

Article

Influence of Different Grouting Methods on the Solidification Uniformity of Marine Silt via SICP Technology

Zhengyu Fan ^{1,2,*}, Yuke Wang ^{1,2,*}, Yang Li ², Shuailiang Song ² and Enyue Ji ¹

¹ Key Laboratory of Reservoir and Dam Safety Ministry of Water Resources, Nanjing 210029, China; zzufanzhengyu@163.com (Z.F.); renmy136@163.com (E.J.)

² School of Water Conservancy and Transportation, Zhengzhou University, Zhengzhou 450001, China; ly787662924@gs.zzu.edu.cn (Y.L.); shuailiangsong@outlook.com (S.S.)

* Correspondence: wangyuke@zzu.edu.cn

Abstract

Marine silt is characterized by a high content of fine particles and low permeability, which often result in uneven urease diffusion, local enrichment, and significant variations in solidification performance during soybean urease-induced calcium carbonate precipitation (SICP) treatment. To address these issues, this study experimentally investigated both the preparation of marine silt mechanical specimens and the injection uniformity of the SICP technique. A cylindrical transparent acrylic mold together with a matching grouting device was developed to enable the observable and standardized preparation of marine silt specimens. On this basis, a series of experiments were conducted, including measurements of urease distribution under single SICP grouting, unconfined compressive strength (UCS) tests of solidified specimens, and quantification of calcium carbonate production. The effects of injection direction, injection volume, and injection rate on solidification uniformity and mechanical strength were systematically examined. The results show that the grouting direction governs the stratification characteristics of urease within the specimens. Increasing the grouting volume significantly enhances the total urease content and improves its distribution uniformity. The UCS of the solidified specimens was found to be closely related to the uniformity of urease distribution. Among the tested methods, the multi-round alternating injection mode from both the top and bottom produced the best overall strength performance. The maximum UCS reached 93.81 kPa at a grouting volume of 150 mL and a grouting rate of 5 mL/min. This study clarifies how injection parameters can be optimized to improve the solidification uniformity of fine-grained marine sediments and provides technical support and parameter references for the standardized preparation of SICP-solidified soil mechanical specimens.

Keywords: marine silt; soybean urease-induced calcium carbonate precipitation (SICP); unconfined compressive strength (UCS); grouting method; reinforcement uniformity

Academic Editor: Jianhong Ye

Received: 30 June 2026

Revised: 23 July 2026

Accepted: 26 July 2026

Published: 28 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The Yellow River Delta is globally recognized for its massive accumulation of terrigenous sediments, creating an environment highly influenced by river–sea interactions. In this estuarine and coastal zone, the extensively deposited sediment transforms into typical marine silt, which poses significant challenges to coastal engineering stability and land reclamation projects [1,2]. Consequently, dredging and managing these massive tidal

flat sediments have become major tasks for coastal infrastructure development, and one effective approach to address this challenge is to promote the resource utilization of this marine silt. As a potential engineering filling material, marine silt has received increasing attention because its beneficial reuse can not only alleviate dredging disposal pressures but also contribute to environmental and resource sustainability [3,4]. However, this marine silt is characterized by fine particle size, large specific surface area, and low permeability [5]. When directly utilized in subgrade filling, coastal dykes, or slope engineering, it frequently suffers from engineering deficiencies such as substantial subgrade settlement and slope instability, primarily due to weak interparticle interlocking, insufficient mechanical strength, and poor overall stability under hydraulic loading [6,7]. Therefore, the development of an efficient and environmentally friendly reinforcement technology tailored for this fine-grained marine silt is of great scientific and practical importance for its engineering applications in coastal zones.

Traditional soil reinforcement methods, such as cement mixing and chemical grouting, are widely used in engineering practice, but they suffer from inherent disadvantages, including high energy consumption, substantial carbon emissions, and considerable environmental disturbance [8]. In contrast, biomineralization-based biogeotechnical engineering has attracted increasing attention because of its low-carbon and environmentally friendly nature [9]. Among these approaches, Microbially Induced Carbonate Precipitation (MICP) has demonstrated promising performance in sand stabilization [10,11]. However, because MICP relies on living bacteria, its application is strongly constrained by factors such as soil pore size, nutrient availability, and oxygen supply. These limitations greatly reduce its applicability in extremely fine-grained marine silt [12].

To overcome the limitations of MICP, Enzyme-Induced Carbonate Precipitation (EICP) has emerged as a promising alternative. EICP directly utilizes free urease extracted from plants, such as soybeans and watermelon seeds [13,14], to catalyze urea hydrolysis and generate calcium carbonate (CaCO_3) as a cementing material [15]. Compared with MICP, EICP offers several distinct advantages, including smaller catalytic components that facilitate better penetration, independence from microbial growth conditions, and more controllable catalytic efficiency [16,17]. Accordingly, extensive studies have been conducted on the stabilization mechanisms, performance enhancement, and environmental adaptability of EICP. Wang et al. [12] compared the reinforcement effects of MICP and EICP on Yellow River silt and demonstrated that EICP is more suitable for fine-grained soils. Joshi et al. [18] further investigated the effect of particle size on the compressive strength of EICP-treated sand. To improve treatment performance, many studies have incorporated additives to alleviate the high brittleness and insufficient strength of EICP-solidified materials [19–21]. In parallel, investigations into environmental adaptability have examined the effects of curing temperature, relative humidity, and pH on EICP performance [22–24], while its application scope has gradually expanded to areas such as desert sand stabilization and heavy metal pollution remediation [25,26].

Although soybean urease-induced calcium carbonate precipitation (SICP) has been widely investigated for soil improvement, its application to extremely fine marine silt is still constrained by poor grouting uniformity. According to the fluid dynamics theory of porous media, grout transport in low-conductivity marine sediments is jointly governed by diffusion and convection, and is therefore susceptible to the formation of preferential flow paths under uneven pressure gradients [27,28]. The effectiveness of SICP treatment fundamentally depends on the coordination between urease-catalyzed urea hydrolysis and calcium ion transport [29]. When injection parameters, such as injection rate and volume, deviate from appropriate ranges, the distribution of crystal nucleation sites may become highly erratic in marine silt due to its intricate pore structure, resulting in local pore clogging or insufficient cementation in certain zones [30]. Existing studies have mainly

focused on improving macroscopic strength through material modification, whereas systematic quantitative research remains limited on enhancing treatment uniformity in extremely fine-grained media, such as marine silt, by regulating the spatiotemporal distribution of the enzyme solution through optimization of physical grouting parameters [31].

In view of these issues, a series of stabilization tests under different grouting schemes was carried out for marine silt characterized by a high content of fine particles and low hydraulic conductivity. Using self-developed visual molds and standardized grouting equipment, a comprehensive experimental program was conducted, including single-injection urease distribution measurements, unconfined compressive strength (UCS) tests, and CaCO_3 content quantification. On this basis, the effects of grouting direction, injection rate, and grouting volume on the treatment performance of SICP-stabilized marine silt specimens were systematically investigated. The aim of this study was to identify the optimal grouting parameters for improving the stabilization uniformity of fine-grained marine sediments, thereby providing a theoretical basis for the practical engineering application of this technology.

2. Materials and Methods

2.1. Experimental Soil

The marine silt used in this study was collected from the intertidal zone near the estuary of the Yellow River. The marine silt contains a high proportion of quartz and other siliceous minerals. Its chemical composition is dominated by silicon dioxide (SiO_2), which accounts for 79.69%, followed by alumina (Al_2O_3) at 9.42%, indicating a typical silica–alumina-based composition. In addition, it contains oxides of iron, magnesium, and calcium, together with trace amounts of K_2O , Na_2O , and TiO_2 , as shown in Figure 1. Overall, the silt exhibits a typical siliceous composition accompanied by minor metal oxides. This composition contributes to its relatively high density, which allows the particles to settle rapidly in flowing water and promotes the formation of stable sediment deposits on riverbeds or reservoir bottoms. Owing to the combined effects of aeolian deposition from the Loess Plateau and short-distance hydraulic transport, the particles are predominantly spherical and have relatively smooth surfaces. Such morphological characteristics lead to low interparticle friction, making it difficult for the silt to form stable accumulations under static conditions. Moreover, the particles are prone to collision and fragmentation under hydraulic erosion, producing even finer grains.

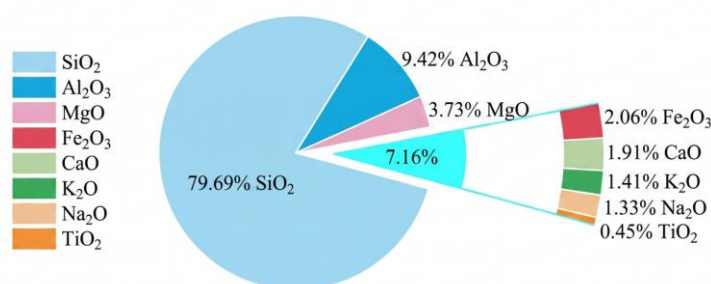


Figure 1. Chemical composition of marine silt. (colors represent different chemical components as indicated in the figure legend).

The grain size distribution of the marine silt is shown in Figure 2. The material is characterized by a high proportion of fine particles and a lack of coarse grains, with all particle sizes being smaller than 0.5 mm. The dominant particle fraction is concentrated in the range of 0.025–0.1 mm. Particles finer than 0.075 mm account for 50.89% of the total

mass, whereas the ultra-fine fraction smaller than 0.025 mm constitutes less than 1%, and the clay content is negligible. The characteristic particle sizes are $d_{60} = 0.081$ mm, $d_{30} = 0.061$ mm, and $d_{10} = 0.048$ mm. The coefficient of uniformity C_u is 1.69 (<5), and the coefficient of curvature C_c is 0.95. These results indicate that the marine silt is extremely poorly graded, with particle sizes concentrated within a narrow range. Such poorly-graded characteristics are typical for estuarine and marine silty sediments subjected to extensive hydrodynamic sorting, which inherently leads to a weak skeletal structure and low inherent stability.

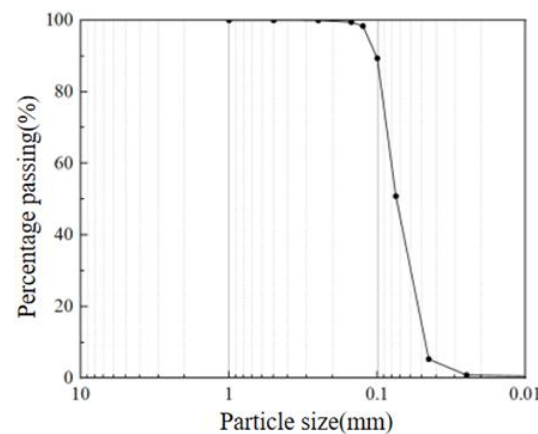


Figure 2. Particle size distribution curve of the marine silt.

The basic physical properties of the marine silt used in this study are summarized in Table 1. The basic physical properties of the soil were measured following the Standard for Geotechnical Testing Methods (GB/T 50123–2019 [32], which generally aligns with ASTM standards). According to these properties, the material can be classified as poorly graded marine silt with a low liquid limit (ML). Its particle size distribution is highly concentrated, with a marked deficiency of intermediate-sized particles, which leads to compactability difficulties and a distinct tendency to form unstable bridging structures. In addition, the fine-grained fraction exhibits mild plasticity, making its strength more susceptible to deterioration upon water exposure. The relatively wide range of void ratio further indicates that the mechanical behavior of the silt is highly sensitive to changes in relative density. In a loose state, the soil shows low shear strength and is prone to liquefaction or internal erosion (piping). With a narrow gradation ($C_u = 1.69$), high fine-particle fraction ($50.89\% < 0.075$ mm), and inherently small pore throats ($d_{10} = 0.048$ mm), this easily suffers localized bioclogging and uneven reinforcement strength during solution injection. Therefore, optimizing the injection process is necessary to promote a more uniform distribution of cementation products within the pore spaces, thereby achieving effective overall reinforcement. It also provides a theoretical basis for the application of SICP in practical engineering.

Table 1. Basic Properties of Marine Sediment.

C_u	C_c	G_s	w_L (%)	w_P (%)	ρ_{dmax} (g/cm ³)	ρ_{dmin} (g/cm ³)	e_{max}	e_{min}
1.69	0.95	2.66	27.49	13.63	1.69	1.30	1.05	0.57

2.2. Soybean Urease Solution and Cementation Solution

The urease solution used in this study was a crude extract prepared in the laboratory from commercially available fresh soybeans. The cementation solution was prepared by mixing 1.0 mol/L anhydrous calcium chloride (CaCl₂, Sinopharm Analytical Pure, $\geq$

96.0%) solution and 1.25 mol/L urea ($\text{CO}(\text{NH}_2)_2$, Sinopharm Analytical Pure, $\geq 99.0\%$) solution at a volume ratio of 1:1 [33]. Both chemicals were obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). The volume ratio of cementation solution to urease solution was also maintained at 1:1 throughout the experiments. The detailed extraction and preparation procedures are illustrated in Figure 3 and described as follows [34]:

(1) Fresh soybeans were rinsed 2–3 times with deionized water and then dried in an oven at 50 °C. The dried soybeans were ground into fine powder using a grinder and passed through a 100-mesh sieve to remove impurities.

(2) A measured amount of soybean powder was added to deionized water to prepare a suspension with a mass concentration of 40 g/L. After preliminary mixing, the suspension was stirred with a magnetic stirrer at 1000 rpm for 15 min until a uniform mixture was obtained.

(3) The suspension was then transferred into centrifuge tubes and centrifuged at 4000 rpm for 30 min at 25 °C. The supernatant was subsequently collected and used as the crude soybean urease solution.

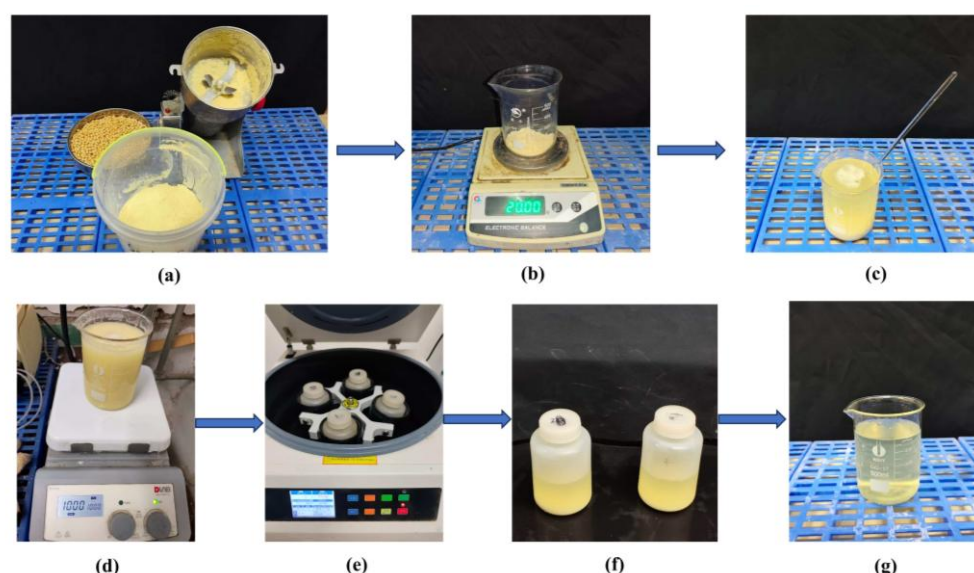


Figure 3. Preparation process of soybean urease solution; (a) Preparation of soybean powder via grinding; (b) Weighing; (c) Dissolution in deionized water; (d) Stirring with a magnetic stirrer; (e) Centrifugation; (f) Supernatant collection; (g) Crude soybean urease solution.

2.3. Specimen Preparation

To facilitate the standardized and repeatable preparation of SICP-solidified marine silt specimens, a cylindrical transparent acrylic mold with simplified grouting and easy demolding features was designed in this study, as shown in Figure 4. The mold adopts a split structure composed of two semi-cylindrical halves. To prevent leakage, the inner wall of the mold was tightly lined with cellophane. Acrylic screw caps were installed at both the top and bottom ends, with a central grouting hole reserved in each cap. The specimen preparation procedures were as follows:

(1) The two halves of the split mold were aligned, and PTFE tape (thread seal tape) was wrapped around the upper and lower threads for at least two full turns. The inner walls of the mold halves were then tightly lined with cellophane, and waterproof tape was applied along the longitudinal joints to ensure effective sealing.

(2) A rubber O-ring was placed in the inner groove of the bottom cap, after which the split mold was securely assembled with the bottom cap. An acrylic permeable plate and a layer of filter paper were then placed into the mold in sequence from the top.

(3) The prepared soil sample with a moisture content of 10% was packed into the mold in five layers. Each layer was compacted to a thickness of 2 cm, and the interface between adjacent layers was scarified to ensure structural continuity and avoid the formation of distinct weak planes. The initial water content was strictly standardized at 10% across all specimens during preparation to maintain a constant initial dry density ($\rho_d = 1.69 \text{ g/cm}^3$) and uniform pore void structure.

(4) After filling was completed, another layer of filter paper and an acrylic permeable plate were placed into the mold from the top. A rubber O-ring was then inserted into the inner groove of the top cap, and the top cap was securely assembled with the side walls of the split mold, thereby completing specimen preparation.

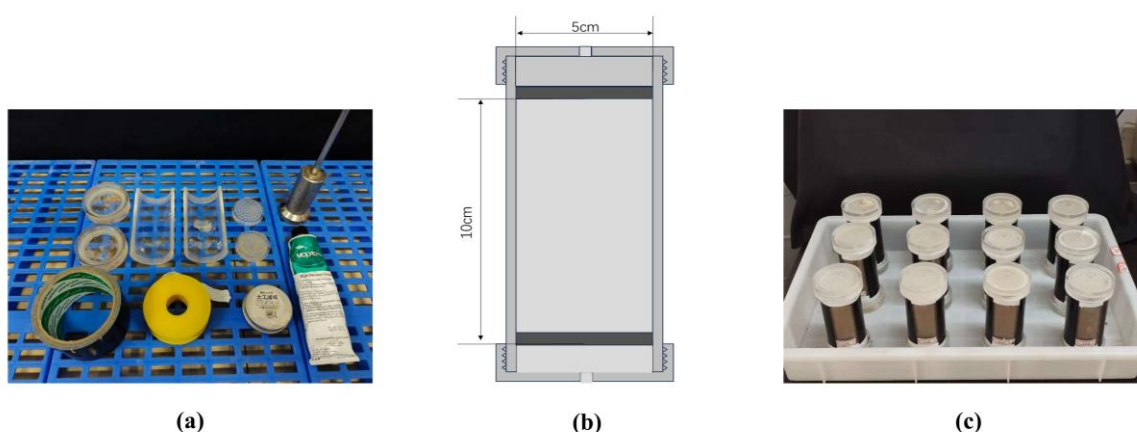


Figure 4. Preparation of solidified marine silt specimens: (a) Specimen preparation tools, (b) Mold dimensions, (c) specimens for solidification.

After specimen preparation was completed, the SICP solidification process was initiated. The solidification process was started following the procedures by Wang et al. [4]:

(1) The tubing of the peristaltic pump was connected to the central grouting hole in the top cap of the specimen. Subsequently, 100 mL of 0.5 mol/L anhydrous calcium chloride (CaCl_2) fixing solution was injected at a constant rate of 1 mL/min, followed by a 12 h resting period to allow sufficient particle surface activation.

(2) The soybean urease solution was then injected using the peristaltic pump according to the predefined experimental scheme, including the specified injection direction, volume, and rate. After a 4 h retention period, the cementation solution was injected under the same conditions. The specimen was then left to stand for another 4 h, thereby completing one treatment cycle (primary cementation).

(3) Step (2) was repeated until the target degree of cementation defined in the experimental program was reached.

(4) After completion of the treatment, excess deionized water was injected to remove residual reaction by-products. The specimens were then placed in a constant-temperature incubator at 25 °C for 48 h for final curing. Finally, the specimens were demolded to obtain the SICP-solidified marine silt specimens, as shown in Figure 5.

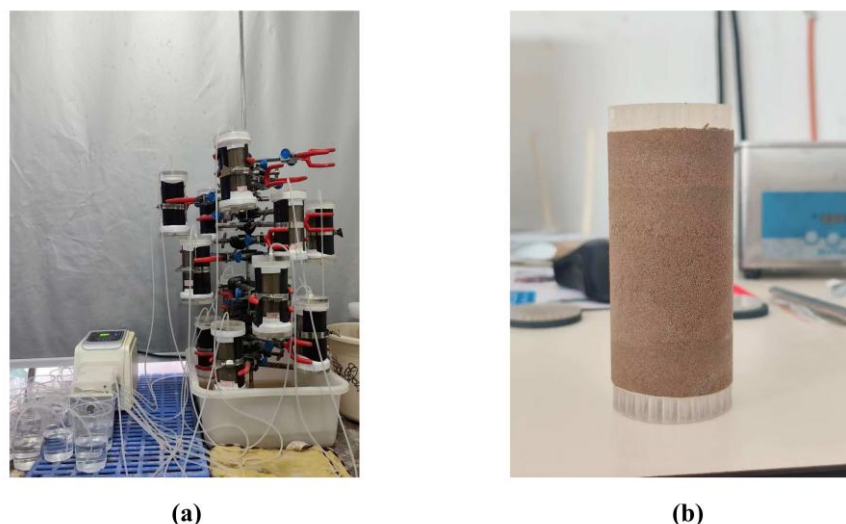


Figure 5. Solidification of marine silt specimens using SICP technology: (a) SICP grouting; (b) solidified specimen.

2.4. Single-Injection Urease Distribution Test

To investigate the influence of grouting parameters on urease diffusion, an orthogonal test was designed considering three factors: injection direction, injection volume, and injection rate, and the test scheme is shown in Table 2. As shown in Figure 6, the test was conducted in a deionized water environment, and the distribution variability of urease was evaluated by measuring the electrical conductivity of samples collected from different parts of the reinforced specimen. The quantification of active urease was performed based on the electrical conductivity (EC) method proposed by Whiffin. During urease-catalyzed hydrolysis, non-ionic urea ($\text{CO}(\text{NH}_2)_2$) is continuously decomposed into ionic ammonium (NH_4^+) and carbonate (CO_3^{2-}):



According to Whiffin [35], an EC increase rate of 1 mS/cm/min quantitatively corresponds to 11.1 mM of urea hydrolysed per minute. Thus, measuring the dynamic rate of EC variation ($\Delta\text{EC} / \Delta t$) provides a direct and reliable metric for spatial urease activity and retention within the soil matrix.

The detailed procedure is as follows:

(1) After injection was completed, the specimens were kept at 25 °C for 4 h to ensure sufficient diffusion and adsorption of urease within the soil matrix.

(2) After the molds were dismantled, 10 g soil samples were collected from the top, middle, and bottom sections using a clean sampling spoon and transferred into 100 mL beakers.

(3) Subsequently, 50 mL of deionized water was added to each beaker, and the suspension was stirred using a magnetic stirrer at 300 rpm for 3 min.

(4) After the suspension was allowed to stand for 1 min, the conductivity electrode was inserted 2 cm below the liquid surface, and the change in electrical conductivity was recorded at 5 min intervals for three consecutive measurements (over 15 min total). The slope of the linear EC increase was converted into the local urease activity.

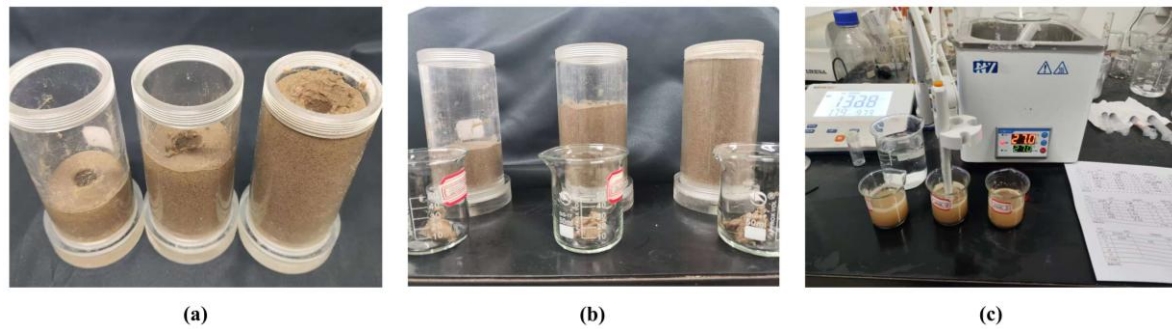


Figure 6. Assessment of urease distribution in soil using the electrical conductivity method: (a) The silt after grouting, (b) Taking silt of equal mass, (c) Determination of suspension activity by the electrical conductivity method.

Table 2. Experimental programs for different SICP grouting methods.

Influencing Factors of Single Injection	Factors
Injection direction	Top-down and bottom-up
Injection volume (mL)	50, 100, 150
Injection rate (mL/min)	5, 10, 15

2.5. Unconfined Compressive Strength (UCS) Test

The ENGERE-WAW-1000C universal testing machine was employed in this test, as shown in Figure 7. This unconfined compressive strength test was performed in accordance with ASTM D2166 (2016), and axial load was applied to the marine silt specimens at a loading rate of 1 mm/min until ultimate failure occurred. Grouting direction, grouting rate and grouting volume were selected as three major influencing factors for the unconfined compressive strength test, and the detailed test scheme is presented in Table 3. To ensure the reliability of experimental data, three parallel specimens were prepared and tested simultaneously under each test condition. The average value of the three sets of test results was adopted as the unconfined compressive strength of specimens under the corresponding working conditions.



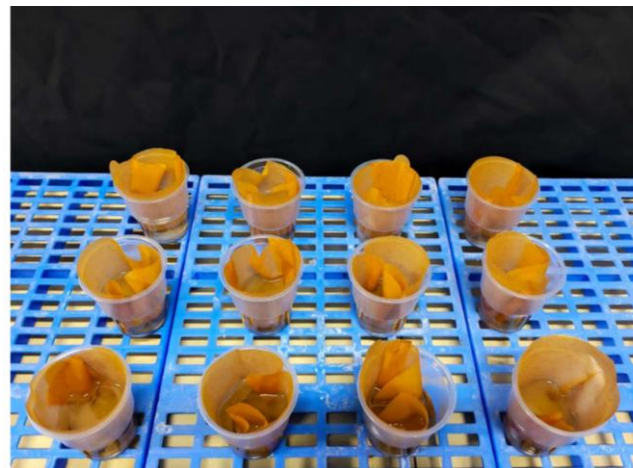
Figure 7. Unconfined compressive strength (UCS) testing apparatus and setup.

Table 3. Experimental program for unconfined compressive strength (UCS) tests.

Influencing Factors of Injection	Factors
Number of treatment cycles	2
Injection direction	Top-down, Bottom-up, Alternating (Top-down to Bottom-up sequence per cycle)
Dose per directional injection	Full targeted volume (V) injected at each entry direction
Injection volume (mL)	50, 100, 150
Injection rate (mL/min)	5, 10, 15

2.6. Calcium Carbonate Content Test

The spatial distribution data of calcium carbonate can be obtained by determining the CaCO_3 content in different sections of the specimen (as shown in Figure 8). It allows for both the quantification of overall uniformity and the localization of defective zones, providing a precise basis for the optimization of grouting protocols. Upon completion of the solidification according to the aforementioned experimental scheme, the split mold was opened while keeping the specimen in situ (without demolding). The specimen was then partitioned into three equal sections—top, middle, and bottom—based on the markings on the mold. Subsequently, the split mold was reassembled, and the sections were dried and cured in a constant-temperature incubator at 30 °C for 7 days. Following the curing period, the three intact solidified sections were demolded and weighed individually to obtain the mass m_1 . The initial mass of each corresponding section before solidification m_0 was referenced from the experimental design. The amount of CaCO_3 precipitated in each section was then calculated as $m_1 - m_0$.

**Figure 8.** Determination of CaCO_3 precipitation using the acid washing method.

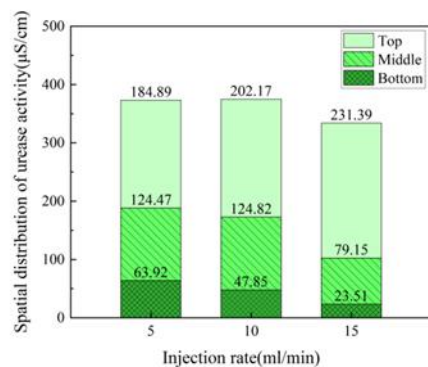
3. Results and Discussion

3.1. Influence of Injection Methods on the Distribution Patterns of Soybean Urease

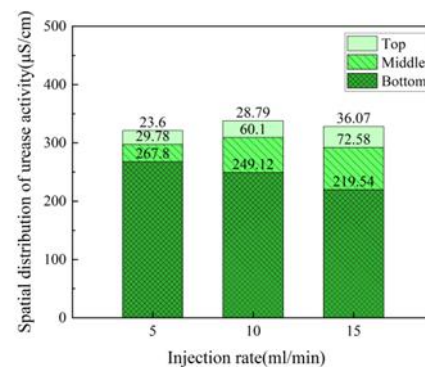
Figure 9 presents the residual urease content in different sections of the specimens 4 h after injection under various grouting methods. It can be seen that injection direction, injection rate, and injection volume all significantly affect urease distribution, with injection direction being the dominant factor controlling the stratification pattern [36]. Top-down injection tends to cause urease enrichment in the upper section, whereas bottom-up injection results in accumulation in the lower section. In general, the former provides better distribution uniformity, whereas the latter fails to deliver an advantage in overall retention and exacerbates spatial polarization. The injection rate further influences the de-

gree of stratification [37]. Under top-down injection, a higher rate intensifies urease enrichment in the upper section while reducing its retention in the middle and lower sections. By contrast, under bottom-up injection, the injection rate has a relatively limited effect on the enrichment in the lower section and only slightly promotes the upward migration of urease. Injection volume directly determines the total amount of retained urease. Increasing the injection volume not only enhances overall urease retention within the specimen, but also effectively alleviates local enrichment and distribution non-uniformity as the adsorption sites in the entry section gradually approach saturation [38].

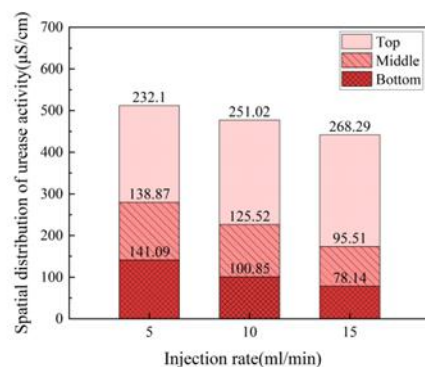
Under top-down injection, the residual urease exhibited a characteristic distribution pattern of enrichment in the upper section followed by a progressive decrease toward the lower section. At an injection volume of 50 mL and an injection rate of 5 mL/min, the urease activity in the upper section reached 184.89 $\mu\text{S}/\text{cm}$, which was significantly higher than that in the middle and lower sections. Because the grout was introduced from the top, urease was more likely to be retained in the upper part of the specimen, resulting in a stratified distribution characterized by higher activity in the upper section and lower activity toward the bottom [39]. In contrast, the residual urease distribution under bottom-up injection showed the opposite trend. As shown in Figure 9 b,d,f, the specimens treated by bottom-up injection exhibited enrichment in the lower section, whereas the urease activity in the upper and middle sections remained relatively low. In this case, when grout was injected from the bottom, the combined effects of injection pressure and gravity promoted urease accumulation in the lower part of the specimen. These results indicate that injection direction directly governs the longitudinal enrichment pattern of urease and is therefore the dominant factor controlling solidification stratification.



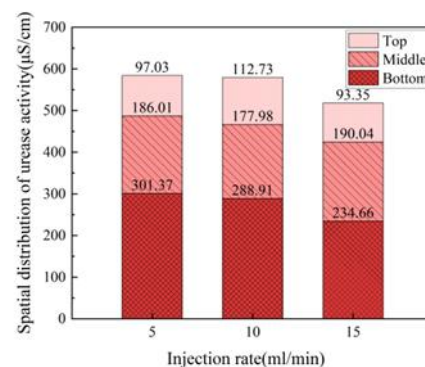
(a)



(b)



(c)



(d)

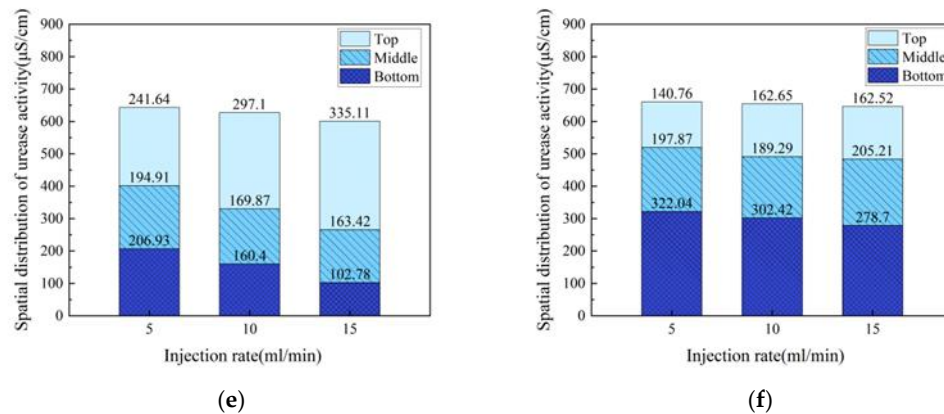


Figure 9. Spatial distribution patterns of urease activity following a single injection: (a) 50 mL, top-down injection; (b) 50 mL, bottom-up injection; (c) 100 mL, top-down injection; (d) 100 mL, bottom-up injection; (e) 150 mL, top-down injection; (f) 150 mL, bottom-up injection.

As the injection rate increased, the residual urease content in the upper section under top-down injection generally showed an upward trend. At an injection volume of 100 mL, the urease activity in the upper section increased from 232.10 to 268.29 $\mu\text{S}/\text{cm}$ with increasing injection rate. A higher injection rate enhanced urease interception in the upper part of the specimen and hindered its effective penetration into the middle and lower sections. As a result, the residual urease content in these lower sections decreased, further aggravating the enrichment effect in the upper section. In contrast, under bottom-up injection, increasing the injection rate tended to reduce urease accumulation in the lower section. At an injection volume of 100 mL, the urease activity in the lower section decreased from 301.37 to 234.66 $\mu\text{S}/\text{cm}$ as the injection rate increased, although this section still remained the zone with the highest activity [40]. Overall, a higher injection rate intensified localized urease enrichment in the upper section under top-down injection, whereas it alleviated excessive accumulation in the lower section under bottom-up injection.

As the injection volume increased, the residual urease content in all sections showed a general upward trend, regardless of injection direction. Notably, under top-down injection, a larger injection volume promoted a more uniform urease distribution. For example, at an injection rate of 5 mL/min and an injection volume of 150 mL, the urease activities in the upper, middle, and lower sections were 241.64, 194.91, and 206.93 $\mu\text{S}/\text{cm}$, respectively, indicating a substantial improvement in homogeneity compared with lower injection volumes. From a reactive transport perspective, this phenomenon is driven by the progressive saturation of soil adsorption sites. In the early injection stage, active urease molecules are rapidly intercepted and adsorbed by the fine marine silt particles near the inlet. As the injection volume increases, the adsorption capacity of the entry zone gradually approaches saturation, forcing subsequently injected enzymes to migrate deeper into the middle and lower pore networks via advective-dispersive transport, thereby mitigating localized enzyme accumulation. In terms of total urease retention, the cumulative urease activity across all sections reached its maximum at an injection volume of 150 mL, providing a favorable biochemical basis for the subsequent solidification process. Although the top-heavy distribution pattern still persisted under top-down injection, the degree of non-uniformity was effectively reduced at lower injection rates, which allowed better urease adsorption and retention throughout the soil matrix [36].

To quantify the degree of uniformity in urease distribution within the specimens under various grouting methods, the coefficient of variation (CV) for urease distribution was introduced. A smaller CV value indicates a more uniform distribution and lower dispersion of urease within the specimen. Conversely, a larger CV value suggests higher fluctu-

ations and greater non-uniformity in the urease distribution. The formula for calculating CV is as follows [40]:

$$CV = \sqrt{\frac{(m_1 - \bar{m})^2 + (m_2 - \bar{m})^2 + (m_3 - \bar{m})^2}{\bar{m}}} \times 100\% \quad (2)$$

where m_1 , m_2 , and m_3 denote the urease activity levels in the top, middle, and bottom sections of the specimen, respectively; and $\bar{m}$ represents the mean value of these three measurements.

Figure 10 presents the coefficient of variation (CV) of urease distribution in the specimens under different grouting methods. Regardless of injection direction, the CV decreased with increasing injection volume, further confirming that a larger injection volume improves urease distribution uniformity. Under top-down injection, a lower injection rate resulted in a smaller CV. The best uniformity was obtained at an injection rate of 5 mL/min and an injection volume of 150 mL, where the CV reached a minimum of 11.32%. In contrast, the opposite trend was observed under bottom-up injection. Owing to the influence of the reverse flow field, the CV decreased as the injection rate increased. For this injection mode, the minimum CV was 27.28%, achieved at an injection rate of 15 mL/min and an injection volume of 150 mL, although the overall uniformity was still inferior to that under top-down injection. Considering both total urease activity and distribution uniformity, the optimal single-injection condition was identified as top-down injection with an injection volume of 150 mL and an injection rate of 5 mL/min.

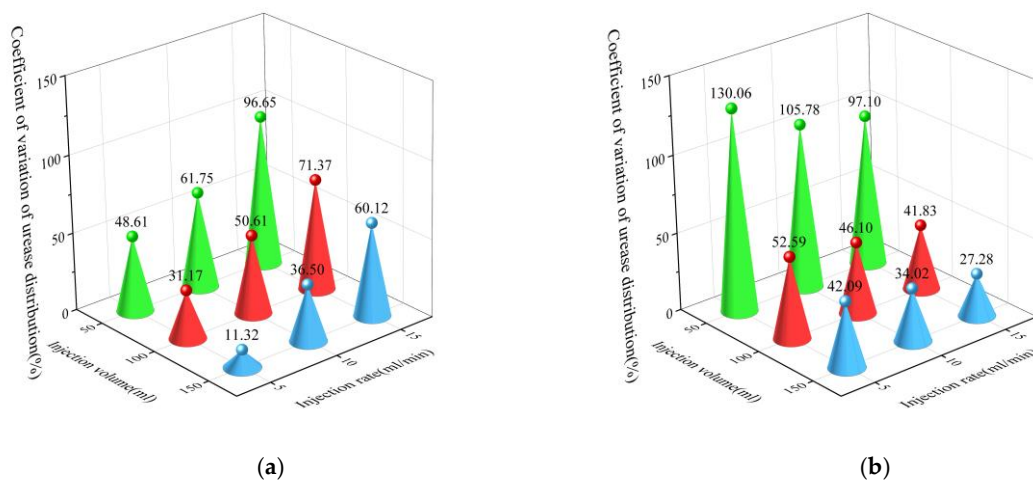


Figure 10. Coefficient of variation (CV) of urease distribution: (a) Top-down injection; (b) Bottom-up injection

3.2. Influence of Injection Methods on the Unconfined Compressive Strength (UCS) of Specimens

The unconfined compressive strength (UCS) directly reflects the macroscopic mechanical performance of SICP-solidified marine silt and is closely related to the uniformity of internal cementation [41]. Figure 11 presents the UCS values of the SICP-solidified specimens after two treatment cycles under different grouting methods. Across all injection volumes, alternating injection from the top and bottom consistently produced higher UCS values than the other injection modes. In particular, the maximum UCS reached 93.81 kPa at an injection volume of 150 mL and an injection rate of 5 mL/min, indicating the superior effectiveness of this method in improving both cementation uniformity and mechanical strength [42]. This can be attributed to the bidirectional penetration mechanism of alternating injection, which effectively compensates for the weakly cemented zones at the distal ends commonly formed under unidirectional injection, thereby promoting more effective reinforcement throughout the speci-

men. In contrast, top-down injection tends to result in insufficient cementation in the lower section because of gravity-driven flow, whereas bottom-up injection is more likely to produce insufficient filling in the upper section. Both conditions lead to lower strength enhancement than that achieved by alternating injection.

The development of UCS showed a distinct threshold effect with respect to injection volume. At an injection volume of 50 mL, the grout was insufficient to fully occupy the internal pores of the specimen, resulting in a non-uniform cementation structure characterized by enrichment at both ends and relative deficiency in the middle [43]. Consequently, the UCS values remained low, generally ranging from about 70 to 77 kPa. When the injection volume increased to 100 mL, the grout was able to more effectively cover the internal pore space, leading to a marked increase in UCS to 93.12 kPa. This value was very close to that obtained at 150 mL (93.81 kPa), suggesting that 100 mL may represent the critical threshold required for effective cementation of marine silt. Further increases in injection volume only provided limited local supplementation, as the strength improvement had already approached a saturation state. At a constant injection volume, the effect of injection rate on UCS was generally consistent with the previously observed urease distribution patterns [44]. Specifically, a low injection rate was more favorable for strength development under top-down injection, whereas a higher injection rate was more beneficial under bottom-up injection. After two treatment cycles, the grouting condition that produced the highest UCS was exactly the same as that identified in the previous analysis as having the highest urease retention and the best distribution uniformity. This further confirms that a uniform urease distribution is a key prerequisite for achieving favorable macroscopic mechanical performance in the solidified specimens.

The selection of two treatment cycles as the standardized solidification protocol was determined by balancing mechanical gain against fluid transport resistance. Preliminary trial tests indicated that a single treatment cycle was insufficient to establish a continuous CaCO_3 crystal network across the fine silt matrix, resulting in unsatisfactory low macroscopic strength. On the other hand, extending treatment beyond two cycles resulted in severe localized bio-clogging near the injection ports. As CaCO_3 accumulated, pore throats ($d_{10} = 0.048$ mm) became constricted, causing a sharp drop in hydraulic conductivity and increasing backpressure during injection. This flow restriction induced preferential flow paths and hindered the uniform transport of subsequent reactant solutions. Therefore, two treatment cycles were identified as the optimal balance—providing sufficient CaCO_3 precipitation to reach a functional mechanical strength threshold (up to 93.81 kPa) without triggering premature fluid flow blockage.

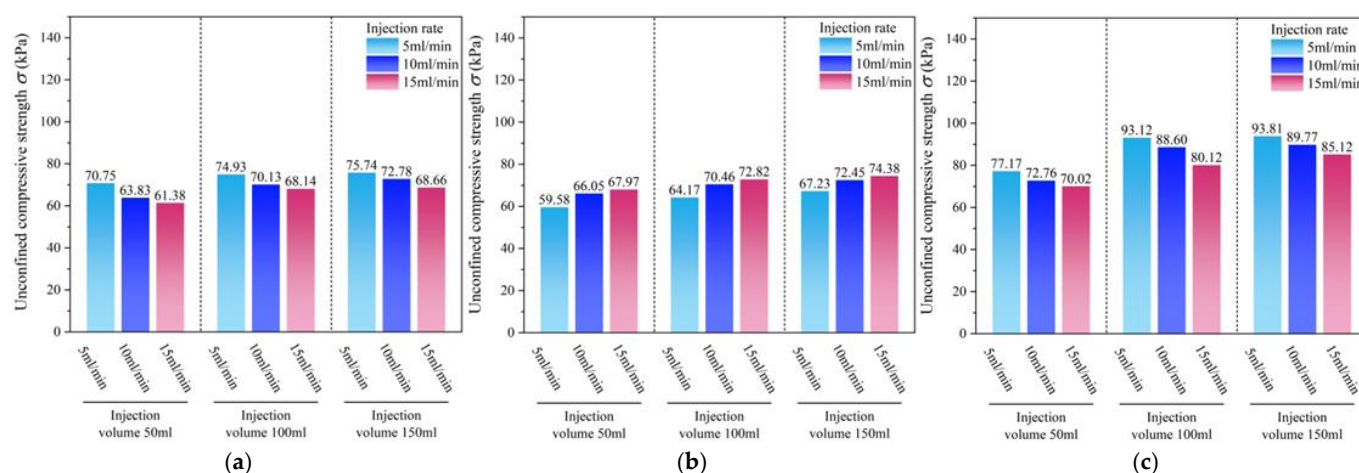


Figure 11. Unconfined compressive strength (UCS) of SICIP-stabilized specimens under different grouting methods: (a) Top-down injection; (b) Bottom-up injection; (c) Alternating injection

At a constant injection rate, the unconfined compressive strength (UCS) increased markedly as the injection volume rose from 50 mL to 100 mL, and then remained nearly unchanged as the volume further increased to 150 mL. For alternating injection, the UCS values at 100 mL and 150 mL were 93.12 kPa and 93.81 kPa, respectively, indicating only a marginal increase beyond 100 mL. At 50 mL, the injected grout was insufficient to adequately fill the internal pores, resulting in a non-uniform cementation structure characterized by stronger cementation at both ends and weaker cementation in the middle. Micro-mechanically, the macroscopic UCS under uniaxial compression is governed by the 'weakest-link' principle. Under loading, stress concentration preferentially occurs within these under-cemented localized zones in the middle section, initiating premature progressive micro-cracks and causing early shear failure of the specimen skeleton before the strength of the higher-cemented ends can be fully mobilized, leading to a relatively low UCS [45]. When the injection volume increased to 100 mL, the grout was able to more effectively cover the internal pore space, and the diffusion range of urease was correspondingly expanded. This improved the cementation of previously weak zones and led to a substantial increase in strength [42]. When the injection volume further increased to 150 mL, the UCS remained close to that at 100 mL, indicating that the sensitivity of strength to injection volume had become limited. This suggests that, once the pore space is sufficiently filled and the reactants are adequately supplied, additional grout contributes only marginally to further effective cementation. Moreover, the bidirectional diffusion associated with alternating injection allows relatively uniform cementation to be achieved even at 100 mL. Therefore, 100 mL can be regarded as the critical injection volume for effective solidification under the present test conditions. Overall, alternating injection promotes a more uniform distribution of urease and reactants, thereby facilitating more homogeneous CaCO_3 precipitation and improved UCS, although the strengthening effect gradually approaches saturation beyond the threshold volume.

3.3. Influence of Grouting Methods on the Calcium Carbonate Content of Specimens

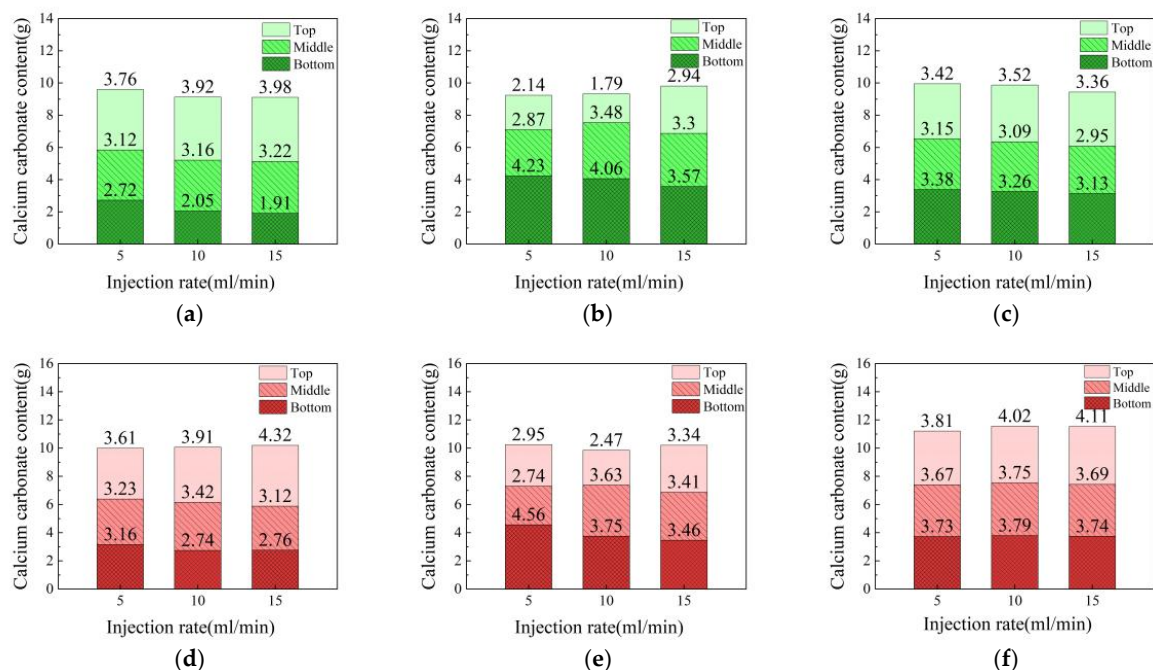
Figure 12 presents the calcium carbonate (CaCO_3) content in the top, middle, and bottom sections of marine silt specimens after two treatment cycles under different injection volumes and rates for the three grouting methods. The amount and spatial distribution of CaCO_3 provide a microstructural basis for explaining the differences in solidification strength. The distribution pattern of CaCO_3 was highly dependent on the grouting method and closely correlated with the urease distribution characteristics. Under unidirectional injection, obvious gradients in CaCO_3 content were observed. Top-down injection caused CaCO_3 to precipitate mainly in the upper section; for example, under the condition of 50 mL and 5 mL/min, the CaCO_3 content in the lower section was only 72% of that in the upper section. In contrast, bottom-up injection led to the cemented zone being concentrated in the lower part of the specimen. This non-uniform mineralization pattern was the main factor limiting the overall mechanical performance of the specimens. By contrast, alternating injection significantly improved the spatial distribution of CaCO_3 by changing the seepage path of the grout [36]. Under alternating injection, the differences in CaCO_3 content among the top, middle, and bottom sections were minimized, resulting in a much more uniform cementation pattern throughout the specimen [39].

Analysis of CaCO_3 precipitation under different grouting modes further demonstrates the strong influence of injection pattern on its spatial distribution. Under top-down injection, the grout infiltrates downward under the combined effect of injection pressure and gravity. Because the upper section is in direct contact with the injection inlet, it receives a greater amount of grout and undergoes a more sufficient reaction, resulting in a gradient distribution with higher CaCO_3 content in the upper section and lower content in the lower section. As shown in Figure 12a, at an injection volume of 50 mL and an

injection rate of 5 mL/min, the CaCO_3 content in the upper section reached 3.76 g, whereas that in the lower section was only 2.72 g. Although the absolute values changed with increasing injection volume, this overall gradient pattern remained essentially unchanged, indicating that gravity-dominated seepage under top-down injection leads to relatively poor cementation uniformity [46].

Under bottom-up injection, the grout permeates upward against the overlying soil resistance. As a result, the lower section becomes the main enrichment zone, whereas the upper section receives insufficient filling, forming an opposite gradient with higher CaCO_3 content at the bottom and lower content at the top. As shown in Figure 12b, under the condition of 50 mL and 5 mL/min, the CaCO_3 content reached 4.23 g in the lower section but was only 2.14 g in the upper section. This non-uniform distribution pattern persisted even when the injection volume increased, highlighting the inherent limitation of unidirectional grouting in achieving uniform cementation [44].

By contrast, alternating injection takes advantage of bidirectional seepage and diffusion, allowing the grout to be replenished from both ends of the specimen and thereby improving pore filling and reaction uniformity. As shown in Figure 12c, at an injection volume of 50 mL, the differences in CaCO_3 content among the top, middle, and bottom sections were already relatively small, with values of 3.42, 3.15, and 3.38 g, respectively. When the injection volume increased to 150 mL, the CaCO_3 content in all sections increased simultaneously. At an injection rate of 15 mL/min, the CaCO_3 contents reached 4.65 g, 3.88 g, and 3.99 g in the top, middle, and bottom sections, respectively, as shown in Figure 12i. These results indicate that alternating injection can markedly improve the uniformity of cementation, confirming its superiority in promoting more homogeneous grout distribution and overall cementation quality [38].



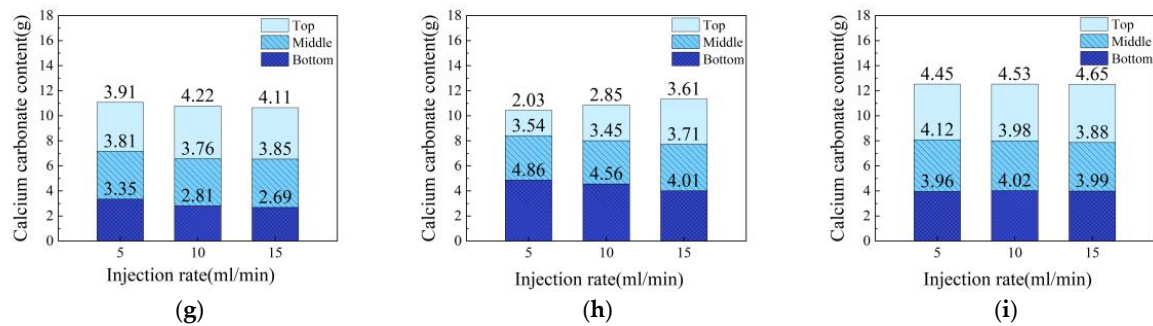


Figure 12. Calcium carbonate content under different SICP grouting methods: (a) 50 mL injection volume, Top-down; (b) 50 mL injection volume, Bottom-up; (c) 50 mL injection volume, Alternating; (d) 100 mL injection volume, Top-down; (e) 100 mL injection volume, Bottom-up; (f) 100 mL injection volume, Alternating; (g) 150 mL injection volume, Top-down; (h) 150 mL injection volume, Bottom-up; (i) 150 mL injection volume, Alternating.

Figure 13 presents a schematic of grout seepage and penetration during SICP treatment. It should be noted, however, that even under alternating injection, the final CaCO_3 distribution still exhibited a pattern of relatively higher content at both ends and lower content in the middle. This specific precipitation profile is dictated by the dynamic coupling between fluid hydrodynamics, seepage boundary conditions, and chemical reaction kinetics. During top-down injection, the grout spreads downward and outward from the inlet, and the downward penetration velocity is relatively high, resulting in a funnel-shaped distribution within the specimen, as illustrated in Figure 13b. As injection continues, the grout is gradually discharged through the bottom outlet. However, because the gravity-driven discharge rate is lower than the injection rate imposed by the peristaltic pump, the residence time of the grout in the lower section becomes longer than that in other regions, corresponding to the conditions illustrated in Figure 13c,d [47]. During this process, the SICP reaction proceeds simultaneously, promoting the rapid formation and accumulation of CaCO_3 in both the upper section near the inlet and the lower section where grout tends to stagnate. As a result, the final CaCO_3 distribution shows enrichment at both ends of the specimen and relatively lower cementation in the middle section [48,49].

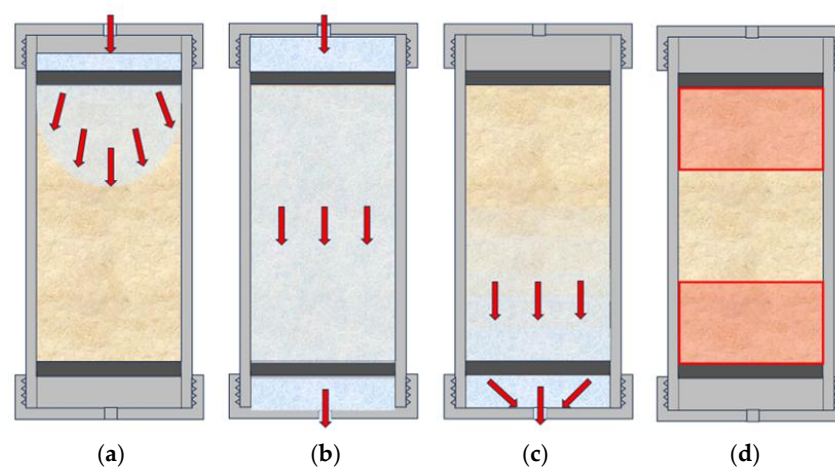


Figure 13. Schematic of grout seepage and penetration during SICP treatment: (a) Initial stage of injection; (b) Middle stage of injection; (c) Final stage of injection; (d) CaCO_3 enriched zone. The red arrows indicate the fluid flow direction; the light blue region represents the injected solution, and the pink/orange shaded areas represent the CaCO_3 precipitation/enriched zones.

Because urea hydrolysis catalyzed by soybean urease occurs continuously during fluid transport, this localized fluid stagnation substantially prolongs the reaction residence time in both the top entrance zone (due to continuous fresh chemical supply) and the bottom boundary layer (due to slow drainage accumulation). Consequently, supersaturation of CaCO_3 is preferentially achieved at both specimen ends, accelerating crystal nucleation and pore-throat precipitation. In contrast, the middle transitional zone experiences continuous fluid displacement with a relatively shorter retention window, yielding lower localized precipitation. The alternating injection mode effectively mitigates this effect compared to unidirectional grouting, yet the fundamental fluid stagnation near boundary outlets remains the primary physical driver of the residual end-enrichment pattern [50].

Based on a comprehensive evaluation of both cementation quality (uniformity) and reaction efficiency (yield), alternating injection with an injection volume of 150 mL and an injection rate of 5–10 mL/min was identified as the optimal grouting condition. This grouting mode makes effective use of bidirectional supplementation, thereby mitigating the inherent non-uniformity associated with unidirectional injection and ensuring a more sufficient and sustained supply of reactants throughout the soil matrix. As a result, it promotes more uniform CaCO_3 filling and interparticle bridging at the microscale, while also providing superior mechanical performance at the macroscale. Therefore, this parameter combination can be regarded as the optimal process condition for the SICP solidification of marine silt.

4. Conclusions

This study systematically investigated specimen preparation and grouting uniformity for the solidification of marine silt using soybean urease-induced calcium carbonate precipitation (SICP) technology. The basic physical properties of marine silt were characterized, and specialized molds and grouting devices were developed to ensure standardized specimen preparation. A multi-parameter experimental program was then designed for comparative analysis. Based on single-injection urease distribution measurements, unconfined compressive strength (UCS) tests, and calcium carbonate (CaCO_3) content analysis, the effects of grouting parameters on solidification uniformity and overall treatment performance were clarified. The main conclusions are as follows:

(1) Injection direction governs the stratification characteristics of urease distribution. Top-down injection led to enrichment in the upper section, whereas bottom-up injection caused accumulation in the lower section. Increasing the injection volume significantly enhanced total urease retention and improved distribution uniformity, with the lowest coefficient of variation (CV) obtained at an injection volume of 150 mL. In addition, the effect of injection rate depended on injection direction: under top-down injection, a low rate (5 mL/min) produced the best uniformity (CV = 11.32%), whereas under bottom-up injection, a high rate (15 mL/min) was more effective in alleviating stratification.

(2) The unconfined compressive strength (UCS) of the solidified marine silt was closely related to the uniformity of urease distribution. Among the tested grouting methods, alternating injection from the top and bottom provided the best overall mechanical performance. The maximum UCS reached 93.81 kPa at an injection volume of 150 mL and an injection rate of 5 mL/min. In addition, the UCS at 100 mL was already close to that at 150 mL, indicating that 100 mL may represent the critical injection volume required for effective solidification under the present test conditions.

(3) Alternating injection showed a clear advantage in improving the uniformity of calcium carbonate precipitation within the marine silt specimens. This mode reduced the differences in CaCO_3 content among different sections, while the overall mineral content increased with injection volume. At an injection volume of 150 mL, the CaCO_3 contents in

the top, middle, and bottom sections reached 4.65, 3.88, and 3.99 g, respectively, indicating favorable distribution uniformity together with relatively high precipitation yield. These results confirm that alternating injection is the most effective grouting strategy among those tested for improving the overall cementation quality of marine silt.

(4) Through a series of urease activity distribution tests, mechanical property tests, and calcium carbonate content measurements, the effects of injection rate and injection volume on the uniformity of SICP-treated marine silt were analyzed from a macroscopic perspective. The optimal injection rate and injection volume were characterized by the unconfined compressive strength and calcium carbonate content of the treated specimens under different working conditions. To better understand the reinforcement mechanism of SICP-treated marine silt, further research should be conducted from microscopic aspects, including experimental studies and numerical simulations on calcium carbonate crystal morphology, precipitation location, and precipitation kinetics. The combination of macroscopic and microscopic analyses will help optimize the reinforcement technology and clarify the reinforcement mechanism, and a theoretical basis can be provided for the application of SICP in marine silt improvement.

Author Contributions: Conceptualization, Y.W. and Z.F.; methodology, Z.F.; validation, Y.L. and S.S.; formal analysis, Z.F.; resources, E.J.; data curation, Y.L.; writing—original draft preparation, Z.F.; writing—review and editing, S.S.; supervision, Y.W.; funding acquisition, E.J. and Yuke Wang. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Open Research Fund of Key Laboratory of Reservoir and Dam Safety Ministry of Water Resources (YK324006); National Natural Science Foundation of China (52178369); Henan Provincial Natural Science Foundation Interdisciplinary Innovative Research Group Project (252300421827); Excellent Youth Fund of Henan Natural Science Foundation (232300421069); Program for Science and Technology Innovation Talents in Universities of Henan Province (24HASTIT014); Central Plains Science and Technology Innovation Leader Project (234200510014). These financial supports are gratefully acknowledged.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Wang, H.; Liu, H.J. Evaluation of storm wave-induced silty seabed instability and geo-hazards: A case study in the Yellow River delta. *Appl. Ocean Res.* **2016**, *58*, 135–145.
2. Wang, H.; Wu, X.; Bi, N.; Li, S.; Yuan, P.; Wang, A.; Syvitski, J.P.; Saito, Y.; Yang, Z.; Liu, S.; et al. Impacts of the dam-orientated water-sediment regulation scheme on the lower reaches and delta of the Yellow River (Huanghe): A review. *Glob. Planet. Change* **2017**, *157*, 93–113.
3. Wang, L.; Chen, L.; Tsang, D.C.; Li, J.S.; Baek, K.; Hou, D.; Ding, S.; Poon, C.S. Recycling dredged sediment into fill materials, partition blocks, and paving blocks: Technical and economic assessment. *J. Clean. Prod.* **2018**, *199*, 69–76.
4. Wang, Y.; Wang, Z.; Chen, Y.; Cao, T.; Yu, X.; Rui, P. Experimental study on bio-treatment effect of the dredged Yellow River silt based on soybean urease induced calcium carbonate precipitation. *J. Build. Eng.* **2023**, *75*, 106943.
5. Wang, Y.; Cao, T.; Gao, Y.; Shao, J. Experimental study on liquefaction characteristics of saturated Yellow River silt under cycles loading. *Soil Dyn. Earthq. Eng.* **2022**, *163*, 107457.
6. Li, C.; Yang, P.; Wu, Z.; Chen, W.; Cai, Y. The dynamic behavior of marine soft soil under cyclic wave loading. *Bull. Eng. Geol. Environ.* **2025**, *84*, 192.
7. Wang, Y.; Jiang, R.; Gao, Y.; Shao, J. Resilient strain and stiffness degradation of Yellow River silt under cyclic loads. *Proc. Inst. Civ. Eng.-Geotech. Eng.* **2024**, *177*, 169–178.
8. Milling, A.; Mwasha, A.; Martin, H. Exploring the full replacement of cement with expanded polystyrene (EPS) waste in mortars used for masonry construction. *Constr. Build. Mater.* **2020**, *253*, 119158.

9. Sharma, B.; Singh, A.; Joshi, S.; Reddy, M.S. Utilization of sandstone waste in cement mortar for sustainable production of building materials through biomineralization. *J. Sustain. Cem.-Based Mater.* **2023**, *12*, 712–720.
10. Gan, W.; Meiju, J.; Yuke, W.; Rui, J. Study on mechanical properties of Yellow River silt solidified by MICP technology. *Geomech. Eng.* **2023**, *32*, 347–359.
11. Karimian, A.; Hassanlourad, M. Mechanical behaviour of MICP-treated silty sand. *Bull. Eng. Geol. Environ.* **2022**, *81*, 285.
12. Wang, Y.; Jiang, R.; Jiao, M.; Cao, T.; Yu, X. Macro and micro experimental study on solidification of Yellow River silt based on different biomineralization technologies. *Environ. Earth Sci.* **2023**, *82*, 86.
13. Wu, M.; Hu, X.; Zhang, Q.; Zhao, Y.; Sun, J.; Cheng, W.; Fan, Y.; Zhu, S.; Lu, W.; Song, C. Preparation and performance evaluation of environment-friendly biological dust suppressant. *J. Clean. Prod.* **2020**, *273*, 123162.
14. Liu, L.; Gao, Y.; Cao, X.; Meng, H.; Wang, Z.; Qi, Y.; Li, R.; He, J. A comparative study of low-cost crude ureases extracted from multi-species of natural plant sources in enzyme-induced carbonate precipitation. *J. Environ. Chem. Eng.* **2024**, *12*, 114824.
15. Meng, H.; Shu, S.; Gao, Y.; Yan, B.; He, J. Multiple-phase enzyme-induced carbonate precipitation (EICP) method for soil improvement. *Eng. Geol.* **2021**, *294*, 106374.
16. Almajed, A.; Abbas, H.; Arab, M.; Alsabhan, A.; Hamid, W.; Al-Salloum, Y. Enzyme-Induced Carbonate Precipitation (EICP)-Based methods for ecofriendly stabilization of different types of natural sands. *J. Clean. Prod.* **2020**, *274*, 122627.
17. Ahenkorah, I.; Rahman, M.M.; Karim, M.R.; Beecham, S. Enzyme induced calcium carbonate precipitation and its engineering application: A systematic review and meta-analysis. *Constr. Build. Mater.* **2021**, *308*, 125000.
18. Joshi, P.; Khosravi, M.; Phillips, A.; Cunningham, A.; Rahn, J.; Olds, S.; Carter, M.; Gupta, M. Influence of Particle Size and Curing Temperature on the Strength of Sand Treated with Enzyme-Induced Carbonate Precipitation. *J. Geotech. Geoenviron. Eng.* **2026**, *152*, 04025187.
19. Arab, M.G.; Omar, M.; Almajed, A.; Elbaz, Y.; Ahmed, A.H. Hybrid technique to produce bio-bricks using enzyme-induced carbonate precipitation (EICP) and sodium alginate biopolymer. *Constr. Build. Mater.* **2021**, *284*, 122846.
20. Zhang, J.; Wang, X.; Shi, L.; Yin, Y. Enzyme-induced carbonate precipitation (EICP) combined with lignin to solidify silt in the Yellow River flood area. *Constr. Build. Mater.* **2022**, *339*, 127792.
21. He, J.; Huang, A.; Ji, J.; Qu, S.; Hang, L. Enzyme induced carbonate precipitation with fibers for the improvement of clay soil slopes against rainfall and surface runoff erosions. *Transp. Geotech.* **2023**, *42*, 101074.
22. Zheng, T.; Qian, C. Influencing factors and formation mechanism of CaCO₃ precipitation induced by microbial carbonic anhydrase. *Process Biochem.* **2020**, *91*, 271–281.
23. Lai, H.J.; Cui, M.J.; Chu, J. Effect of pH on soil improvement using one-phase-low-pH MICP or EICP biocementation method. *Acta Geotech.* **2023**, *18*, 3259–3272.
24. Chen, Y.W.; Cui, M.J.; Lai, H.J.; Zheng, J.J.; Ren, Y.X. Modified one-phase-low-pH EICP method using low-pH cementation solution for soil biomineralization. *Acta Geotech.* **2025**, *20*, 4133–4146.
25. Wu, L.; Miao, L.; Sun, X.; Wang, H. Effect of calcium sources on enzyme-induced carbonate precipitation to solidify desert aeolian sand. *J. Environ. Manag.* **2024**, *366*, 121687.
26. Bian, H.; Zhang, Z.; Li, J.; Zhang, X.; Li, Z.; Yang, Q. Application of EICP Technology in the Remediation of Lead-and Zinc-Contaminated Sand and Improvement of Its Mechanical Properties. *J. Environ. Eng.* **2025**, *151*, 04025018.
27. Du, X.; Liu, C.; Wang, C.; Fang, H.; Xue, B.; Gao, X.; Han, Y. Diffusion characteristics and reinforcement effect of cement slurry on porous medium under dynamic water condition considering infiltration. *Tunn. Undergr. Space Technol.* **2022**, *130*, 104766.
28. Duan, H.; Xie, Y.; Zou, L.; Li, B.; Håkansson, U.; Cvetkovic, V. Analysis of grout radial propagation in water-saturated rough-walled rock fractures. *Int. J. Rock Mech. Min. Sci.* **2025**, *190*, 106101.
29. Liu, L.; Chen, Y.; Gao, Y.; Liu, B.; Zhou, Y.; Li, C. Effect of urease enrichment degree of multiple sources of urease on biocementation efficacy via enzyme-induced carbonate precipitation. *Can. Geotech. J.* **2023**, *60*, 1923–1937.
30. Zhang, Q.; Ye, W.; Liu, Z.; Wang, Q.; Chen, Y. Influence of injection methods on calcareous sand cementation by EICP technique. *Constr. Build. Mater.* **2023**, *363*, 129724.
31. Wang, Z.; Qin, H.; Dong, X.; Zhang, W. Classification of additives and their influence mechanisms in improving the performance of biologically induced carbonate precipitation. *Environ. Res.* **2025**, *275*, 121376.
32. GB/T 50123–2019; Standard for Geotechnical Testing Methods. China Planning Press: Beijing, China, 2019.
33. Wang, Y.; Chen, Y.; Marchelina, N. Crack repairing performance by soybean urease induced calcium carbonate precipitation (SICP) combined with fibers and lightweight aggregates. *Constr. Build. Mater.* **2025**, *458*, 139678.
34. Gao, Y.; He, J.; Tang, X.; Chu, J. Calcium carbonate precipitation catalyzed by soybean urease as an improvement method for fine-grained soil. *Soils Found.* **2019**, *59*, 1631–1637.

35. Whiffin, V.S. Microbial CaCO_3 Precipitation for the Production of Biocement. Doctoral Dissertation, Murdoch University, Perth, Australia, 2004.
36. Martinez, B.C.; DeJong, J.T.; Ginn, T.R.; Montoya, B.M.; Barkouki, T.H.; Hunt, C.; Tanyu, B.; Major, D. Experimental optimization of microbial-induced carbonate precipitation for soil improvement. *J. Geotech. Geoenviron. Eng.* **2013**, *139*, 587–598.
37. Ma, G.L.; Yin, Z.Y.; Xiao, Y. Numerical modeling of MICP grouting in homogeneous and layered heterogeneous soils. *Int. J. Numer. Anal. Methods Geomech.* **2025**, *49*, 1769–1789.
38. Chu, J.; Ivanov, V.; Naeimi, M.; Stabnikov, V.; Liu, H.L. Optimization of calcium-based bioclogging and biocementation of sand. *Acta Geotech.* **2014**, *9*, 277–285.
39. Harkes, M.P.; Van Paassen, L.A.; Booster, J.L.; Whiffin, V.S.; van Loosdrecht, M.C. Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground reinforcement. *Ecol. Eng.* **2010**, *36*, 112–117.
40. Tian, Z.; Tang, X.; Xiu, Z.; Xue, Z. The spatial distribution of microbially induced carbonate precipitation in sand column with different grouting strategies. *J. Mater. Civ. Eng.* **2023**, *35*, 04022437.
41. Wang, Y.; Chen, H.; Chen, Y.; Jiao, M.; Fan, Z. Experimental study on macro-micro effectiveness of Yellow River silt solidified by using soybean-induced carbonate precipitation (SICP) technology. *Mar. Georesour. Geotechnol.* **2025**, *43*, 112–122.
42. Al Qabany, A.; Soga, K.; Santamarina, C. Factors affecting efficiency of microbially induced calcite precipitation. *J. Geotech. Geoenviron. Eng.* **2012**, *138*, 992–1001.
43. He, J.; Gao, Y.; Gu, Z.; Chu, J.; Wang, L. Characterization of crude bacterial urease for CaCO_3 precipitation and cementation of silty sand. *J. Mater. Civ. Eng.* **2020**, *32*, 04020071.
44. Cheng, L.; Cord-Ruwisch, R.; Shahin, M.A. Cementation of sand soil by microbially induced calcite precipitation at various degrees of saturation. *Can. Geotech. J.* **2013**, *50*, 81–90.
45. Cui, M.J.; Zheng, J.J.; Zhang, R.J.; Lai, H.J.; Zhang, J. Influence of cementation level on the strength behaviour of bio-cemented sand. *Acta Geotech.* **2017**, *12*, 971–986.
46. Jiang, N.J.; Soga, K. The applicability of microbially induced calcite precipitation (MICP) for internal erosion control in gravel–sand mixtures. *Géotechnique* **2017**, *67*, 42–55.
47. Wu, C.; Chu, J.; Wu, S.; Cheng, L.; van Paassen, L.A. Microbially induced calcite precipitation along a circular flow channel under a constant flow condition. *Acta Geotech.* **2019**, *14*, 673–683.
48. Jiang, N.J.; Tang, C.S.; Yin, L.Y.; Xie, Y.H.; Shi, B. Applicability of microbial calcification method for sandy-slope surface erosion control. *J. Mater. Civ. Eng.* **2019**, *31*, 04019250.
49. Hao, M.; Song, S.; Duan, H.; Li, X.; Zhong, Y.; Zhang, J. Effect of fracture aperture on propagation properties of self-expanding polyurethane grout. *Constr. Build. Mater.* **2025**, *458*, 139496.
50. Duan, H.; Zou, L.; Li, B.; Håkansson, U.; Cvetkovic, V. Effect of rheological model selection on prediction of cement grout propagation in rock fractures. *Int. J. Rock Mech. Min. Sci.* **2026**, *202*, 106523.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.