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EXPERIMENTAL INVESTIGATION INTO THE UNCONFINED COMPRESSION STRENGTH OF SILT TREATED WITH XANTHAN GUM

EKSPERIMENTALNA RAZISKAVA NEOMEJENE TLAČNE TRDNOSTI MULJA OBDELANEGA S KSANTANSKO GUMO

Xu-Nan Li[1*], Xiang Zhou[2], Michael Adeyemi[3]

[1]School of Civil Engineering, Xijing University, Xian, Shaanxi Province, China, 0009-0003-7507-2842
[2]School of Civil Engineering, Xijing University, Xian, Shaanxi Province, China, 0009-0009-5305-353X
[3]School of Civil Engineering, Changsha University, Changsha, Hunan Province, China, 0009-0000-1279-3819

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To address the engineering challenges of low strength and poor water stability in low liquid limit silt, this study investigated the improvement effect and reinforcement mechanism of xanthan gum through laboratory experiments. Unconfined compression tests were conducted on specimens with seven xanthan gum dosages ranging from 0 to 3.0 % at 0.5 % increments. Scanning electron microscopy was employed to observe microstructural changes. The results indicated that xanthan gum significantly enhanced the unconfined compressive strength of low liquid limit silt. A strong exponential relationship was observed between strength and xanthan gum dosage with a coefficient of determination of 0.98, and the reinforcement effect approached saturation beyond a dosage of 2.0 %. After modification, the stress-strain response of the silt improved, with increased tangent modulus and reduced strain at peak stress, demonstrating enhanced deformation resistance and load-bearing capacity. The reinforcement mechanism involved dual effects of pore filling and cementation, where the hydrated gel filled interparticle voids and bonded loose particles, thereby strengthening the soil skeleton. This study provided a theoretical basis and technical reference for environmentally friendly and efficient improvement of low liquid limit silt.

Keywords: silt, xanthan gum, dosage, unconfined compression test

Da bi se avtorji tega članka spopadli z inženirskimi izzivi, ki jih predstavlja nizka trdnost, slaba vodna stabilnost in nizka meja tekočnosti drobno zrnatega mulja, namenjenega za utrjevanje nasipov, avtocest, železniških prog in drugih podlag v gradbeništvu, so raziskali učinke izboljšanja in mehanizem njegove ojačitve s ksantansko gumo. To je polisaharidni zgoščevalec, stabilizator in emulgator v prahu, ki se uporablja za različne namene. Laboratorijsko določanje neomejene tlačne trdnosti so avtorji tega članka izvedeli na vzorcih s sedmimi odmerki ksantan gumija v razponu od 0 % do 3,0 % v korakih po 0,5 %. Za opazovanje mikrostrukturnih sprememb so uporabili vrstični elektronski mikroskop (SEM). Rezultati so pokazali, da je dodatek ksantanskega gumija znatno izboljšal neomejeno tlačno trdnost mulja z nizko mejo tekočnosti. Med trdnostjo in odmerkom ksantan gumija je bila opažena močna eksponentna povezava s koeficientom determinacije 0,98, učinek ojačitve pa se je pri odmerku 2,0 % približal nasičenosti. Po modifikaciji se je odziv napetosti in deformacije mulja izboljšal s povečanim tangentnim modulom in zmanjšano deformacijo pri največji napetosti, kar kaže na povečano odpornost proti deformacijam in izboljšano nosilnost. Mehanizem ojačitve je vključeval dvojni učinek polnjenja por in cementacije, kjer je hidrirani gel zapolnil praznine med delci in povezal ohlapne delce, s čimer je okrepil talni skelet. S to študijo so avtorji zagotovili teoretično osnovo in tehnično referenco za okolju prijazno in učinkovito izboljšanje lastnosti mulja z nizko mejo tekočnosti.

Ključne besede: mulj, ksantan gumi, doziranje, preizkusi neomejene tlačne trdnosti

1 INTRODUCTION

Silt is a common fine-grained soil widely distributed in geotechnical engineering applications such as highway subgrades, railway foundations, and embankment construction.[1–3] Due to its particle composition dominated by silt-sized fractions with a limited clay content, natural silt typically exhibits poor engineering properties, including low water stability, weak cohesion, and low compressive strength.[3,4] Under variations in moisture content or external loading, this soil is highly susceptible to softening, disintegration, and even strength loss, which can lead to engineering hazards such as differential settlement and slope instability.[5] Therefore, research on effective reinforcement and improvement of silt holds significant engineering practical value.

Currently, the improvement techniques for low liquid limit silt are mainly divided into two categories, namely physical modification, and chemical modification.[6] Physical modification typically involves adding aggregates such as sand or gravel to adjust the particle size distribution or employing compaction methods to increase soil density.[6] Although this approach is environmentally friendly, it has several limitations. These include relatively modest improvement effects, long construction periods, and poor adaptability.[7] Therefore, physical modification is only suitable for engineering projects with low requirements for soil mechanical properties. In contrast,

*Corresponding author's e-mail:
lixunanxj@163.com (Xu-Nan Li)

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chemical modification involves adding chemical agents to the soil. These agents undergo physical and chemical reactions with soil particles, altering the soil structure and enhancing its mechanical properties.[8–10] This method offers significant advantages, including notable improvement effects, convenient construction, and short construction periods.[9] As a result, it has been widely applied in treating low liquid limit silt in various engineering projects, such as highway subgrades, railway slopes, and building foundations.[10,11] Traditional chemical modification materials primarily include cement and lime.[11] These materials generate cementitious products through hydration reactions, which effectively bond soil particles and fill soil pores.[12,13] This process significantly enhances the compressive strength, cohesion, and water stability of low liquid limit silt, and these materials have played an important role in engineering practice.

However, the production processes of traditional materials such as cement and lime consume substantial amounts of resources, including coal and limestone.[14] This results in high energy consumption and significant carbon emissions, conflicting with the requirements of green and low-carbon engineering construction under current sustainability goals. Furthermore, these materials are prone to excessive hydration reactions in the soil, leading to densification and stiffening of the internal soil structure.[15] This impairs the original permeability and aeration of the soil. Long-term use can also induce soil cracking and strength degradation. In addition, these materials may pose potential ecological risks to surrounding soil and groundwater. Consequently, their application scenarios are becoming increasingly restricted. With the continuous advancement of green engineering concepts and the increasing demand for environmentally friendly, efficient, and sustainable modification materials in geotechnical engineering, the development of novel alternatives to traditional chemical materials has become a research hotspot.

This is essential for addressing both the ecological and technical challenges associated with improving low liquid limit silt. In recent years, biopolymers have gradually attracted widespread attention from researchers due to their excellent environmental compatibility, biodegradability, and unique rheological properties.[16] Biopolymers are natural polymer materials obtained through microbial fermentation or plant extraction. Common types include xanthan gum, gellan gum, guar gum, and chitosan.[17–19] Xanthan gum, as an anionic polysaccharide produced by the fermentation of bacteria of the genus Xanthomonas, exhibits excellent water solubility, thickening ability, and gel-forming capacity.[20] It is one of the most widely applied biopolymers. Existing studies have demonstrated that xanthan gum has significant improvement effects on the strength, permeability, and erosion resistance of sands and clays.[21,22] However, for low liquid limit silt, which is a widely distributed soil type with unique engineering properties, systematic research on the influence of xanthan gum dosage on strength development remains relatively limited. Furthermore, its microstructural reinforcement mechanisms in this specific soil type require further investigation.

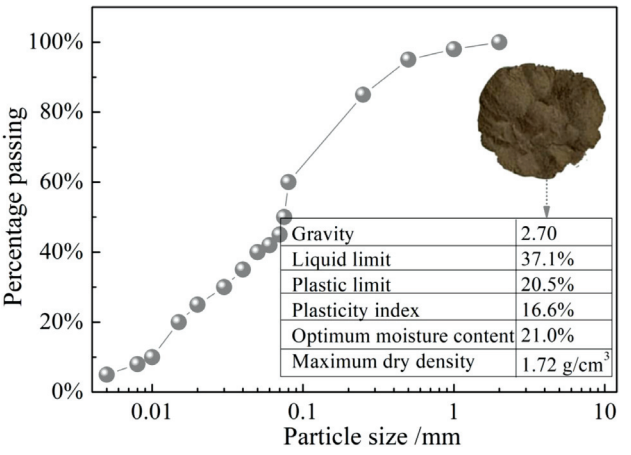

Figure 1: Physical parameters of soil for testing

In this study, low liquid limit silt from the Qinghai Lake area was selected as the research object. The effect of xanthan gum dosage on the unconfined compressive strength of treated silt was systematically investigated. The stress-strain behavior and strength development characteristics were analyzed. Scanning electron microscopy was employed to reveal the microstructural reinforcement mechanism of xanthan gum in this specific silt. The research findings contribute to the theoretical framework of biopolymer-modified low liquid limit silt and elucidate the applicability of xanthan gum in silt improvement.

2 MATERIALS AND METHODS

The silt used in this test was collected from the Qinghai Lake area. Its basic physical properties were determined in accordance with the Standard for Geotechnical Testing Method (GB/T 50123-2019).[23] The results are presented in **Figure 1**. The particle composition of this silt was dominated by silt-sized particles, with low proportions of sand and clay. Its physical behavior exhibited significant water sensitivity. In the dry state, the interparticle cementation was weak, and the soil did not feel sticky to the touch. In the moist state, it showed good plasticity and fluidity and could be molded into a coherent mass.

Xanthan gum is a natural polysaccharide produced through fermentation by bacteria of the genus Xanthomonas.[24] Its molecular structure comprises two glucose units, two mannose units, and one glucuronic acid unit. This unique molecular configuration endows xanthan gum with excellent rheological and functional properties. The molecular structure of xanthan gum is presented in **Figure 2**. The main chain consists of β-1,4-linked glucose units, while the side chains contain mannose and glucuronic acid units. This complex branched structure

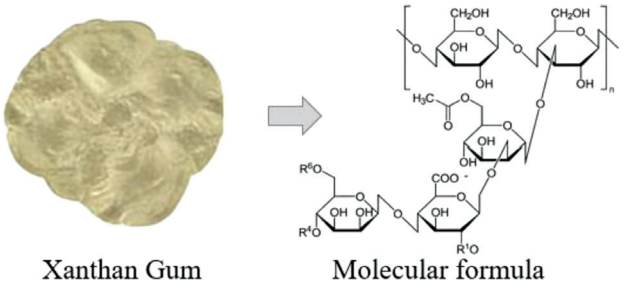

Figure 2: Molecular formula of xanthan gum

contributes to its exceptional high viscosity in aqueous solutions. The xanthan gum utilized in this experiment was a commercial-grade product manufactured by Baikang Food Factory in Xinjiang, China. It appears as a light-yellow powder with a slight odor, is readily soluble in water, and forms a neutral solution (pH ≈ 7.0), exhibiting notably high viscosity. To ensure the accuracy and reproducibility of the test results, all xanthan gum samples were stored in sealed containers and strictly followed a practice of immediate use upon taking to prevent moisture absorption and degradation.

This study investigated the effect of xanthan gum dosage on the unconfined compressive strength (UCS) of xanthan gum-treated silt. Seven xanthan gum mass fractions, including (0, 0.5, 1, 1.5, 2, 2.5 and 3.0) % were designed, with three parallel specimens prepared for each group for unconfined compression testing. The experimental procedure is illustrated in **Figure 3**. The silt was air-dried, crushed, and sieved prior to use. For each designated dosage, 160 g of the prepared soil was thoroughly mixed with the corresponding mass of xanthan gum. The mixture was then adjusted to achieve the optimum moisture content of 21 %. The prepared soil mixture was placed in a sealed bag and allowed to rest for 24 h to ensure complete dissolution and homogenization of the xanthan gum. Subsequently, specimens were prepared using the compaction method. Prior to molding, a thin layer of Vaseline was uniformly applied to the inner walls of the mold to facilitate demolding. The soil mixture was compacted in three layers, with each layer compacted to a height of 27 mm. To ensure proper bonding between layers, the surface of each compacted layer was scarified before the placement of the subsequent layer. This process produced cylindrical specimens with a diameter of 39.1 mm and a height of 80 mm. After extraction from the mold, each specimen was immediately wrapped with plastic film to prevent moisture loss and cured under ambient indoor conditions for 7 d. Following the curing period, the specimens were placed in a strain-controlled unconfined compression apparatus. Loading was applied by raising the platen at a constant strain rate of 0.005 % per minute, during which axial force and displacement data were synchronously recorded.

3 RESULTS

Figure 4 presents the stress-strain curves of low liquid limit silt specimens with varying xanthan gum dosages. All specimens exhibited similar stress-strain behavior. The axial stress increased with axial strain until reaching a peak value, after which it decreased, indicat-

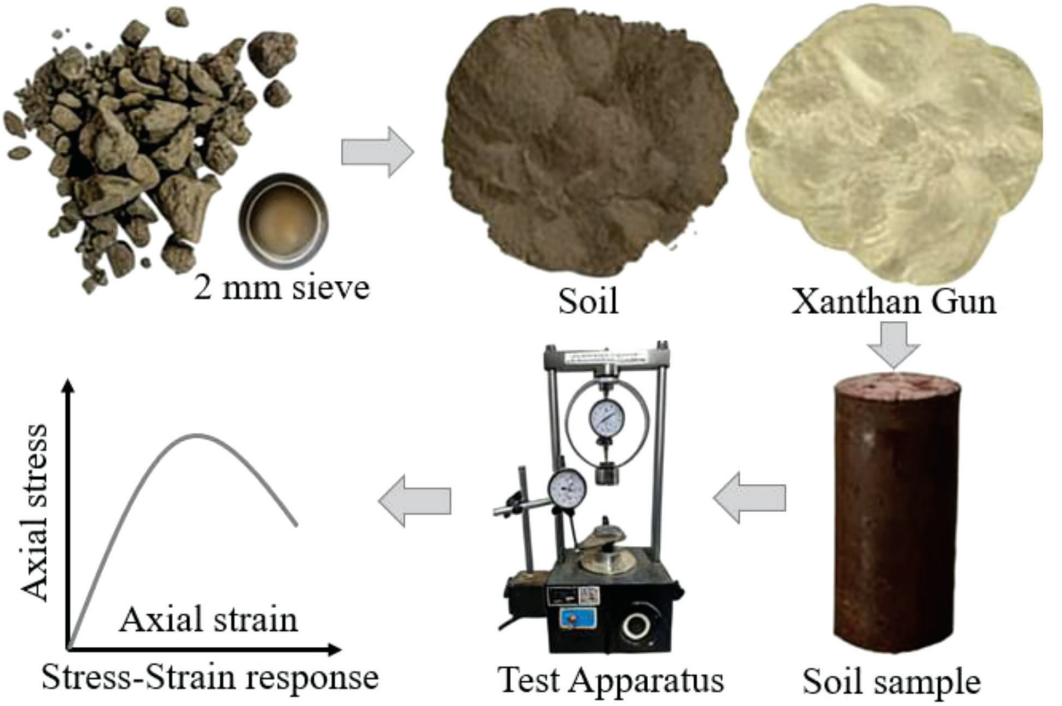

Figure 3: Unconfined compression testing procedure

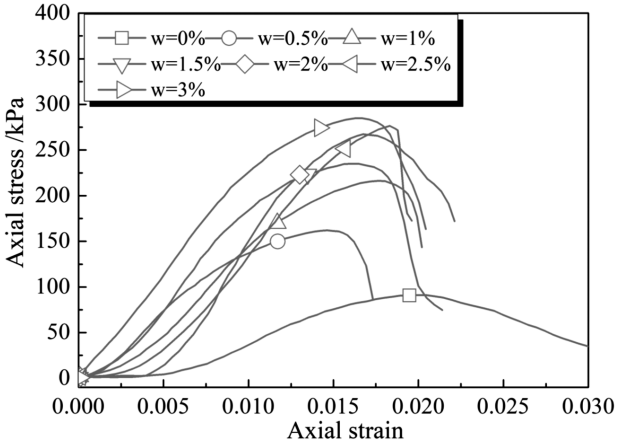

Figure 4: Stress-strain curves of specimens with varying xanthan gum dosages

ing specimen failure. The stress-strain curves can be divided into three stages. The first stage is initial compaction. The curve is concave upward with a small tangent modulus, reflecting specimen compaction under initial loading. The second stage is stress hardening. The curve increases approximately linearly with a larger tangent modulus, indicating faster stress growth. The third stage is post-peak failure. Stress decreases rapidly after reaching the maximum value (unconfined compressive strength), and the specimen loses bearing capacity and fails. Compared with untreated silt, xanthan gum-modified specimens showed smaller strains in the compaction and hardening stages and exhibited sharper peak points. In the failure stage, stress decreased gradually in untreated silt but dropped sharply in treated specimens. These results indicate that xanthan gum significantly increased the unconfined compressive strength of low liquid limit silt but reduced its plastic deformation capacity, making the failure mode more brittle.

Figure 5 illustrates the variation in normalized unconfined compressive strength (σ_N) with xanthan gum dosage (w) and the corresponding fitting curve. The normalized strength is defined as:

$$\sigma_N = \frac{(\sigma - \sigma_{w=0\%})}{\sigma_{w=0\%}} \quad (1)$$

where σ represents the unconfined compressive strength of treated silt and $\sigma_{w=0\%}$ represents that of untreated silt. The test results show that as xanthan gum dosage increased from 0 to 3.0 %, the normalized unconfined compressive strength exhibited a significant increase. The experimental data closely followed an exponential function, with the fitting equation $\sigma_N = 2.27(1-\exp(-w))$ and a coefficient of determination $R^2 = 0.98$, demonstrating that this model effectively characterizes the relationship between strength and dosage. The inset further quantifies the improvement effect of xanthan gum on the unconfined compressive strength of the soil. The UCS of untreated silt was approximately 91.2 kPa. When the dosage increased to 2.0 %, the UCS rose to about 266.5 kPa. However, as the dosage further increased from 2.0 % to 3.0 %, the UCS only reached approximately 275.2 kPa, indicating a notable slowdown in the rate of increase. Combined with the characteristics of the fitting curve in the main figure, it can be observed that when xanthan gum dosage exceeded 2.0 %, the growth rate of normalized strength decreased significantly, and the strengthening effect became markedly less pronounced. This suggests that the reinforcement effect of xanthan gum on low liquid limit silt gradually approached saturation beyond this dosage level.

To investigate the microstructure of xanthan gum-treated silt and elucidate its reinforcement mechanism, a Quanta 600FEG field emission scanning electron microscope (SEM) was employed to observe the micromorphology of both untreated low liquid limit silt and xanthan gum-modified low liquid limit silt. The corresponding SEM images are presented in **Figure 6**. As shown in **Figure 6a**, the untreated low liquid limit silt exhibits relatively large interparticle voids and high porosity, with angular particles and a predominantly open fabric structure, which accounts for its inherently low strength. The gel formed by xanthan gum upon contact with water creates bridge connections between soil aggregates, cementing the originally loose soil mass into a relatively stable entirety, as illustrated in **Figure 6b**. Concurrently, this gel effectively fills the pores between soil particles and binds dispersed particles into larger agglomerates through cohesive action, as depicted in **Figure 6c**. The reinforcement mechanism of xanthan gum in low liquid limit silt can be summarized in two aspects. The first is pore filling, whereby the gel formed by xanthan gum hydration permeates and occupies the original macropores between soil particles. This gel exhibits strong water absorption and swelling characteristics. Upon expansion, it effectively compacts and densifies the internal voids within the soil mass. This process substantially reduces the porosity and enhances the inter-

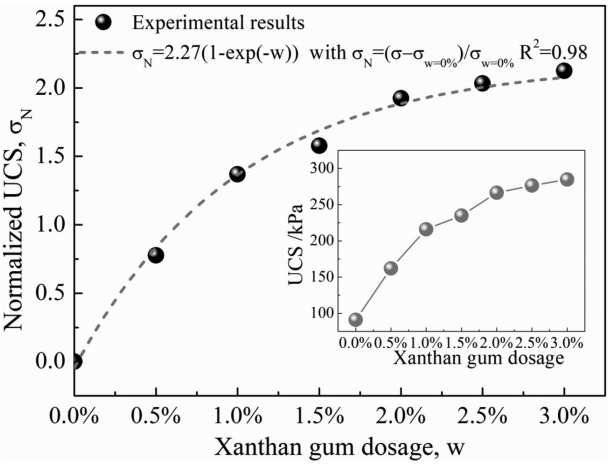

Figure 5: Relationship between normalized unconfined compressive strength and xanthan gum dosage

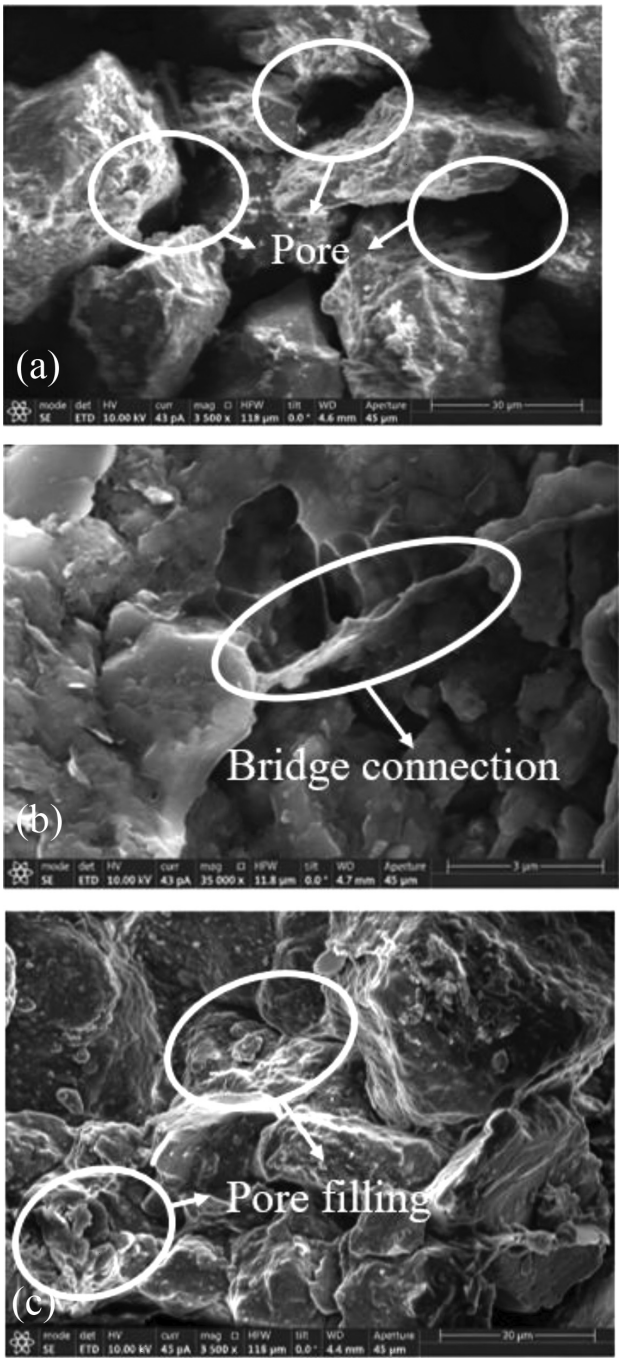

Figure 6: SEM images of soil samples: a) pore, b) bridge connnection, c) pore filling

locking and embedding effects between particles, thereby significantly improving the compactness and overall strength of the modified soil. The second aspect includes cementation and reinforcement, through which the gel binds individual loose silt particles into an integrated structure via bridging and binding effects, strengthening the soil particle skeleton and enhancing the soil integrity. This consequently leads to a marked increase in the soil strength.

4 CONCLUSIONS

Based on laboratory tests on xanthan gum-modified low liquid limit silt from the Qinghai Lake area, this study systematically investigated the effects of xanthan gum dosage on the unconfined compressive strength and stress-strain behavior of the treated soil. Scanning electron microscopy was employed to reveal the reinforcement mechanism. Based on the test results and analysis, the following conclusions are drawn:

(1) Xanthan gum significantly enhances the unconfined compressive strength of low liquid limit silt. A strong exponential relationship exists between strength and xanthan gum dosage. The optimal dosage for this region is 2.0 %, as strength improvement notably slows beyond this level and approaches saturation.

(2) Xanthan gum alters the stress-strain behavior of the soil. All specimens exhibited three stages: initial compaction, stress hardening, and post-peak failure. Modified specimens showed higher tangent modulus and smaller strain at peak stress compared to untreated silt, indicating improved deformation resistance and load-bearing capacity.

(3) The reinforcement mechanism involves dual effects of pore filling and cementation. Xanthan gum gel fills interparticle voids, reducing porosity and increasing density. The gel also bonds loose particles through bridging connections, forming stable agglomerates, and strengthening the soil skeleton. These combined effects significantly enhance overall soil strength and engineering stability.

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Data-availability statement

All data generated and analyzed in the course of this study are contained within the present article.

Generative AI statement

The authors declare that no generative artificial intelligence tools were used in the preparation or writing of this manuscript.

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