

Article

Evaluating the Efficacy of Enzyme-Induced Carbonate Precipitation (EICP) for Aeolian Sand Fixation

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Abstract: Enzyme-Induced Calcium Carbonate Precipitation (EICP) shows promise for desertification control. This study investigates the effects of solid-to-liquid ratio, calcium sources, Ca^{2+} concentration, temperature, enzyme-to-liquid ratio (ELR), and pH on the activity of soybean crude urease (SCU). Furthermore, the impact of EICP treatment cycles on the mechanical properties, compressive behavior, and wind erosion resistance of aeolian sand (AS) was systematically evaluated, with microstructural evolution and pore characteristics of cemented specimens analyzed through SEM and X-CT. Key findings reveal that SCU activity and the calcium carbonate precipitation rate (PR) reached optimal levels (80~99%) under conditions of a 1:10 solid-to-liquid ratio, 1.0~1.5 M CaCl_2 concentration, 35~70 °C temperature range, and pH 7. After seven EICP treatments, AS specimens exhibited complete cementation with an unconfined compressive strength (UCS) of 580 kPa and a reduced wind erosion rate of 0.151 g/min, effectively mitigating desertification. SEM and X-CT analyses confirmed significant pore infilling and bridging between particles, accompanied by a reduction in pore quantity and permeability coefficient by over two orders of magnitude. EICP demonstrates notable advantages in enhancing mechanical performance, environmental compatibility, and cost efficiency, positioning cemented AS as a viable construction material while offering insights for sand stabilization engineering. These findings provide essential technical support for material innovation, wind and sand disaster prevention, and the sustainable construction of desert highway bases and subbases.



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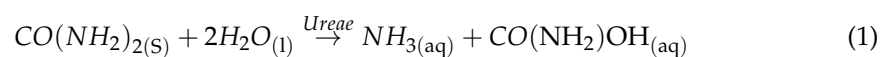
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Keywords: EICP; aeolian sand; UCS; permeability coefficient; SEM; X-CT

1. Introduction

Aeolian sand, characterized by its extensive distribution and high mobility, not only degrades arable lands but also constitutes a major source of fugitive dust emissions [1]. The resultant airborne particulates threaten public health through air pollution [2] while severely compromising regional economic development and ecosystem integrity [3]. Current stabilization strategies predominantly employ mechanical, chemical, and integrated approaches [4,5]. However, conventional techniques suffer from technical limitations including prohibitive costs, low operational efficiency, inadequate durability, and risks of secondary contamination, rendering them incompatible with modern demands for ecological sustainability and cost-effective desertification mitigation [6].

Recent advancements in biogeochemical precipitation techniques have established carbonate-induced mineralization as an environmentally sustainable soil stabilization method, demonstrating advantages in operational efficiency, process controllability, and minimal construction disturbance [2,7,8]. This technology has been extensively implemented in geotechnical reinforcement, coastal dune stabilization, and erosion mitigation [9–11]. Scholars have defined the process system as *Bacillus mucilaginosus*-induced calcium carbonate (BICP). Studies show that, when supplied with an appropriate calcium source, silicate-mineralizing microorganisms are activated, leading to calcium carbonate production—similar to MICP. Additionally, carbonic anhydrase (CA) secreted by these microorganisms efficiently captures atmospheric CO₂, facilitating biomineralization. This process holds significant scientific value in providing a theoretical foundation for CO₂ solidification and biomineralization [12]. Leveraging BICP principles, researchers have developed a novel carbon-trapping microbial cement applicable to surface stabilization, such as dust suppression and desert remediation [12]. Traditional chemical sand fixation involves spraying chemical adhesives to form a rigid, flexible, or elastic consolidation layer that prevents wind erosion and retains moisture [13]. However, this method lacks environmental compatibility and poses risks of secondary pollution [14]. However, widespread application of Microbial-Induced Carbonate Precipitation (MICP) remains constrained by prohibitively expensive microbial agents and complex bio-processing requirements including bacterial inoculation, cultivation, and purification [15,16]. Comparative studies reveal the superior technical feasibility of Enzyme-Induced Carbonate Precipitation (EICP) [17]. EICP offers several advantages over MICP, primarily due to the short growth cycle of urease, enabling faster bioprecipitate formation. Unlike MICP, EICP does not require oxygen consumption [18]. The bacterial size typically ranges from 50 to 5000 nm [15], whereas plant-derived urease measures approximately 12 nm [19]. Notably, plant-derived urease functions without bacterial involvement, exhibits nanoscale dimensions, dissolves in water, and does not form biofilms. The relative size of calcium carbonate crystals and soil particles significantly influences the curing effect [16]. Due to its small particle size, plant-derived urease facilitates nanoscale urease-mediated urea hydrolysis, promoting a more uniform CaCO₃ distribution and mitigating the risk of biological clogging, which operates through bacteria-independent reaction pathways (as per Equations (1)–(3)), employing nanoscale enzymatic catalysts with aqueous solubility and eliminating biofilm formation risks. The interfacial compatibility between CaCO₃ crystallite dimensions (typically 2–10 µm) and host soil matrices critically governs stabilization efficacy [16], where phyto-derived urease nanoparticles (20–50 nm) effectively mitigate bioclogging risks while maintaining hydraulic conductivity.



Extensive studies have demonstrated that EICP technology enhances soil properties through pore-filling cementation, effectively reducing permeability [20], increasing unconfined compressive strength (UCS) [7], and mitigating surface erosion by suppressing dust emissions and reinforcing surface integrity [21,22]. The principle of this technology is to use soybean urease. The carbonate produced by enzyme hydrolysis of urea combines with calcium ions to fill and cement the soil. While substantial research has explored EICP applications [23,24], few studies have systematically optimized soybean crude urease (SCU)-mediated cementation for aeolian sand (AS) stabilization.

Key factors influencing soil stabilization efficiency—urease activity [25,26], cementation solution concentration [27], and environmental conditions [28]—were rigorously investigated. This study first characterizes SCU's fundamental properties, focusing on the impacts of the solid-to-liquid ratio, calcium source/concentration, temperature, the enzyme-to-liquid ratio (ELR), and pH on enzymatic activity. Subsequently, AS specimens treated under optimized SCU conditions were evaluated for chemical stability, mechanical performance, permeability, compressibility, and wind erosion resistance. Advanced SEM and X-CT analyses elucidated microstructural evolution and pore network modifications, providing mechanistic insights to guide desertification control strategies

2. Materials and Methods

2.1. Aeolian Sand

The aeolian sand (AS) used in this study was sourced from shallow sand layers at the southern margin of the Gurbantunggut Desert in Xinjiang, China, exhibiting a brown coloration (Figure 1a). X-ray diffraction analysis revealed a mineral composition dominated by quartz 60.05%, potassium feldspar 18.4%, and albite 14.48%, with trace constituents accounting for 7.07%. Specimens were prepared via grouting using cylindrical plexiglass molds with 62 mm diameter $\times$ 140 mm height. The molds were sealed at both ends with perforated rubber stoppers covered by permeable stones and connected to an infusion funnel upper end and a TL-LL-100W peristaltic pump (Tianli Fluid Technology Co., Ltd., Ningbo, China) lower end via silicone tubing (Figure 1b). Laser granulometry BT-2002 analyzer (Dandong Bettersize Instruments Ltd., Dandong, China) indicated that 94.95% of AS particles fell within the 0.1~0.25 mm range (Figure 1c). Gradation parameters included $d_{10} = 0.10$ mm, $d_{60} = 0.16$ mm, $d_{30} = 0.12$ mm, uniformity coefficient $C_u = 1.57$, and curvature coefficient $C_c = 0.85$, classifying the AS as poorly graded.

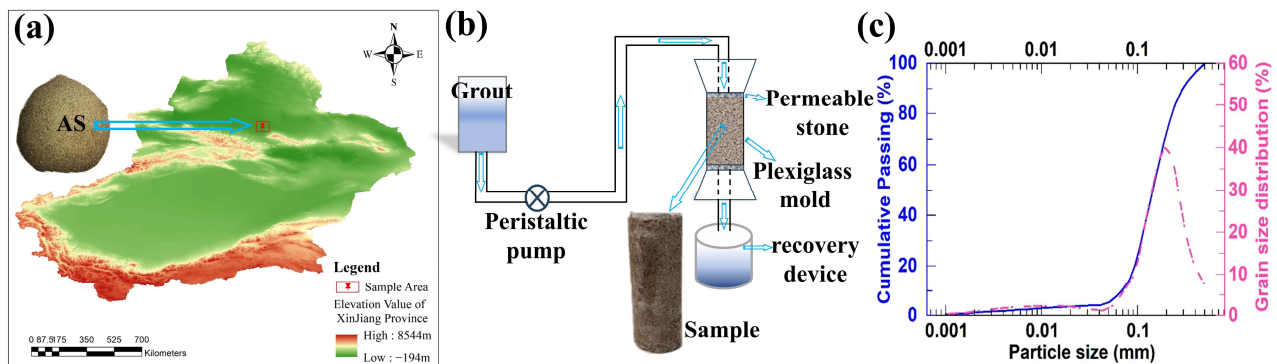


Figure 1. AS sampling location, grouting sample preparation, and particle size distribution: (a) sampling location and AS picture; (b) schematic diagram of liquid injection device; (c) particle size distribution curves.

2.2. Basic Physical and Chemical Indicators and UCS

Material characterization was conducted in accordance with the standard for geotechnical test methods (GB/T 50123-2019) [29]: bulk density, specific gravity, natural moisture content, and hydraulic conductivity via variable-head permeability test. Table 1 summarizes the AS's geotechnical properties. Cemented specimens underwent direct shear testing using an LT1008 servo-controlled shear (Nanjing Binzhenghong Instrument Co., Ltd., Nanjing, China) apparatus and UCS evaluation via hydraulic universal testing machine under displacement-controlled loading 0.05 mm/min.

Table 1. Basic physical and mechanical performance indicators.

Bulk Density (g/cm ³)	Maximum Dry Density (g/cm ³)	Permeability Coefficient (cm/s)	Natural Density (g/cm ³)	Natural Moisture Content (%)	Gradation Coefficient	Specific Gravity of Soil Particles G _s	a _v (MPa ^{−1})
1.28	1.712	0.015	1.29	0.97	1.10	2.56	1.892

2.3. Soybean Crude Urease

The purchased soybeans were crushed by a grinder, passed through a 100-mesh steel sieve, and placed in a refrigerator for later use. The appropriate amounts of soybean powder and distilled water containing 30% ethanol were prepared into different concentrations of solid–liquid ratios (1:5, 1:10, 1:15, 1:20), and stirred for 30 min by magnetic stirrer, so that urease can be dissolved into the solution. Placed in a refrigerator at 4 °C for 16 h, the supernatant was centrifuged at 8000 rpm for 12 min to extract soybean crude urease.

2.4. Determination of Urease Activity

Urease is a urea catalyst. According to the mechanism of EICP, as shown in Equations (1) and (2), the ion concentrations in the solution (NH₄⁺, CO₃^{2−}) increase in parallel with the rate of urea hydrolysis, leading to enhanced conductivity. The change in solution conductivity is directly proportional to the amount of urea hydrolysis. Since resistance (R) is the ratio of voltage (U) to current (I), representing the ability of a material to resist current flow, conductivity (E) is the inverse of resistance, indicating the ability of a material to conduct current. Therefore, conductivity can be measured using a Shanghai Leici DDS-307A (Shanghai INESA Scientific Instrument Co., Ltd., Shanghai, China) conductivity meter in conjunction with a Shanghai Leici DJS-10C electrode (Shanghai Leici Instrument Co., Ltd., Shanghai, China). Given the generally low conductivity of the solution, conductivity is typically measured in mS/cm (millisiemens per centimeter). Research has shown that in a 1.5 M urea solution, the change of 1 mS/cm conductivity reflects the hydrolysis amount of 11.11 mmol urea [30]. The conductivity change value of the soybean crude urease solution mixed with the urea solution was measured by Shanghai Yidian DDS-307 A conductivity meter. The crude urease activity (UA) of soybean was calculated by Formula (4). The UA was statistically validated using analysis of variance (ANOVA), and the error margins were determined based on the standard deviation.

$$UA = 11.11 \times \frac{\Delta E \times k}{T} \quad (4)$$

In the formula, UA is the activity of the urease solution per unit volume (mM/min), ΔE is the change value of solution conductivity (mS/cm) in time T, and K is the dilution factor of the urease solution [31].

2.5. Solid-to-Liquid Ratio

UA under varying solid-to-liquid ratios (1:5, 1:10, 1:15, 1:20) was quantified by mixing 5 mL of the soybean crude urease (SCU) solution with 45 mL of the 1.11 mol/L urea solution. The electrical conductivity of each mixture was monitored for 5 min, with triplicate measurements averaged to determine the enzymatic activity for each ratio.

2.6. Calcium Source

Reaction solutions of 100 mL each were prepared using calcium chloride, calcium acetate, calcium nitrate, and calcium lactate as calcium sources at 1.0 M concentration. For each solution, 13.5 mL was mixed with 1.5 mL of soybean crude urease SCU in test tubes, incubated for 24 h, and repeatedly washed with distilled water. SCU solutions with a

1:10 solid-to-liquid ratio were further reacted with calcium solutions of varying concentrations (0.5~2.5 M). Filter paper mass m_0 was recorded prior to vacuum filtration. Precipitates retained on filter paper were dried at 60 °C for 24 h and weighed (m). Calcium carbonate precipitation rate PR was calculated as $m_A/m_T \times 100\%$, where m_A represents the actual CaCO_3 yield and m_T denotes the theoretical yield under complete Ca^{2+} mineralization, per Equations (5)–(7).

$$m_A = m - m_0 \quad (5)$$

$$m_T = C_{\text{Ca}^{2+}} \cdot V \cdot M_{\text{CaCO}_3} \quad (6)$$

$$PR = \frac{m_A}{m_T} \times 100 \quad (7)$$

2.7. Temperature, ELR, and pH

Additional experiments evaluated temperature 25~80 °C and enzyme-to-liquid ratio ELR effects on CaCO_3 precipitation using 1.5 M cementation solutions with equal volumes of urea and CaCl_2 with a total reaction volume of 50 mL; the detailed protocols are provided in Table 2. Parallel trials at ELR 0.6 assessed the UA, CaCO_3 yield (m_A), theoretical yield (m_T), and precipitation rate (PR) across pH 5~10. The temperature range of 25–80 °C was chosen to reflect practical conditions and the thermal stability of urease. In arid and semi-arid regions, surface temperatures can exceed 60 °C during peak sunlight, making this range relevant for real-world applications. Testing up to 80 °C allows for the assessment of enzymatic activity and cementation performance under extreme conditions, providing valuable insights into the feasibility of EICP in high-temperature environments. Furthermore, this range corresponds to the thermal tolerance of urease, enabling the evaluation of its activity and degradation behavior under varying environmental conditions.

Table 2. Preparation scheme of urease and cementing solution.

Temperature (°C)	Soybean Urease (mL)	Deionized Water (mL)	ELR	Cementation Concentration (M)	Cementing Fluid (mL)	Total Volume of Solution (mL)
25, 35, 45, 55, 60, 65, 70, 80	5	20	0.2	2.0	25	50
	10	15	0.4			
	15	10	0.6			
	20	5	0.8			
	25	0	1			

2.8. Wind Erosion Resistance Rate

The wind erosion resistance of EICP-treated aeolian sand was evaluated using a custom-built test apparatus (Figure 2). A 1.5 kg sand sample was compacted in a $35 \times 25 \times 4 \text{ cm}^3$ tray and sprayed sequentially with EICP solution and cementation liquid 3 L/m^2 application rate; the control group received deionized water. After 7-day air-drying at $25 \pm 2 \text{ °C}$ to enable continuous mineralization, the samples were oven-dried at 60 °C to terminate reactions. The wind erosion rate mass loss per unit time was measured in a wind tunnel aligned with airflow direction under 10 m/s wind velocity for 8 min. A wind speed of 10 m/s with a duration of 8 min was selected based on its relevance to real-world conditions and its effectiveness in testing EICP-treated sand. A wind speed of 10 m/s (approximately Beaufort scale 5) is a common threshold for strong winds in arid and semi-arid regions, representing critical conditions for wind erosion and sand transport, as noted in Wind-Sand Environmental Engineering. This speed effectively simulates natural wind-blown sand erosion while preventing atypical failure modes, such as structural collapse, which may occur at higher speeds ($\geq 12 \text{ m/s}$). Additionally, a sensitivity analysis of the EICP treatment showed that wind speeds below 8 m/s resulted in minimal

surface erosion (<1%), making it difficult to distinguish the wind resistance of different formulations, while speeds above 12 m/s caused insufficiently cured sand particles to be stripped away, masking the true erosion resistance of the cemented layer. Therefore, 10 m/s was chosen as the optimal balance between test sensitivity and result reliability, effectively demonstrating the improvement in wind erosion resistance achieved through EICP cementation.

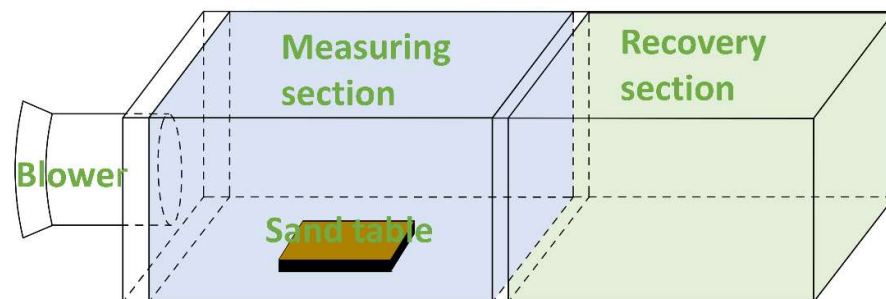


Figure 2. Custom-built wind erosion simulation apparatus.

2.9. SEM and X-CT

Post-UCS specimens were pulverized to particles <80 μm and sputter-coated with gold. The focused electron beam of the ZEISS EVO LS15 scanning electron microscope was used to perform point-by-point surface scanning to obtain the SEM image of the sample, as shown in Figure 3a. Surface morphology was analyzed using a ZEISS EVO LS15 SEM (Carl Zeiss AG, Oberkochen, Germany) operated at 15 kV, with the accelerating voltage instrument schematic shown in Figure 3a. X-CT scans were performed on AS specimens with varying ELR (Table 3) via a nanoVoxel-3000 system Sanying Precision (Sanying Precision Instruments Co., Ltd., Tianjin, China). As illustrated in Figure 3b,c, the samples were positioned between an X-ray source and a silicon-based multichannel CCD detector, generating position-encoded coordinate arrays. Three-dimensional grayscale reconstructions derived from X-ray attenuation coefficients enabled quantitative pore analysis (size distribution and density) across specimens AS0~AS3, elucidating EICP-mediated pore-filling efficacy.

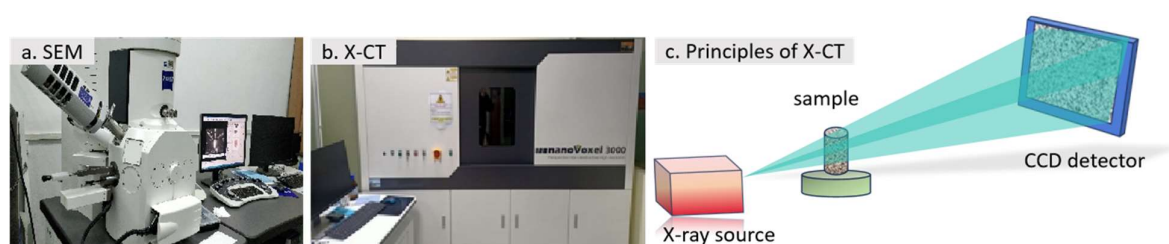


Figure 3. SEM, nanoVoxel 3000 X-CT and its technical principle.

Table 3. AS cemented with varying ELR.

Contents	AS0	AS1	AS2	AS3
ELR	0	0.6	0.8	1.0

3. Results and Discussions

3.1. The Activity of Crude Soybean Urease with Different Solid–Liquid Ratios

Prior studies demonstrate that soybean flour quality critically governs urease solution activity [17,32], with controlled flour dosages ensuring consistent enzymatic extraction.

Urease, a catalyst for urea hydrolysis, operates within EICP through tripartite interactions involving urease, $\text{CO}(\text{NH}_2)_2$, and Ca^{2+} , as outlined in Equations (1)–(3) [33]. As reactions progress in Equations (1) and (2), NH_4^+ and CO_3^{2-} ion concentrations rise proportionally to reaction kinetics, elevating solution conductivity. This correlation enables electrical conductivity changes to serve as a proxy for urea hydrolysis rates. Subsequent CaCO_3 precipitation in Equation (3) further validates UA, with urea decomposition or CaCO_3 yield per unit time acting as quantifiable metrics. As shown in Figure 4, SCU activity increases with a higher solid-to-liquid ratio. However, when the solid-to-liquid ratio is 1:10, the rate of increase in SCU activity per unit mass is at its highest. At this ratio, the effectiveness of the EICP process was maximized, providing a good balance between ensuring sufficient solution for chemical reactions and avoiding excessive dilution that could hinder precipitation efficiency. Therefore, in subsequent experimental studies, the solid-to-liquid ratio was set at 1:10.

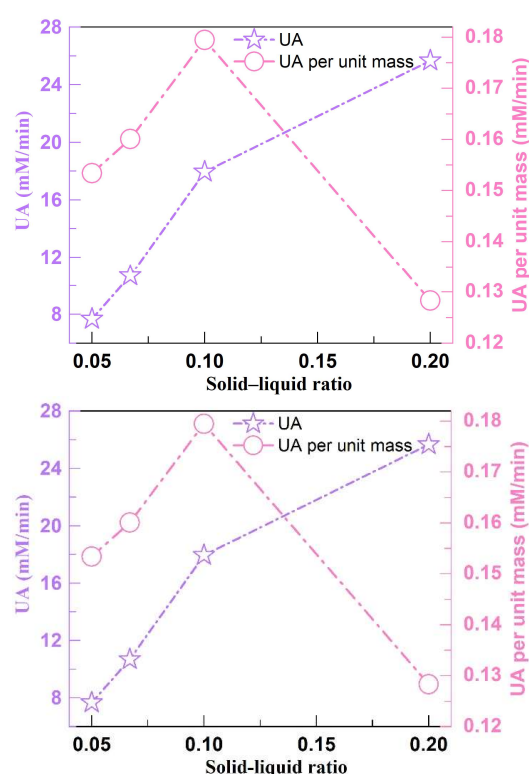


Figure 4. Effect of S/L on UA.

3.2. Effect of Calcium Source and Calcium Ion Concentration

The crystalline morphology and yield of bioinduced calcium carbonate CaCO_3 are intrinsically linked to calcium source selection and ion concentration [34,35]. This study employed CaCO_3 yield as the control metric to evaluate EICP performance across varying calcium sources and concentrations. Precipitation rate PR —defined as the ratio of actual CaCO_3 yield (m_A) to theoretical yield m_T under complete Ca^{2+} mineralization [36,37]—served as a critical indicator of geotechnical improvement efficacy.

Figure 5a demonstrates significant disparities in CaCO_3 yields among tested calcium sources. CaCl_2 achieved the highest m_A and PR values, followed sequentially by $\text{Ca}(\text{NO}_3)_2$, $\text{Ca}(\text{CH}_3\text{COO})_2$, and $\text{Ca}(\text{C}_3\text{H}_5\text{O}_3)_2$. However, all PR values plateaued below 100% (maximum 74.07%), indicating incomplete urea hydrolysis and suboptimal CO_3^{2-} availability. Notably, while studies suggest $\text{Ca}(\text{NO}_3)_2$ and CaCl_2 as sole viable calcium sources for biocementation—with nitrate ions exhibiting urease inhibition [38,39]—this work recom-

mends CaCl_2 as the optimal choice (excluding chloride compatibility concerns), aligning with MICP precedents [40,41].

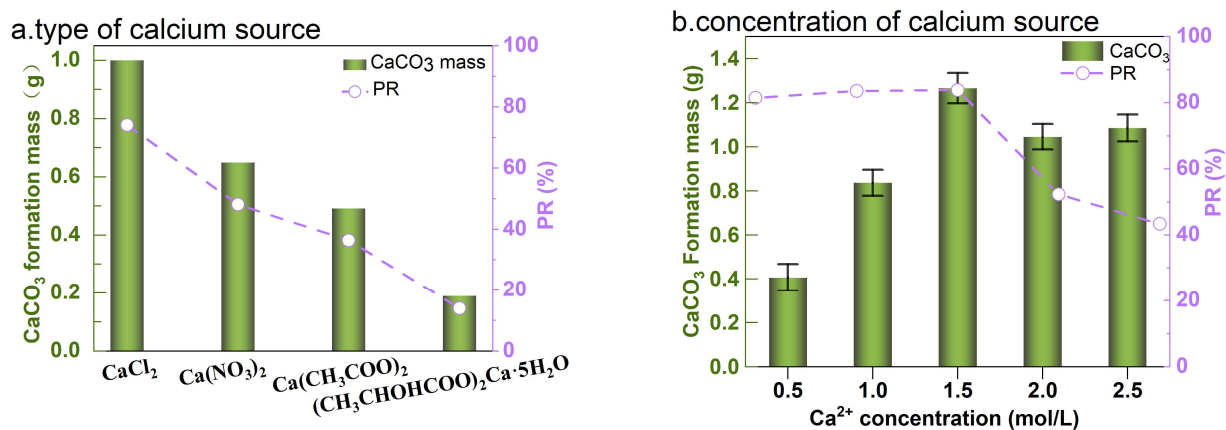


Figure 5. The effects of the type of calcium source and the concentration of calcium chloride on the production of calcium carbonate were studied.

Varying CaCl_2 concentrations (0.5–2.5 M) reacted with SCU 1:10 solid-to-liquid ratio revealed a non-linear relationship (Figure 5b). As the calcium source concentration increased, both m_A and PR initially rose, peaking at 1.5 M before declining, which contradicts the theoretically expected monotonic increase. The reason for this phenomenon is that the non-linear relationship between $[\text{Ca}^{2+}]$ and precipitation rate (Figure 5b) arises from competing kinetic limitations rather than thermodynamic violations. At low concentrations, Le Chatelier's principle dominates as Ca^{2+} availability drives nucleation. Beyond 1.5 M, however, enzyme inactivation by surface encrustation and ionic strength effects override the thermodynamic driving force. This suppression effect at elevated Ca^{2+} levels [42] underscores the necessity for concentration optimization. Balancing yield and cost-efficiency, a 1.0–1.5 M Ca^{2+} range is proposed for field applications.

3.3. Effects of Temperature and ELR on UA

Figure 6 illustrates the variation of CaCO_3 yield (m_A) with enzyme-to-liquid ratio (ELR) and temperature at a fixed solid-to-liquid ratio of 1:10. m_A initially increased with temperature before declining, peaking at 60 °C across all ELR conditions. At this temperature, ELR 1.0 achieved near-complete urea hydrolysis (PR $\approx$ 100%). While PR exceeded 99% for $\text{ELR} \geq 0.6$, lower ELR values (<0.6) resulted in markedly reduced m_A , with PR plateauing at 86% even under optimal thermal conditions. SCU demonstrated a broad catalytic temperature window (35–65 °C), outperforming MICP-associated bacterial ureases constrained to sub-50 °C environments [43]. Notably, conductivity assays recorded maximal initial UA at 60 °C. However, at higher temperatures, the enzyme undergoes thermal denaturation, altering its three-dimensional structure, exposing the active site, and causing structural instability, which reduces its activity [44]. As a result, diminished CaCO_3 yields were observed due to accelerated enzyme denaturation at elevated temperatures [45]. The 35–65 °C range was selected to maximize UA while avoiding protein denaturation. Above 65 °C, UA rapidly declines, while below 35 °C, its activity remains low. In both cases, reduced calcium carbonate precipitation weakens the wind erosion resistance of aeolian sand.

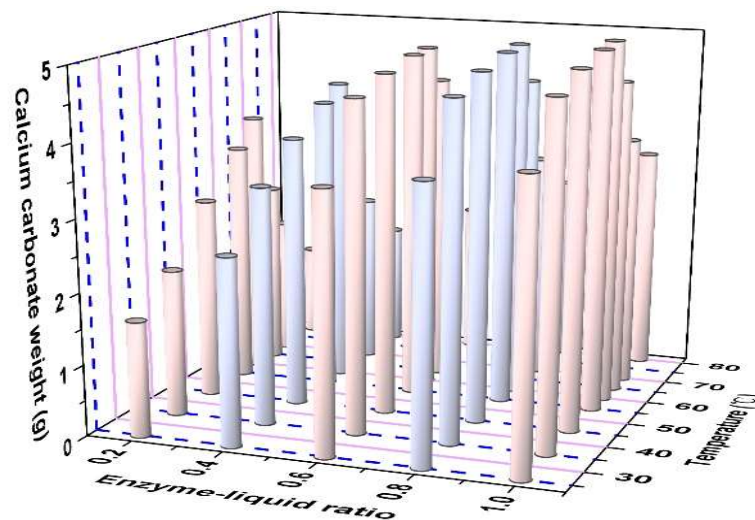


Figure 6. CaCO_3 yield variation with ELR and temperature.

3.4. Effect of pH Value on UA

The effects of pH on SCU activity (UA), CaCO_3 yield (m_A), and precipitation rate (PR) were investigated under fixed conditions of 1.5 M cementation solution, ELR 0.6, as shown in Figure 7. UA and m_A increased progressively at pH < 7, peaking at pH 7, followed by declines at higher pH levels. These trends confirm SCU's optimal catalytic efficiency within pH 6–8. Extreme acidity or alkalinity suppressed urease solubility and urea hydrolysis capacity [37], aligning with observed reductions in enzymatic activity.

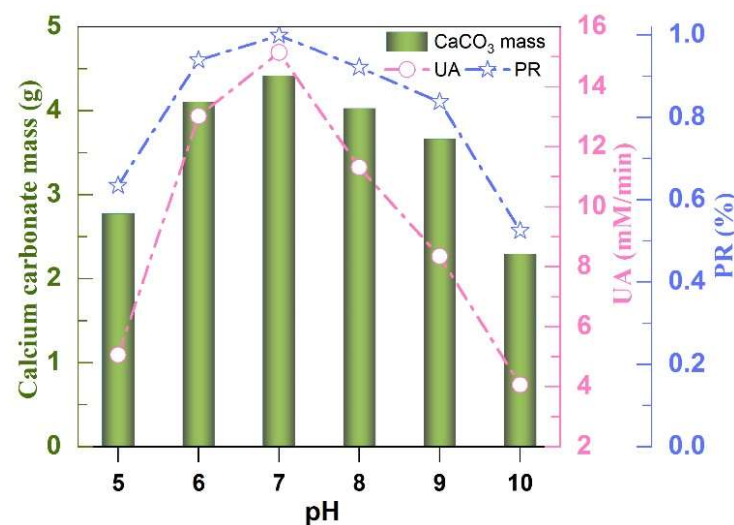


Figure 7. Effect of pH on SCU activity.

3.5. Analysis of Mechanical Properties of Aeolian Sand

To assess mechanical enhancement, the shear strength, cohesion, and internal friction angle of AS under varying normal stresses were plotted against EICP treatment cycles (Figure 8a,b). All parameters exhibited monotonic increases with treatment frequency. Specimens treated seven times achieved peak shear stress earliest across stress levels, attributed to intensified cementation from CaCO_3 -dominated pore filling.

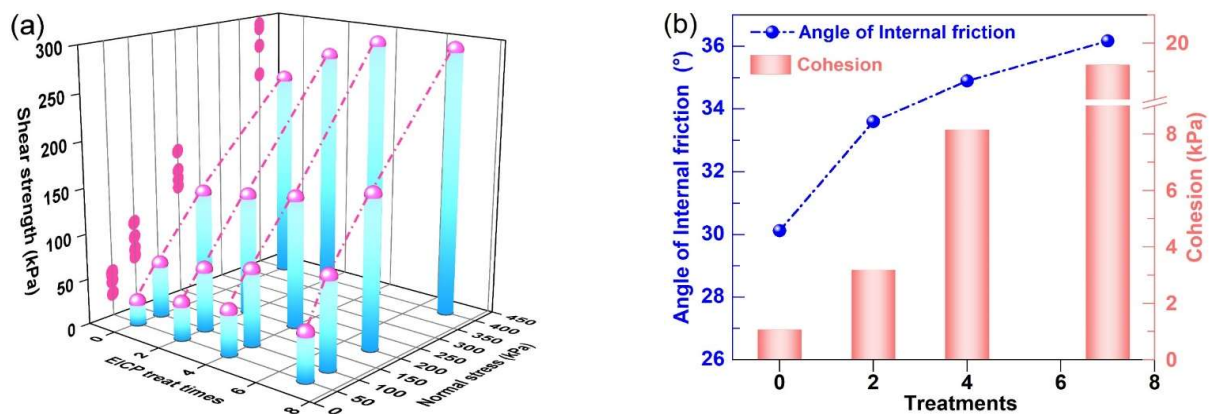


Figure 8. Variation in shear strength parameters in AS specimens under varying EICP treatment cycles: (a) variation in shear strength; (b) cohesion and angle of internal friction.

3.6. UCS

The evolution of unconfined compressive strength UCS and failure modes in AS under varying EICP treatment cycles (2, 4, 7) is shown in Figure 9. Specimens treated twice exhibited no cementation (Figure 9a), while partial cementation occurred near injection/drainage ports after four cycles. Seven-cycle treatments yielded fully consolidated sand columns with progressively enhanced structural integrity. UCS testing of seven-cycle specimens (Figure 9b) revealed a maximum strength of ~580 kPa without residual strain, confirming EICP's efficacy in transforming loose AS into cohesive, compression-resistant matrices. Figure 9c further demonstrates brittle rock-like failure characteristics post-treatment, indicative of homogeneous CaCO_3 cementation.

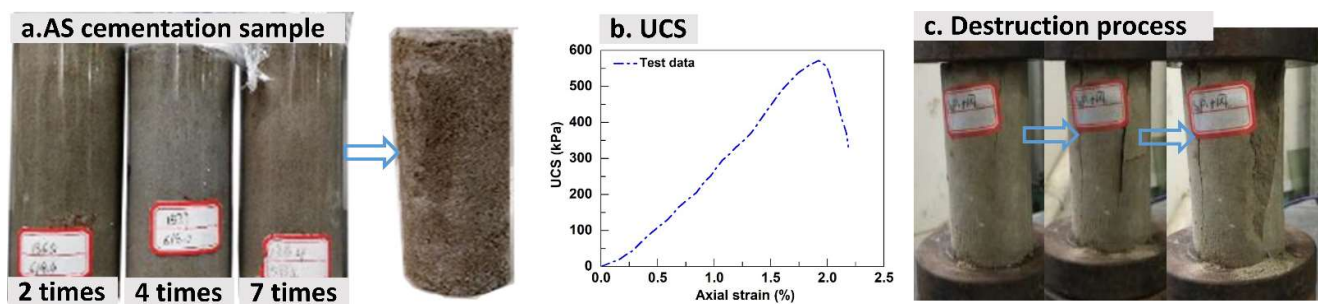


Figure 9. UCS and compressive failure behavior of cemented AS specimens.

3.7. Wind Erosion Resistance

The results of the AS wind erosion resistance test are shown in Figure 10. The wind erosion rate of the control group was 22.6 g/min, and the wind erosion rates of the AS samples treated with EICP for 2, 4, and 7 times were 0.235 g/min, 0.216 g/min, and 0.156 g/min, respectively. The wind erosion rate of sand samples in the control group was higher, which indicated that the AS surface layer was loose and did not form effective cementation, and it was difficult to resist wind erosion. However, the wind erosion rate of AS samples after EICP treatment decreased significantly. It can be seen that SCU-induced mineralization treatment can effectively improve the wind erosion resistance of AS, and a few treatments can meet the sand fixation needs of the sand control area.

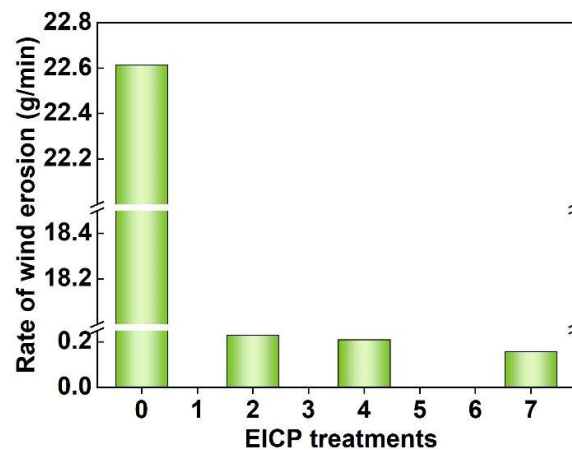


Figure 10. The wind erosion resistance of AS changes with the number of EICP treatments.

3.8. Permeability Coefficient

As illustrated in Figure 11, the permeability coefficient of AS specimens decreased progressively post-cementation. During the initial two treatment cycles, the permeability curve of AS1 exhibited no distinct inflection point, while AS3 demonstrated a gradual decline in permeability that accelerated subsequently. In later-stage cementation, the permeability reduction rates of AS1 and AS2 slowed significantly. After treatment, the final permeability coefficient of AS3 reached the maximum value of 4.66×10^{-5} cm/s, whereas AS2 displayed the minimum value (1.12×10^{-5} cm/s), with its permeability reduction exceeding two orders of magnitude. This suggests that both excessively high and low ELR values lead to less effective pore channel clogging compared to the optimized ELR of AS2. The initial permeability of AS was approximately 1.0×10^{-3} cm/s, and the final value represented by K_f . For precise quantification, permeability coefficients before and after cementation were statistically analyzed (Table 4). Notably, AS2 exhibited the most pronounced permeability reduction ($K_0/K_f = 147.92$), while AS3 showed the minimal reduction ($K_0/K_f = 28.53$), aligning with observed microstructural modifications.

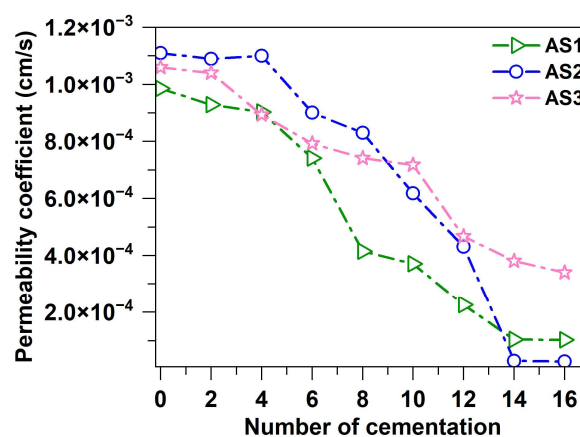


Figure 11. The relationship between the permeability coefficient and the number of cementation treatment.

Table 4. Variation in permeability coefficient before and after cementation.

Sample	K_0 (cm/s)	K_f (cm/s)	$\frac{K_0}{K_f}$
AS1	9.23×10^{-4}	1.59×10^{-5}	58.11
AS2	1.65×10^{-3}	1.12×10^{-5}	147.92
AS3	1.33×10^{-3}	4.66×10^{-5}	28.53

3.9. Microscopic Characteristics

3.9.1. SEM

The microstructural characteristics of calcium carbonate minerals induced by SCU under four calcium sources (CaCl_2 , $\text{Ca}(\text{NO}_3)_2$, $\text{Ca}(\text{CH}_3\text{COO})_2$, and $\text{Ca}(\text{C}_3\text{H}_5\text{O}_3)_2$) were examined via SEM at $90\times$ magnification. To facilitate observation, minerals were pre-isolated, resulting predominantly in discrete particles with occasional aggregates, as shown in Figure 12. In solution-phase environments, SCU-induced CaCO_3 primarily exhibited spherical morphologies with uniform particle sizes (Figure 13). Figure 13 reveals clustered CaCO_3 spheroids, which is aligned with Figure 12. Observations of them being interspersed with fibrillated surface textures and irregular morphologies. Notably, in the absence of porous media, CaCO_3 crystals retained homogeneous spherical forms, whereas the inclusion of porous media triggered a phase transition to rhombohedral calcite. The distribution density and interstitial arrangement of these calcite crystals critically enhanced the mechanical performance of AS. Figure 14 shows contrasts SEM images of AS pre- and post-EICP treatment. Untreated AS particles displayed smooth surfaces with sporadic abrasions and pits (Figure 14a), attributable to aeolian weathering. Post-treatment, particle morphology, spacing, and cementation intensity underwent marked alterations (Figure 14b), manifesting as macroscopic cementation. Higher magnification revealed rhombohedral CaCO_3 crystals adhering to particle surfaces and densely filling interstitial voids (Figure 14c). Partial pores remained unoccupied, yet crystal interlocking established bridging structures that reinforced specimen integrity. Localized exfoliation of calcite crusts from AS surfaces (Figure 14d) further validated the robust cementation efficacy of EICP.



Figure 12. SEM of calcium carbonate minerals corresponding to different calcium sources.

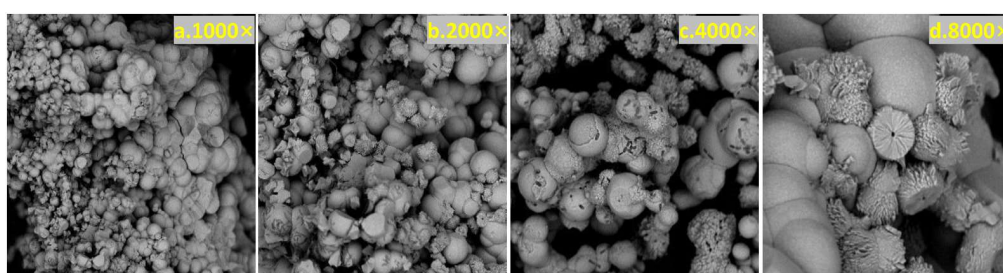


Figure 13. SEM diagram of CaCO_3 mineral corresponding to CaCl_2 as calcium source.

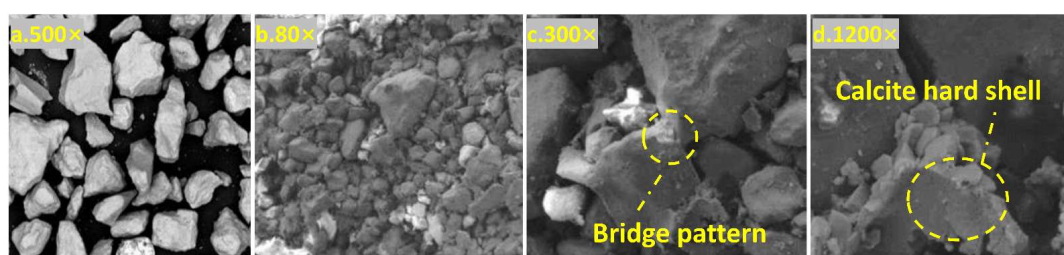


Figure 14. SEM before and after cementation of AS.

3.9.2. X-CT

Figure 15 presents X-CT-derived pore volume distribution histograms for AS specimens subjected to varying ELR treatments. Untreated specimen AS0 exhibited a negligible presence of pores exceeding 0.1 mm^3 . For AS1, pores within the $0.01\text{--}0.1 \text{ mm}^3$ range showed a marked reduction in quantity, while sub- 0.01 mm^3 pores displayed a paradoxical increase. AS2 demonstrated a moderate decline in both large- ($>0.1 \text{ mm}^3$) and small-sized pores, whereas AS3 exhibited reduced sub- 0.01 mm^3 porosity with minimal variation in the $0.01\text{--}0.1 \text{ mm}^3$ category. These trends underscore ELR-dependent pore refinement dynamics, where optimized ELR (AS2) achieved balanced porosity reduction across multiple size domains.

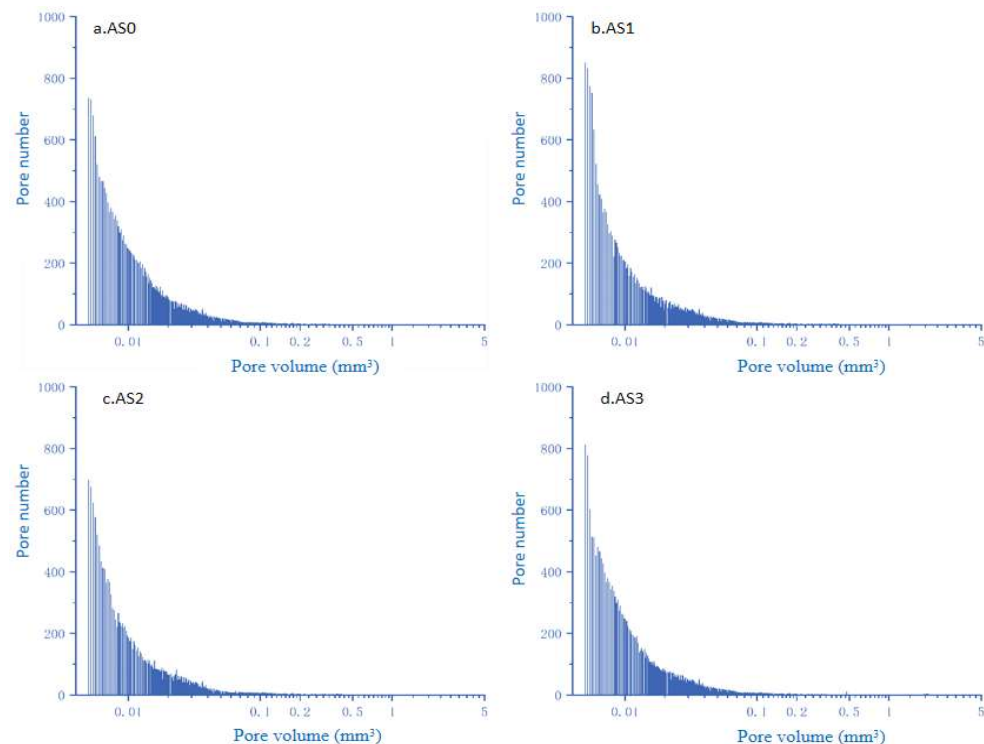


Figure 15. Pore volume distribution histogram of AS sample.

Table 5 summarizes the pore analysis results derived from X-CT for AS specimens. Cementation treatment significantly reduced pore count, pore volume, and porosity across all samples. AS2 exhibited the most pronounced reductions in these parameters, followed by AS3, while AS1 displayed marginal decreases. This trend aligns with permeability test outcomes, confirming a direct correlation between permeability coefficients and pore count metrics.

Table 5. Analysis results of AS sample pore data.

Test Specimen	Effective Volume (mm^3)	Number of Pores	Void Content (mm^3)	Porosity (%)	Porosity Decline Value Δn (%)
AS0	9769.256	1,334,679	3525.29472	36.09	-
AS1	7739.214	1,013,265	2052.647	26.53	9.56
AS2	9131.873	875,841	2429.782	27.01	9.08
AS3	8107.352	1,078,465	2255.765	29.83	6.26

4. Future Scope and Recommendation

With its environmental friendliness, cost-effectiveness, and engineering applicability, EICP technology holds great promise for future applications in geotechnical engineering, environmental remediation, and green construction. Advancements in material modification, process optimization, and interdisciplinary integration are expected to accelerate its transition from laboratory research to large-scale engineering practice, providing robust technical support for achieving sustainable development goals. However, translating these advantages into practical applications requires overcoming critical technical barriers.

While this study confirms the feasibility of EICP in mitigating wind erosion of AS under controlled conditions, several challenges and opportunities require further exploration. The maximum precipitation rate reached was around 74.07%, indicating incomplete urea hydrolysis or limited carbonate ion availability. This phenomenon may be attributed to the increase in pH above 9.5 in aeolian sand due to urease-mediated urea hydrolysis, which inhibits UA. Additionally, premature calcium precipitation disrupts synchronization with urea hydrolysis, reducing yield. Future studies could explore cyclic grouting to continuously supply urease and calcium sources, aiming to enhance calcium carbonate production.

Optimizing EICP formulations by investigating eco-friendly alternatives, such as plant-derived ureases or enzymatic cascades, could enhance sustainability and reduce environmental risks in large-scale applications. The long-term durability of EICP-treated sand under multi-hazard environmental conditions, including cyclic wet–dry weathering, extreme temperature fluctuations, and acid rain, remains unquantified, necessitating extended field trials in arid regions. Additionally, assessing the scalability and economic viability of EICP compared to traditional stabilizers, such as cement or polymers, is crucial, particularly for sand dune stabilization in transportation corridors and desertified farmlands. Furthermore, integrating intelligent monitoring systems, such as wireless pH and conductivity sensors, with EICP injection processes could enable real-time assessment of cementation homogeneity and facilitate adaptive remediation strategies, ensuring more effective and efficient sand stabilization.

5. Conclusions

The construction of highways in desert regions is critically constrained by harsh environmental conditions—including extreme aridity and intense wind erosion—coupled with the scarcity of suitable road construction materials. Conventional roadbed construction relies on loose, low-cohesion AS, which exhibits a UCS below 100 kPa. This insufficient strength results in poor subgrade stability and operational challenges for construction machinery. This study systematically investigated EICP-cemented AS through three phases: (1) the characterization of AS's fundamental physical properties; (2) the optimization of soybean crude urease (SCU) activity by evaluating solid-to-liquid ratios, calcium sources, Ca^{2+} concentrations, pH, and temperature, (3) macro-mechanical and microstructural analyses of post-treatment specimens. The key conclusions are as follows:

1. The optimal EICP parameters include a 1:10 solid-to-liquid ratio, CaCl_2 as the preferred calcium source (1.0~1.5 mol/L concentration range), a catalytic temperature window of 35~65 °C, and pH 7. Elevated calcium concentrations moderately enhanced CaCO_3 yield and precipitation efficiency.
2. Porous media critically influenced CaCO_3 crystallization: homogeneous spherical particles formed in solution, while rhombohedral calcite dominated in porous environments. These crystals strengthened AS via dual mechanisms of surface coating and interparticle pore filling. As a result, UCS increased to 580 kPa, and the wind erosion rate decreased to 0.151 g/min, significantly surpassing the minimum requirements for desert highway subbase ($\text{UCS} \geq 550$ kPa, wind erosion rate ≤ 0.2 g/min). SCU-

induced mineralization significantly improved wind erosion resistance, achieving stabilization thresholds with minimal treatments.

3. Infiltration-based EICP effectively consolidated loose AS, with cementation efficacy positively correlating with treatment cycles. Progressive alterations in particle morphology, spacing, and cementation intensity elevated internal friction angles and cohesion. Post-treatment specimens demonstrated enhanced integrity, compressive strength, and brittle failure characteristics, with cohesion being particularly treatment-dependent.
4. ELR optimization (0.8) maximized reductions in permeability coefficients, pore counts, volumes, and porosity. Permeability exhibited strong dependence on pore quantity. Microscopic analysis confirms that calcium carbonate crystals fill and bridge the pores, reducing the permeability coefficient by two orders of magnitude and effectively blocking water infiltration and sand migration pathways.
5. Under optimized conditions, EICP technology enables efficient cementation of AS, eliminating the need for long-distance material transportation required by traditional gravel bases. This approach allows for the direct utilization of in situ AS in road construction, reducing engineering costs and mitigating chemical pollution risks. The solidified layer offers both high load-bearing capacity and ecological adaptability.

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