

Mechanisms and Influencing Factors in Xanthan Gum-EICP Treatment of Calcareous Sand

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Abstract: The primary material for expanding the South China Sea islands and reefs is calcareous sand, which contains up to 90% calcium. This sand exhibits physical properties such as porous particles, high brittleness, easy cementation, and irregular shapes. However, its mechanical properties are relatively poor, characterized by low bearing capacity and susceptibility to deformation, necessitating reinforcement to meet subsequent construction requirements. In recent years, biopolymer soil reinforcement and enzyme-induced calcium carbonate precipitation (EICP) have emerged as popular environmentally friendly methods for foundation treatment. Numerous studies have attempted to combine these two techniques to achieve optimal reinforcement effects, but the influencing factors for combined reinforcement are complex, and the reinforcement mechanisms differ from the original methods. To explore the feasibility, influencing factors, and reinforcement mechanisms of combining xanthan gum (XG) with EICP for calcareous sand reinforcement, this paper first investigates the potential of such combined reinforcement.

Keywords: Xanthan Gum; EICP; Calcareous Sand.

1. Introduction

The South China Sea, located south of the China's mainland, is not only China's largest offshore area but also a vital passage for China to Southeast Asia, South Asia, the Middle East, Africa, Europe, and Oceania, holding extremely important strategic value for China's foreign trade and economic development. The development of a maritime power cannot be separated from the expansion and construction of islands and reefs in the South China Sea. The primary material for expanding these reefs is calcareous sand, which has a calcium content as high as 90%, with particles exhibiting physical properties such as porous structure, easy fragmentation, easy cementation, and irregular shapes. Additionally, calcareous sand has poor mechanical properties, including low bearing capacity and susceptibility to deformation. In reef construction projects, ordinary backfilling of calcareous sand foundations inevitably faces various loads from waves, tides, ocean currents, and earthquakes. The challenges of building structures on calcareous sand areas remain significant, necessitating the treatment of calcareous sand foundations to improve their physical and mechanical properties [1]. Due to the physical and mechanical characteristics of calcareous sand, traditional foundation treatment methods such as grouting and deep mixing of cement are not suitable for large-scale calcareous sand foundations. Moreover, these methods require substantial amounts of building materials like cement and lime, and the remoteness of reefs from the mainland leads to high transportation costs for these materials, often resulting in significant environmental issues and marine pollution [2]. Therefore, selecting a new, environmentally friendly, and efficient foundation treatment method is particularly crucial in reef construction.

Green biological cementation technologies, represented by microbial-induced calcium carbonate precipitation (MICP), have rapidly developed as an environmentally friendly new foundation treatment method. With advantages such as excellent reinforcement effects, high application value, and

environmental sustainability, they can be applied in various fields including subgrade and foundation reinforcement, slope support, and dam seepage prevention [3]. However, MICP technology still faces challenges during its development, such as potential environmental impacts from introducing exogenous microorganisms, complex bacterial cultivation processes, and high treatment costs. In recent years, enzyme-induced calcium carbonate precipitation (EICP) has emerged as a bio-cementation alternative to MICP. EICP directly extracts urease from plants, promoting urea hydrolysis into carbonate ions, which then react with calcium ions in the cementation solution to form calcium carbonate precipitates. These precipitates cement soil particles into an ensemble, thereby improving soil mechanical properties [4]. Additionally, the generated free urease is biodegradable, causing no long-term environmental impact, and its small size allows it to pass through even smaller soil pores, reducing the risk of clogging during calcium carbonate formation. Compared to MICP, EICP eliminates the microbial metabolic process for urease production while retaining MICP's advantages of low energy consumption, environmental friendliness, short construction periods, minimal soil disturbance, operational convenience, cost-effectiveness, and broad applicability [5]. As a result, EICP has gradually become a research hotspot in soil improvement studies. As domestic and international scholars continue to advance research on EICP technology, it has been found that while this technique can partially address the limitations of MICP, the treated soil exhibits minimal residual strength and significant brittle failure, resulting in suboptimal reinforcement effects. Additionally, traditional EICP technology lacks nucleation sites for calcium carbonate, making its soil stabilization performance inadequate for diverse application requirements [6]. Therefore, it is imperative to refine EICP technology to enhance its soil solidification efficacy.

To enhance reinforcement effectiveness, xanthan gum was selected to improve traditional EICP technology. Xanthan gum, a biopolymer also known as Hansell gum, is white or pale yellow in color and is extracted from *Xanthomonas*

species. It exhibits excellent adhesion and pseudoplasticity even at low concentrations, making it widely used in soil improvement and reinforcement in recent years [7]. As an environmentally friendly and effective non-traditional material for soil reinforcement, xanthan gum matrix fills voids between soil particles, increasing their contact area. When combined with water, xanthan gum forms a highly viscous gel that establishes bridging connections between non-contacting soil particles, thereby enhancing inter-particle interaction forces and improving soil integrity. The strength of the xanthan gum matrix and its binding properties with soil particles increase the soil's resistance to deformation, thus elevating soil strength [8]. Compared to other biological adhesives, xanthan gum demonstrates higher stability across a wider range of temperatures and pH levels [9]. As a sustainable soil improvement additive, xanthan gum holds broad prospects for application.

2. Feasibility of Calcareous Sand Treatment Using Xanthan Gum and EICP

Xanthan gum has been widely applied in soil improvement and stabilization in recent years. Cabalar et al. [10] investigated the effect of low-dose xanthan gum on sand strength through unconfined compression tests. The results showed that the compressive strength of xanthan-gelled soil increased by more than two times at a 1.5% dosage. Jing et al. [11] explored the performance changes of sand-clay mixtures after xanthan gum incorporation via unconfined compression tests, demonstrating that mechanical strength was effectively enhanced with increasing xanthan gum dosage. Hang Lei et al. [12] utilized unconfined uniaxial compression tests to investigate the reinforcement effects of microbial-induced calcium carbonate precipitation (MICP) combined with xanthan gum on sand mechanical properties. The results indicated that the MICP-xanthan gum method significantly improved sand stability, with unconfined compressive strength increasing markedly as xanthan gum content in the treatment solution rose. When xanthan gum dosage reached a certain threshold, it significantly enhanced the reinforcement efficiency of both microbial gelling and xanthan gum, while also improving water erosion resistance. Under identical conditions, the unconfined compressive strength of sand stabilized by MICP-xanthan gum was 18.12 times and 6.45 times higher than that of sand stabilized by xanthan gum or MICP alone, respectively. An Ran et al. [13] conducted systematic laboratory experiments to study the influence of xanthan gum dosage on mechanical properties and microstructure of coral sand, discussing its reinforcement mechanism. The results show that the bonding material of the samples with 0.5%~2% xanthan gum is increased by 53.57%~88.43% compared with the samples without xanthan gum. The unconfined compressive strength of the samples with 1.0% xanthan gum is 6.23 MPa, which is 2.56 times higher than that of the samples without xanthan gum.

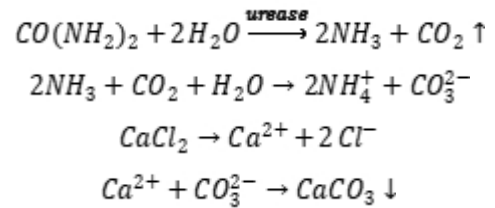
The comprehensive research demonstrates that xanthan gum exhibits significant enhancement effects in soil improvement and consolidation. Moreover, the application of microbial-induced calcium carbonate precipitation (MICP) combined with xanthan gum reinforcement demonstrates notable consolidation efficacy. Given the similar mechanisms underlying EICP and MICP technologies, the integration of xanthan gum with EICP for soil reinforcement proves feasible

and represents a promising research direction.

3. Factors in the Xanthan Gum-EICP Treatment of Calcareous Sand

3.1. Factors in Urease-Induced Calcium Carbonate Precipitation

Enzyme-induced calcium carbonate precipitation (EICP) is a biomimetic technique that utilizes free urease to catalyze urea into carbonate ions in soil, which then combine with calcium ions to form calcium carbonate precipitates. The resulting calcium carbonate acts as a cementitious agent, binding soil particles at contact points to enhance soil strength and stiffness while reducing permeability and porosity. Consequently, EICP technology finds applications in foundation improvement, construction materials, and erosion control for traditional binders [14]. The reaction equation is as follows:



The calcium acid precipitate formed through enzymatic reactions can cement soil particles into a cohesive unit. Compared to microorganisms, urease exhibits smaller particle size and demonstrates broader applicability across soil types [15]. The use of plant-derived urease to induce calcium carbonate deposition avoids the bacterial cultivation process, thereby enhancing urease extraction efficiency. Moreover, EICP technology directly utilizes small-sized free urease to promote calcium carbonate deposition, enabling penetration through finer soil particles and reducing clogging risks, making it suitable for fine-grained soil stabilization. Wang Hengxing et al. [16] demonstrated that during sand stabilization using EICP technology, optimal results are achieved when temperature is below 55°C by controlling urease mass fraction, while temperatures above 55°C require increased urease mass fraction and reduced pH for maximum stabilization. Xiong Huihui et al. [17] conducted comparative studies on different plant-derived ureases and calcification variables. The urease activity showed continuous growth with increasing urease concentration, with extraction efficiency remaining relatively stable. Urea concentration initially increased but then decreased with higher urease levels, reaching peak activity at approximately 1.3 mol/L. Urease activity exhibited significant temperature-dependent growth between 5°C and 55°C, while pH effects followed a similar pattern, with soybean-derived urease showing optimal activity at pH 8. Wu Yulin [15] and colleagues investigated the effect of pH on calcium carbonate production. When pH increased from 7 to 9, calcium carbonate yield first rose and then declined. At pH 8, the maximum yield reached 82%. The optimal activity of soybean urease in the experiment coincided with the pH level that achieved the highest calcium carbonate production, demonstrating a direct correlation between solution pH and urease activity. Ren Guanzhou et al. [18] conducted experiments to enhance calcium carbonate yield during urease-induced soil solidification. By controlling the reaction solution-cement ratio, enzyme-cement ratio, and cement concentration, they optimized the solution formulation under aqueous conditions. Results showed that

under different concentrations, the optimal calcium chloride-to-urea ratio was 1:1 at low concentrations and 1:1.5 at high concentrations. The optimal enzyme-cement ratio was 1:1, with cement concentration at 2.8 mol/L. When calcium chloride dosage remained constant, increasing urea dosage significantly boosted calcium carbonate production. Ahmed Miftah et al. [19] applied seawater to prepare EICP solutions for calcareous sand treatment. Tests on unconfined compressive strength and calcium carbonate content revealed that 10% seawater had minimal impact on precipitation formation and sample strength improvement. This indicates EICP technology holds great potential for marine applications. The above research shows that when using EICP technology to treat soil, it is worth studying the conditions of selecting appropriate ambient temperature, mass fraction of urease, enzyme-gel ratio, appropriate PH value, etc. to obtain the best reinforcement effect.

3.2. Study on Methods for Soil Treatment Using EICP

For calcium carbonate to fully exert its cementing effect on soil, the precipitate must concentrate at soil particle contact points. Inappropriate calcium carbonate distribution may compromise this cementing function, making homogeneity a critical factor that largely depends on treatment methods [20]. The selection of appropriate EICP treatment methods significantly impacts soil stabilization outcomes. Common laboratory techniques include immersion, pre-mixing, single-phase, and staged infusions. As these methods yield varying calcium carbonate distribution patterns, their reinforcement effects differ. Identifying the optimal treatment approach to achieve maximum stabilization efficiency remains a key research direction.

The soaking method requires uniformly mixing the sample with urease, then encapsulating the mixture in geotextile and immersing it in a cementing solution of specific concentration for a set duration. This process utilizes diffusion effects to allow the cementing solution to gradually penetrate the sample's interior. Typically, the cementing solution is not replenished. Due to weak hydrodynamic forces, the characteristic of the soaking method is that the outer layer of the sample reacts with the cementing solution first, forming a dense calcium carbonate layer that restricts further penetration of the cementing solution, resulting in limited and uneven calcium carbonate formation [21]. The pre-mixing method [22] requires pre-mixing urease with sand, followed by repeated or single-time cementing solution infusion over a period, or direct mixing of urease and cementing solution. The mixed infusion method [23] involves mixing urease solution with cementing solution and promptly adding it to the sand sample. After a period of chemical reaction, the same rate of mixed solution infusion is applied, repeating this process. Since the urease solution reacts immediately with the cementing solution, calcium carbonate crystals form before sand infusion, which can easily clog the infusion end, leading to uneven calcium carbonate distribution and poor integrity in the cemented sample. The stepwise infusion method [24] requires first infusing urease solution into the sample, followed by adding cementing solution. After completion of the initial infusion, a period of static placement is needed for urease to diffuse and penetrate the sample, allowing direct adsorption on sand particle surfaces. Subsequent urease solution infusion ensures uniform distribution within the sample, followed by cementing solution infusion to achieve

optimal results.

Since the EICP treatment method for soil significantly impacts subsequent reinforcement effectiveness, researchers have optimized various grouting techniques. Cheng et al. [25] employed a staged grouting method with multi-layer alternating injection, using a micro-penetrator to measure post-cementation local strength. Their results demonstrated that four-layer sand grouting resulted in uniform calcium carbonate distribution, higher calcium carbonate content, and consistent overall strength. Cui et al. [26] found that single-phase low-pH grouting produced more uniform calcium carbonate distribution. Both MICP and EICP techniques yielded similar total calcium carbonate content, but EICP-treated samples exhibited higher unconfined compressive strength. Shuang et al. [27] proposed a multiphase EICP method for sand treatment: first mixing urease with cementing fluid and injecting it into sand columns, followed by the first round of cementing fluid injection after 3 hours, with subsequent rounds every 4 hours for three cycles. Compared to other methods, the multiphase approach showed higher chemical conversion rates, more uniform sediment distribution, and greater unconfined compressive strength. The findings indicate that grouting methods significantly influence calcium carbonate crystal distribution and content in sand. Therefore, selecting appropriate reinforcement methods that balance efficiency and effectiveness remains a key research focus.

3.3. Influence of Particle Gradation on the EICP Treatment of Calcareous Sand

In the process of sand consolidation, particle gradation is a critical factor influencing the mechanical properties of sand. Li Yuanyuan [28] conducted physical property tests, unconfined compressive strength tests, uniaxial dynamic triaxial tests, and scanning electron microscopy (SEM) microstructural analyses to investigate the effects of particle gradation on the mechanical properties of solidified calcareous sand from both macroscopic and microscopic perspectives. The results demonstrated that under conditions where the curvature coefficient was altered while the non-uniformity coefficient remained constant, the effective calcium carbonate content initially increased and then decreased with rising curvature coefficients. Calcareous sand with optimal particle gradation exhibited the highest effective calcium carbonate generation, which enhanced the bonding between adjacent sand particles, thereby improving compressive strength and liquefaction resistance. Li Zirui et al. [29] found that the absence of particle gradation significantly affected the shear strength of soil samples, with coarse-grained sand showing more pronounced effects than fine-grained sand. Sand with well-graded particles demonstrated higher shear strength due to its rational force chain network structure, where coarse particles formed primary force chains responsible for internal stress transfer. Fine-grained sand formed finer force chains that filled interstitial spaces, providing lateral support to the primary chains. Chen Qingsheng et al. [30] conducted a series of direct shear tests and SEM microstructural analyses to study the evolution of shear strength, cohesion, and internal friction angle parameters in polymer-modified calcareous sand as polymer content and particle gradation varied, while also elucidating the microscopic mechanisms of polymer modification. The results confirmed that particle gradation significantly enhances the performance of polymer-modified

calcareous sand. The higher the proportion of coarse particles in calcareous sand, the larger its pore size becomes, leading to more pronounced polymer reactions and more significant strength variations. The shear strength of calcareous sand increases markedly with the increase in coarse particles within its gradation. However, when the sample contains a higher proportion of fine particles, the inter-particle pores become smaller, thereby reducing the improvement effect of polymer-modified calcareous sand. Nevertheless, fine-grained calcareous sand still retains pore channels, and as the polymer content increases, the cementation effect of the polymer can be further enhanced.

The study demonstrates that particle size distribution significantly impacts the stabilization of calcareous sand, constituting a critical influencing factor.

4. Study on the Reinforcement Mechanism of Soil Treated with Xanthan Gum and EICP

As shown in Figure 1, under the action of EICP, xanthan gum undergoes cross-linking reactions with Ca^{2+} to form calcium carbonate mixtures, producing more precipitates compared to pure EICP. Unlike pure XG which exhibits high water absorption, this mixed compound demonstrates better water solubility and enhanced stability, effectively mitigating soil degradation caused by dry-wet cycles. The calcium carbonate precipitates generated by EICP coagulate soil particles and fill pores, improving sample integrity and reducing erosion from repeated moisture cycles. Mechanistically, the colloid's encapsulation and sustained hardening strengthen the bond between calcium carbonate and calcareous sand particles, enhancing tensile, compressive, and shear strength. Additionally, xanthan gum's organic properties provide nucleation sites for urease-catalyzed calcium carbonate formation, ensuring uniform distribution within the sand and improving mechanical performance. The resulting water-insoluble precipitates further enhance the stabilized material's water stability and overall strength.

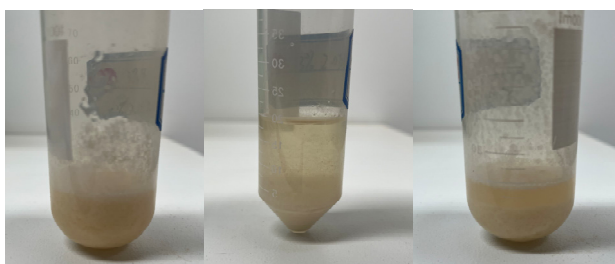


Figure 1. XG reaction solution; EICP reaction solution; XG-EICP reaction solution

5. Conclusion

This paper summarizes the feasibility of the Xanthan gum combined with EICP curing calcium sand, and the key influencing factors, and briefly analyzes the reinforcement principle, and comes to the following conclusions.

1) The microbial-induced calcium carbonate precipitation (MICP) technology combined with xanthan gum for soil stabilization has demonstrated significant engineering improvement effects. Given the consistency between the plant urease-induced calcium carbonate precipitation (EICP) technology and MICP technology in their core mechanisms of calcium carbonate precipitation formation and soil particle

cementation, it can be inferred that the combined application of xanthan gum and EICP technology for soil stabilization is theoretically and technically feasible.

2) The final treatment efficacy of calcium carbonate precipitation (EICP) reinforced with xanthan gum and plant urease is influenced by multiple factors. Future research should focus on optimizing key process parameters (including ambient temperature, urease concentration, urease-to-xanthan gum ratio, and reaction system pH), as well as refining reinforcement techniques and determining optimal calcium sand particle gradation. These efforts will be crucial for enhancing the reliability and applicability of this technology.

3) In the EICP reaction system, xanthan gum forms complex crosslinks with free Ca^{2+} ions, creating a xanthan-gum-calcium carbonate co-precipitate. This composite demonstrates higher yield and larger particle size compared to calcium carbonate precipitates from pure EICP. Notably, it exhibits significantly reduced water solubility and enhanced structural stability compared to pure xanthan gum, which has higher hydrophilicity. These combined properties effectively improve the hydraulic stability of cured soil and further enhance its mechanical strength.

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