For specimens with gum dosage w≥1%, a clear peak point was observed in all curves, after which stress decreased gradually with increasing strain. Faster post-peak stress reduction and more pronounced brittle failure characteristics were associated with higher gum dosages. This suggests that a cementation structure is established within the soil matrix by the incorporation of xanthan gum, by which the failure mode is fundamentally altered. Curing time was also found to exert a significant influence on the curve characteristics. As curing time was extended from 0 days to 14 days, the slope of the rising segment was continuously increased for specimens at all gum dosages. The peak point was shifted toward higher strain and higher stress levels, and the post-peak descending segment was steepened. This trend can be illustrated by specimens with w=3% gum dosage. At 0 days of curing, the peak strain was approximately 0.131, and stress decreased gradually after the peak, with certain ductility being exhibited. At 14 days of curing, the peak strain was increased to approximately 0.148, and a rapid stress drop was observed after the peak, indicating significantly enhanced brittle failure characteristics. This trend demonstrates that the cementation bonding between xanthan gum and soil particles is progressively strengthened with curing time. Consequently, a transition from plastic flow to brittle failure is induced in soil behavior, while both the initial stiffness and peak strength of the specimens are significantly improved. The peak position, rising slope, and post-peak decay rate of the stress-strain curves are jointly determined by xanthan gum dosage and curing time through the regulation of the development degree of the internal cementation structure. The failure mode and macroscopic mechanical behavior of the modified soil are profoundly influenced by this synergistic effect.

Figure.4 Typical stress-strain Responses



(a) 0 day **(b) 4 day**

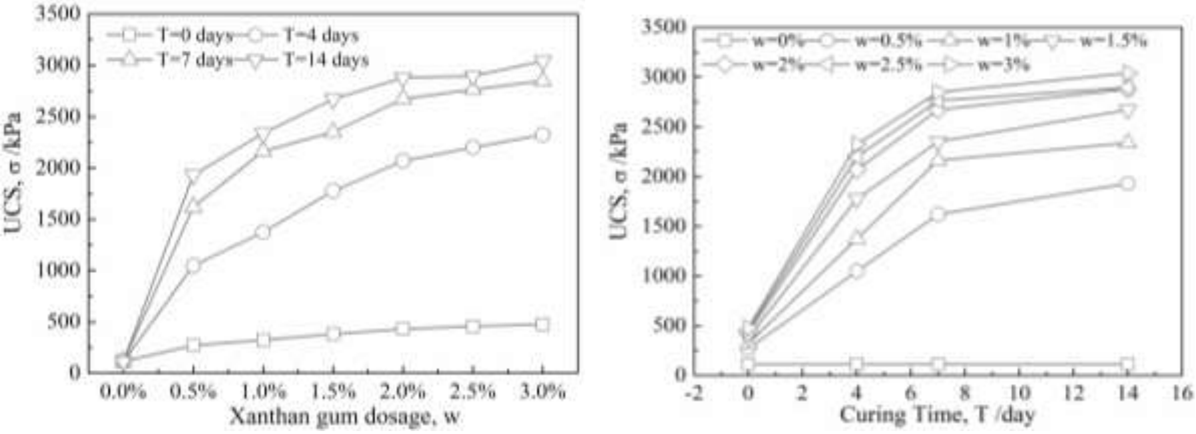


(c) 7 day **(d) 14 day**

Unconfined compressive strength

The variation in unconfined compressive strength (UCS) of soil with different xanthan gum dosages and curing times is presented in Figure 5. The experimental results indicate that for the control specimens without xanthan gum (w = 0%), the strength remained at a very low level (approximately 450 kPa) across all curing stages and did not increase with prolonged curing. This reflects the inherently weak interparticle bonding and lack of effective cementation in the native soft soil. As xanthan gum dosage increased, the strength of specimens at each curing time showed a significant increasing trend; however, the magnitude of increase was strongly influenced by curing time. At 0 days of curing, increasing the gum dosage from 0% to 3% resulted in a modest strength increase from approximately 116.1 kPa to approximately 477.3 kPa. In contrast, at 14 days of curing, the same increase in gum dosage led to a substantial strength increase from approximately 116.1 kPa to approximately 3042.5 kPa, representing more than a 26-fold improvement. The underlying mechanism is that xanthan gum molecules must gradually unfold in the aqueous environment, forming hydrogen bonds and electrostatic adsorption with soil particle surfaces. Through the entanglement and cross-linking of polysaccharide chains, a three-dimensional network structure is established, binding discrete soil particles into an integrated matrix. The full development of this structure requires sufficient curing time. Regarding the effect of gum dosage, the strength increase followed a pattern of rapid initial growth followed by gradual stabilization. The most significant strength gain occurred within the gum dosage range of 2% to 3%, while excessively high dosages did not yield a linear strength improvement. This is because an optimal amount of xanthan gum can adequately coat soil particles and form a continuous cementation network. Excessive gum dosage, however, may lead to over-entanglement of molecular chains, hindering effective contact between the cementation structure and soil particles. Additionally, it may introduce excessive weakly bound water, weakening the overall skeleton strength. These observations indicate that there exists an optimal gum dosage range for xanthan gum-modified soil. From the perspective of curing time, the strength of specimens at all gum dosages continued to increase with prolonged curing, and the rate of strength gain accelerated with increasing gum dosage. For example, for specimens with w = 3% gum dosage, the strength was approximately 477.3 kPa at 0 days, increased to approximately 2325.8 kPa at 4 days, further increased to approximately 2849.3 kPa at 7 days, and approached 3042.1 kPa at 14 days, demonstrating a pronounced time-dependent strengthening characteristic. The mechanism is that as curing time progresses, the hydration, hydrogen bonding, and ionic bonding interactions between xanthan gum molecules and soil particles continue to intensify. The density and stiffness of the network structure progressively increase, while gradual moisture loss further densifies the cementation film, thereby continuously enhancing the overall load-bearing capacity of the soil. The synergistic effect of xanthan gum dosage and curing time is the key factor determining the strength of modified soil. By regulating the formation rate, development degree, and densification level of the polysaccharide cementation network, these two factors jointly achieve a significant improvement in the mechanical properties of the soil.

Figure.5 Evolution of Unconfined compressive strength



(a) Xanthan gum dosage **(b) Curing Time**

Mathematical Model for Predicting Unconfined Compressive Strength

To quantify the effects of xanthan gum content and curing time on the unconfined compressive strength (UCS) of soil, the variation of normalized UCS (σ^N) with xanthan gum dosage (w) at different curing stages was fitted using an exponential function, as shown in Figure 6(a). The model can be uniformly expressed as:

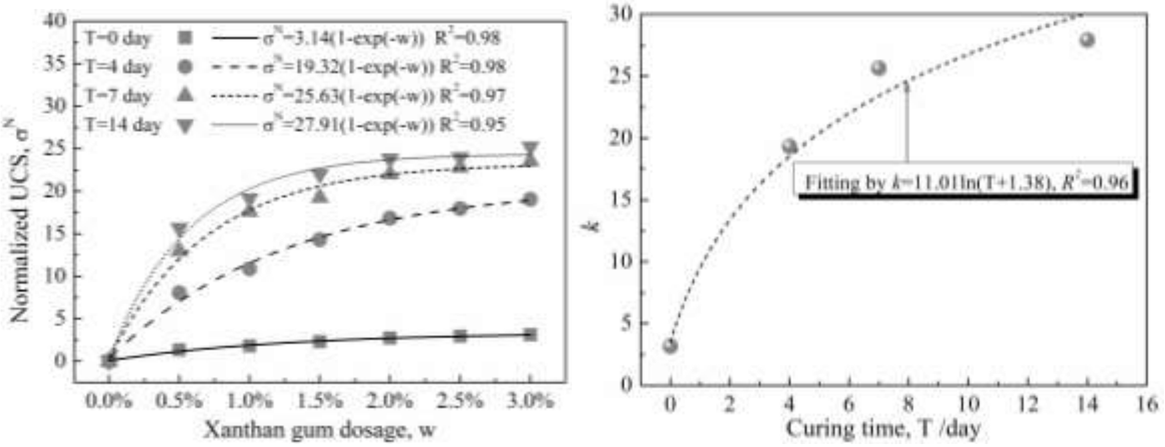
$$\sigma^N = \frac{\sigma - \sigma_{\mathrm{w=0\%}}}{\sigma_{\mathrm{w=0\%}}} = k(1-\exp(-w)) \qquad (1)$$

where σ^N is the normalized unconfined compressive strength, $\sigma_{\mathrm{w=0\%}}$ is the unconfined compressive strength of the specimen with 0% xanthan gum dosage, and k is the model coefficient. The fitting determination coefficients (R^2) for each curing time are all greater than 0.95, indicating that this function effectively describes the increasing trend of normalized strength with gum content. Furthermore, the decay parameter k in the model gradually increases with curing time, reflecting that the strengthening effect of xanthan gum on the soil progressively enhances over time. The relationship between the model parameter k and curing time (T) was further fitted, yielding a logarithmic empirical model:

$$k = a\ln(T+b) \qquad (2)$$

Regression analysis of the relationship between parameter k and curing time (T) yields the model parameters a and b as 11.01 and 1.38, respectively, with a determination coefficient of 0.96, accurately capturing the evolution of the parameter with curing time, as shown in Figure 6(b). The parameter k can be interpreted as the development rate of the xanthan gum cementation network. Its logarithmic growth with curing time indicates that the cementation structure develops rapidly in the early stages and gradually stabilizes over time. This behavior is consistent with the hydration and cementation process, where xanthan gum molecules progressively unfold between soil particles and form a three-dimensional network structure through hydrogen bonding and electrostatic interactions. Through the proposed mathematical model, the normalized strength of modified soil under different xanthan gum contents and curing times can be quantitatively predicted, providing a theoretical basis and calculation tool for optimizing modification schemes in engineering applications.

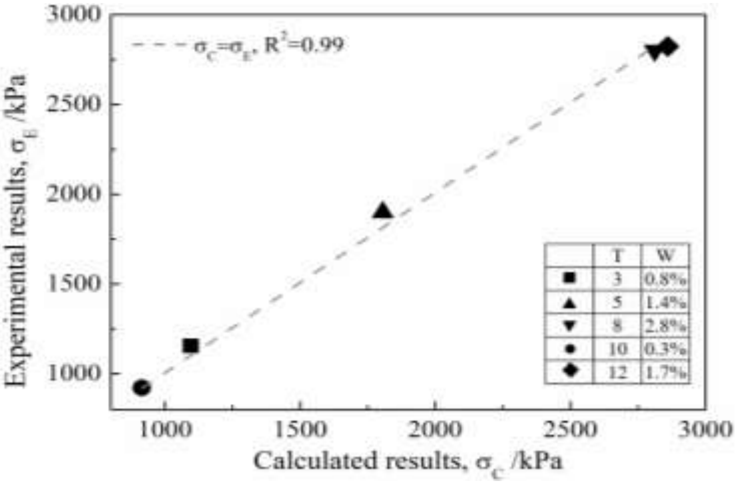
Figure.6 Prediction model for unconfined compressive strength of xanthan gum-modified soil



(a) Normalized UCS vs. dosage **(b) Model parameter k vs. curing time**

To verify the reliability of the established mathematical model for the unconfined compressive strength of xanthan gum-modified soil, multiple groups of specimens with different curing times and xanthan gum contents were selected for validation tests, as shown in Figure 7. As can be seen from Figure 7, the model-calculated values σ_C were compared with the experimental measured values σ_E. The results show that all data points are tightly clustered near the 1:1 line $\sigma_E = \sigma_C$, with a fitting determination coefficient R² as high as 0.99. This indicates an excellent agreement between the predicted and measured values, demonstrating the high prediction accuracy of the model. This finding confirms that the established mathematical model can accurately capture the synergistic effects of xanthan gum content and curing time on soil strength. It provides a reliable prediction of the unconfined compressive strength of modified soil under different conditions, offering robust theoretical support and a quantitative tool for engineering design and the optimization of modification schemes.

Figure.7 Model validation



	T	W
■	3	0.8%
▲	5	1.4%
▼	8	2.8%
●	10	0.3%
◆	12	1.7%

4. Conclusions

Based on unconfined compression tests, the effects of xanthan gum dosage and curing time on the mechanical properties of soft soil were systematically investigated in this study, and a corresponding strength prediction model was established. Based on the experimental results and mechanistic analysis, the following conclusions can be drawn:

(1) The incorporation of xanthan gum significantly enhances the unconfined compressive strength of the soil, which continuously increases with increasing gum dosage and curing time. Meanwhile, the failure mode of the soil gradually transitions from plastic flow to brittle failure, indicating a substantial improvement in the mechanical performance of the soft soil.

(2) The strength of the modified soil exhibits a rapid initial increase followed by gradual stabilization with increasing xanthan gum dosage, with an optimal dosage range of 2%–3%. The strength increases logarithmically with curing time, and the internal cementation structure develops rapidly during the early curing stage before gradually stabilizing.

(3) The proposed mathematical model can accurately predict the normalized strength of xanthan gum-modified soil under different conditions. The model validation results demonstrate excellent agreement between the calculated values and experimental measurements, with a determination coefficient of 0.99, confirming its good potential for engineering applications.

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Data Availability

All data generated or analyzed during this study are included within the submitted article.

Conflicts of interest

The authors declare that no competing financial or non-financial interests exist in relation to the work described in this paper.

Author Contributions

All authors contributed to conceptualizing the investigation into mechanical properties of xanthan-modified silty soil and the strength prediction approach in this study.

References

1. Proteau A, Guittonny M, Bussière B. Impact of roots on the hydrogeological properties of silty soil covers. Canadian Geotechnical Journal, 2024, 61(8):116-132.
2. Zhang X, Cao W, Zhang X. Experimental study on mechanical and hydraulic properties of xanthan gum improved low liquid limit silty soil. Scientific Reports, 2024, 14(1):1112-1135.
3. Yu Y, Li J, Peng W, Chen Y, Chen C, Luo E, Liu E. Experimental Study on Unloading Mechanical Properties of Deep-Buried Silty Soil. International Journal of Civil Engineering, 2025, 23(4):655-670.
4. Orioli M A, Costa W G S, Baldin C R B. Silty soil resilient modulus stabilised with cement and recycled aggregate. International Journal of Pavement Engineering, 2024, 25(1): 2378334.
5. Li H, Ma W, Wang K, Feng Y, Zhang S, Zhou S, Zhang H. Preparation of a Low-Cement-Content Silty Soil Stabilizer Using Industrial Solid Wastes. Applied Sciences-Basel, 2024, 14(1):13-26.
6. Govindasamy P, Taha M R. Changes in Chemical Concentration of Silty Clay Added with Lime and Nanolime. Advanced Structured Materials, 2024,11(2):85-100.
7. Shi Y, Li S, Zhang T, Liu J, Zhang J. Compaction and shear performance of lime-modified high moisture content silty clay. Case Studies in Construction Materials, 2024, 21:e03529.
8. Akhtar S, Li B. Experimental study of mechanical behaviours of lime-treated Quebec silty clay

soils under freeze–thaw cycles. Environmental Geotechnics, 2025, 12(7):499-516.

9. Wang S, Hui H, Guo P C Z. Permeability and strength characteristics of silty sands grouted with cement and polymer. Acta Geotechnica: An International journal for Geoengineering, 2024, 19(4):2125-2143.
10. Wang Y Z, Chen F Y, Gao Y, Zhuang M L, Ge F H, Tang Z J. Unconfined Compressive Strength Optimization of Industrial Solid Waste-Based Soil Stabilizers. Strength of Materials, 2025, 57(6):1357-1364.
11. Marjadi H K, Jang J. Compressional behavior of fine-grained soils: Clastic and biogenic silty soils. Geomechanics and Engineering, 2025, 41(1):71-82.
12. Tomasello G, Porcino D D. Energy-Based Pore Pressure Generation Models in Silty Sands under Earthquake Loading. Geosciences, 2024, 14(6):166-179.
13. Guo H, Sun Q, Yuan C, Li X, Zhao Y. Experimental investigation on the physical and mechanical properties of silty clay enhanced by microencapsulated phase change materials. Case Studies in Construction Materials, 2024, 20(c):e03151.
14. Xiao Y, Hu J, Shi J, Zhang L, Liu H. Undrained cyclic responses of biocemented calcareous silty sand. Acta Geotechnica, 2024, 19(10):256-282.
15. Shaji S, Gade V K, Sundaram B, Bande G R. Evaluating the Effectiveness of Xanthan Gum Biopolymer as a Soil Stabiliser. Indian Geotechnical Journal, 2025, 55(5):2909-2919.
16. Ma Y, Dong X, Wang Z, Liu T, Ma W. Mechanical behavior and erosion resistance of desert soil stabilized with guar gum biopolymer. Bulletin of Engineering Geology and the Environment, 2025, 84(11):1325-1342.
17. Hamza M, Khan M I. Mechanical and hydraulic improvement of highly organic soil using Xanthan Gum: A strength-microstructure approach. Geomechanics and Engineering, 2025, 43(1):13-26.
18. Mohamed A M O, O'Kelly B C, Soltani A. Xanthan Gum-Soil Interactions. Green Energy and Technology, 2024, 11(2):99-123.
19. Baghdir B, Abed Y, Feia S, Denine S, Beyaz T, Cherifi A. Effect of Xanthan gum biopolymer combined with fibre as soil- stabilization binder of dune sand in Southern Algeria. Geomechanics and Engineering, 2024, 39(2):115-127.
20. GB/T 50123-2019. Standard for geotechnical testing method. Bejjing, China: Ministry of Housing and Urban-Rural Development, PRC; 2019.