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Research Article

Experimental Study on Microbial Solidification of Gravel-Containing Silty Clay under Different Calcium Sources

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Crushed silty clay is widely distributed in engineering foundations. Because of its local hardness and uneven soil distribution, it is not a good foundation material. Based on microbial solidification technology, microbial solidification tests of silty clay containing crushed stone were carried out by selecting cementing liquids with different calcium sources to study the effect of the calcium source on the solidification effect. With *Pasteurella* as the main solidified bacterial solution, calcium chloride, calcium acetate, and calcium gluconate were mixed into urea to prepare cementing solutions with different calcium sources at concentrations of 0.6, 1.0, and 1.4 mol/L. Microbial solidification tests were carried out under different calcium source concentrations, the calcium carbonate formation of the samples after solidification was examined, and unconfined compressive strength and triaxial tests were conducted. When calcium chloride and calcium acetate were used to solidify the clay, the solidification strength gradually decreased with the increase in the concentration, while the solidification strength of calcium gluconate was the highest at 1.0 mol/L. When calcium chloride with a concentration of 0.6 mol/L was used as the calcium source, the curing effect was the best. The internal friction angle and cohesion of the triaxial test were increased by 35.19% and 99.1%, respectively, and the unconfined compressive strength was increased by 37.94%. The yield ratio was 3.76%. The concentration of 1.0 mol/L was the best concentration of calcium gluconate as the calcium source, and the reinforcement effect was slightly less than that of 0.6 mol/L calcium chloride.

1. Introduction

With the development of science and technology and the progress of the times, cutting-edge technologies of many biological and material disciplines are increasingly being applied to geotechnical engineering. Traditional foundation treatment mostly uses large-scale mechanical compaction of soil or chemical synthesis materials to reinforce a foundation by grouting [1]. Mechanical construction is time-consuming and expensive, creates large soil disturbances, involves a high cost of the chemical grouting, and has a limited reinforcement effect [2]. Some grouting reinforcement materials include sodium silicate, polyurethane, epoxy resin, and acrylate. Aside from sodium silicate, which has a small impact on the environment, the other chemical materials cause greater harm to the environment [3, 4]. Therefore, scholars around the world seek to find a new type of foundation treatment method that is green and sustainable. Microbially induced carbonate precipitation (MICP) uses the metabolic function of microorganisms to act on free calcium ions in a specific cementing solution to form calcium deposits that have a cementing ability and can strengthen the soil [5]. MICP technology has attracted the attention of many scholars because of its environmental friendliness, low price, and low dependence on mechanical equipment [6].

Whiffin [7] took the lead in using MICP technology to solidify loose sand and improve its macroscopic mechanical properties. Hanlong et al. [8] believed that when the sand particles are coarser and the pores are larger, microorganisms are more likely to be cemented in them to strengthen the soil. Clay has a high compressibility, strong plasticity, low permeability, and low strength [9, 10], and with high moisture and organic content, it is considered a problematic soil in engineering [11, 12]. It is widely distributed in China, especially in Hubei, Jiangsu, Sichuan, and other provinces. However, because clay contains many small molecular particles and pores, microorganisms are limited by pore size, and the curing effect is not well understood. In the process of cohesive soil construction, the cohesive soil needs to be mixed with fly ash, cement, and other reinforcement materials to meet the engineering needs [13], and sometimes more crushed stones are added. In the actual construction, when encountering crushed silty clay, the soil can be taken directly in situ, and the foundation can be directly compacted after being mixed with microorganisms and cementation solution, which greatly reduces costs. Therefore, the study of MICP-solidified silty clay containing gravel has good engineering practical application value. This study seeks to find a microbial curing calcium source additive that is more efficient for silty clays for application in engineering practices.

The choice of the calcium source in the cementation solution affects the metabolic function of microorganisms and the process of metal precipitation. Muynck [14] found that calcium ions from different calcium sources will form calcium carbonate precipitates with different crystal morphologies. For example, when calcium chloride is the calcium source, the precipitated crystals are mostly rhombic, and when calcium acetate is the calcium source, the precipitated crystals are mostly spherical. Zhang et al. [15] tested calcium acetate as a calcium source for sand samples, and the unconfined compressive strength of sand samples could reach 1.4 times that of calcium chloride and calcium nitrate as calcium sources. It has been found that the spherical precipitate generated by calcium acetate as a calcium source is more suitable for bonding between soil particles to achieve a better curing effect. However, the economic cost of calcium acetate is higher than that of calcium chloride. Whether the solidification effect of calcium acetate on cohesive soil is equivalent to that of sandy soil is still unclear and needs to be verified by conducting experiments. Gorospe et al. [16] studied the mechanical properties and microscopic characteristics of calcium acetate, calcium lactate, and calcium gluconate as calcium source alternatives to calcium chloride. The results were similar to those of Muynck and Zhang et al. [14, 15]; the microscopic pattern was vaterite when calcium lactate and calcium gluconate were the calcium sources. In particular, when calcium gluconate is used as a calcium source, it can not only improve the performance of the soil but also provide nutrients for the microorganisms so that the microorganisms can secrete more urease, thereby improving the solidification ability.

Most of the cementitious solutions in MICP research around the world are urea-Ca^{2+} mixed solutions. Different concentrations and proportions of cementing solution have a significant influence on characteristics such as the microbial activity, Ca^{2+} precipitation, cementation rate, and microstructure [17]. Nemati et al. [18] used Proteus vulgaris to explore the effect of the urea and Ca^{2+} concentrations on the cementitious ability. It was found that when the concentration ratio of calcium chloride to urea was 2.5 or 3.0 (corresponding to molar ratios of 1.0 or 1.2, respectively), the precipitation efficiency of Ca^{2+} could reach 99%. Too high or too low of a concentration would affect the precipitation efficiency and reduce the soil reinforcement effect. Qabany and Soga [19] used *Pasteurella* to study the sizes and distributions of Ca^{2+}-precipitated microcrystals under different concentrations of cement. Within the concentration range of 0.25–1.0 mol/L, the size and range of the precipitated crystals increased with the increase in the concentration.

Based on the above analysis, the MICP solidification test of silty clay containing crushed stone was carried out with different calcium sources and concentrations of the cementitious liquid using *Pasteurella*, and the solidification effects of the soil samples before and after solidification were evaluated. The most economical anhydrous calcium chloride, calcium acetate that cures best in sandy soils, and calcium gluconate that has minimal environmental impact and provides nutrients to microorganisms were chosen. Gelling solutions with concentrations of 0.6 mol/L, 1.0 mol/L, and 1.4 mol/L were produced, and microbial curing tests were carried out at different calcium source concentrations. Through the calcium carbonate generation test, the unconfined compressive strength test, and the triaxial test, the effect of MICP curing and crushing powder clay was studied, and the test data can provide a certain reference for actual construction to seek efficient, green economic, and pollution-free calcium-based additives.

2. Experimental Materials

The soil used for the tests was taken from a construction site in Optics Valley, Wuhan, China, where the soil 3 m below the ground was mostly silty clay containing gravel. The silty clay contained a certain amount of iron-manganese oxides and a large number of iron-manganese nodules. The main components of the crushed stone were siltstone and flint. The soil samples were reddish brown and yellowish brown, and the soil quality was uneven, saturated, mainly hard plastic, and partially hard.

The soil samples were air-dried, as shown in Figure 1(a). Stones larger than 2 mm were sieved out, leaving 2–5 mm of gravels and gently crushing the remaining powdery clay on a rubber table with a wooden stick. The silty clay was mixed with the crushed stone under the optimal water contents. The proportion of crushed stone in the undisturbed soil was approximately 15%. To ensure the same proportion of gravel in the reshaped soil, the soil samples were mixed for particle analysis tests. Figure 2 shows the particle size distribution of the soil samples after adding 15% crushed stone. According to the "Geotechnical Test Regulations" SL/T 237-1999 of China, samples with dimensions of 80×39.1 mm were made to measure the physical indices of the silty clay containing crushed stone, as shown in Table 1.

2.1. Microbial Culture. Pasteurella is a kind of Gram-positive bacteria with good stability, high-temperature resistance, and oxidation resistance. It can grow at 15°C–37°C, and the effect is better under alkaline conditions. One of the good

(a) Undisturbed soil after air-drying

(b) Remodeled soil

Figure 1: Crushed silty clay.

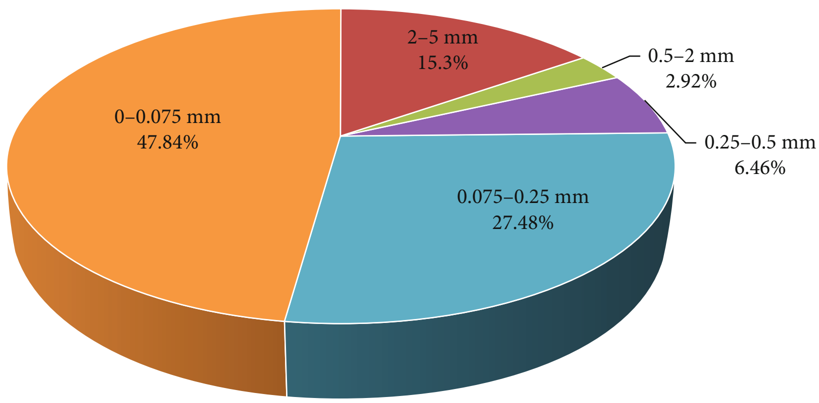

Figure 2: Particle size distribution ratio.

Table 1: Physical indices of crushed silty clay after remodeling.

Water content	Dry density	Void ratio	Liquid limit	Plastic limit	Plasticity index	Liquid index	Compression modulus
24%	1.58 g/cm^3	0.722	39.4%	23.5%	15.9	0.10	6.7 MPa

strains of *Pasteurella* from Shanghai Biotechnology Center (SHBCC), numbered ATCC11859, was selected, and the strain state was determined using the lyophilized powder. The strains were expanded in a liquid medium, and the medium composition is shown in Table 2. A 1 mol/L NaOH solution was used to adjust the pH of the medium to 7.3, which was an alkaline state. After the preparation was completed, 1 mg of lyophilized powder was dissolved in liquid with 0.2 mL of lysing solution, and then, it was transferred to a liquid medium. The liquid medium containing the strains was put into a constant-temperature shaking incubator and shaken for 36 h at 30°C and 200 r/min. The above operation was repeated twice, and the culture was proportionally expanded to obtain a sufficient amount of bacterial liquid [20, 21]. The OD600 of the bacterial solution was measured to be 1.493 using an ultraviolet-visible (UV-Vis) spectrophotometer (TU-1810), and the bacterial solution was diluted with distilled water after high-temperature sterilization. A conductivity meter (DDS-12A) was used to measure the cell activity of 0.312 ms/(cm·min^{-1}).

2.2. Configuration of Cementitious Liquid. The cementing solution used in the MICP reinforcement was mostly a mixed solution of calcium chloride and urea. Calcium chloride provided the calcium source for the reinforcement of the microorganisms, and urea ($CO(NH_2)_2$) enabled the microorganisms to have energy and maintain their activity to form $CaCO_3$ precipitation and provide ${CO_3}^{2-}$. The reaction equations are as follows:

$$\begin{gathered} Ca^{2+} + \text{Cell} \longrightarrow \text{Cell} - Ca^{2+}, \\ CO(NH_2)_2 + 2H_2O \overset{\text{Urease}}{\longrightarrow} 2{NH_4}^{+} + {CO_3}^{2+}, \\ {CO_3}^{2-} + \text{Cell} - Ca^{2+} \longrightarrow \text{Cell} - CaCO_3\downarrow. \end{gathered} \tag{1}$$

To explore the effect of the calcium source type and concentration changes on the reinforcement effect of crushed silty clay, three calcium sources, calcium chloride, calcium acetate, and calcium gluconate, were selected with

Table 2: Composition and content of medium per liter.

Element	Caso agar+urea	Peptone from casein	Peptone from soymeal	NaCl	Agar	ddH2O
Content	20 g	15 g	5 g	5 g	20 g	900 mL

Table 3: Sample no. and binder configuration.

Sample no.	L1	L2	L3	Y1	Y2	Y3	P1	P2	P3
Calcium source		Calcium chloride			Calcium acetate			Calcium gluconate	
Concentration (mol/L)	0.6	1.0	1.4	0.6	1.0	1.4	0.6	1.0	1.4

concentrations of 0.6, 1.0, and 1.4 mol/L (the calcium source and urea were placed in equal proportions with the same concentration). Three calcium sources and three concentrations were cross-prepared and divided into nine samples, as shown in Table 3, and one untreated soil was selected as the control sample.

2.3. Sample Making. To determine the most suitable curing method for the silty clay containing gravel, a pretest was carried out before the test. First, a grouting method was attempted [22]. The silty clay containing crushed stone was freely scattered in a detachable cylindrical transparent tube (the inner dimension of the tube was 80 mm (height) × 39.1 mm (diameter)) until the filling was complete. The seal was then tightened, and the upper and lower openings were opened. The peristaltic pump introduced a mixed solution of a calcium source and urea from the lower opening, and the flow exited through the upper opening. However, after pouring the cementing solution several times, the solution was difficult to introduce into the soil, and a large amount of soil flowed out with the solution from the upper opening, which did not allow easy cementing. Thus, a soaking method was adopted [23]. The soil column was made by mixing microorganisms with the soil. It was wrapped with permeable geotextiles and soaked in the cementing solution for 28 d. It can be seen that the grouting method and the soaking method were not suitable for the microbial solidification of the soil in this study.

The mixing method was used in experiments to microbially immobilize soil. The optimum moisture content of the silty clay containing crushed stone was 24%. A mixed solution of microorganisms and cement was used to replace the water required for optimal moisture content, and cylindrical specimens with heights of 80 mm and diameters of 39.1 mm were made. The maximum dry density of silty clay containing crushed stone was 1.58 g/cm^3. According to the maximum dry density of the test soil and the bacterial liquid and cementitious liquid that replace the best moisture content, it can be calculated that 152 g of soil, 19 g of bacterial liquid, and 19 g of cementation liquid were required to make a sample. After stirring 19 g of bacterial liquid and 152 g of soil, the mixture was allowed to stand for 3 d so that the bacterial liquid was adsorbed on the soil particles. The mixture was then fully stirred with 19 g of cementing liquid to obtain 190 g of bacteria-containing soil. In the saturator, light compaction was carried out in four layers, and the contact surface between the layers was roughened, and the prepared samples were placed at a temperature of 30°C and a humidity of 95% ± 2% (the cured samples were sealed in a humid sample pot, and the sample pot was placed in a 30°C incubator) for 28 d of curing. The sample after curing is shown in Figure 3.

3. Cured Specimen Strength Test

To test the effects of different calcium sources and concentrations on the strength change of the microbial-solidified gravel-containing silty clay, triaxial tests and unconfined compressive strength tests were carried out on the solidified samples after curing at constant temperature and humidity for 28 d.

3.1. Triaxial Consolidation Undrained Test. In the natural environment, the underground soil is under the action of a confining pressure, which increases as the soil depth increases. The greater the confining pressure is, the more difficult it is for the soil body to deform laterally. It is difficult to achieve real soil stress conditions in general tests. The triaxial shear test produces stress-strain changes. It has the advantages of a uniform and strict control of the inflow and drainage and a measurable pore water pressure, which can effectively simulate the actual environment [24, 25].

The test used a TSZ-2 automatic triaxial instrument with an axial force accuracy of 0.01 kN, an axial displacement accuracy of 0.01 mm, inlet and drainage, and a volume deformation of 0.001 mL. The test specimens were a plain soil control and nine different test groups. The test conditions for each group were effective stress confining pressures of 50, 100, and 200 kPa. The sample needed to be evacuated and saturated before testing to make the sample void-free and fully saturated. However, during the curing process, due to the proliferation of microorganisms, the volume of the sample expanded, it was difficult to put it into the saturator, and demolding after saturation could easily destroy the integrity of the sample, so this step was skipped directly. The sample was not vacuum saturated and was only stabilized before shearing the soil sample. By shearing at a rate of 0.05 mm/min to an axial strain of 20%, the deviator stress $(\sigma_1 - \sigma_3)_f$ and axial strain (ε) curves were obtained.

Figure 3: Sample of silty clay containing crushed stone after curing for 28 d.

The shear strength of the soil was expressed by the Coulomb formula, which is expressed as

$$\tau_f = c + \tan \varphi, \tag{2}$$

where τ_f is the shear strength of the soil (kPa), c is the cohesion (kPa), and φ is the friction angle in the soil (°). The maximum deviatoric stress $(\sigma_1 - \sigma_3)_f$ was selected as the point of destruction. In the τ–σ coordinate system, a Mohr circle with the failure stress as the radius and $(\sigma_1 + \sigma_3)_f/2$ as the center of the circle was drawn. The envelopes (common tangent) of the stress circle under different confining pressures (50, 100, and 200 kPa) were found. The envelope was equivalent to τ. The intercept of the vertical axis was c, and the angle from the axis was φ. However, according to the three stress circle combinations (50/100 kPa, 100/200 kPa, and 50/200 kPa), the error between the envelope curves was too large. Thus, the common tangent point was directly fitted, and the six tangent points were directly fitted with the following equation to obtain the common tangents of the three circles [26, 27]:

$$\frac{\sigma_1 - \sigma_3}{2} = c \cos \varphi + \frac{\sigma_1 + \sigma_3}{2} \sin \varphi, \tag{3}$$

where σ_1 is the maximum principal stress (kPa), σ_3 is the minimum principal stress (kPa), and φ is the friction angle within the soil (°).

The deviatoric stress-axial strain curve of the specimen and the maximum failure deviatoric stress are shown in the Mohr stress circles in Figures 4–9. Because the variation trends of the same calcium source curves are similar, only T0, L1, and P2 are shown. The failure deviatoric stress, cohesion, and internal friction angle of the test soil samples under different confining pressures are shown in Table 4.

Under different confining pressures, in the low confining pressure test, the soil sample quickly reached the failure envelope with the increase in the shear stress, and the stress and strain increased slowly under the condition of a high confining pressure. Thus, for the soil mass under low confining pressure conditions, deformation was more likely to occur, but with the increase in the degree of cementation, the strength of the soil increased, the stress changed linearly, and the soil exhibited strain softening. The conclusion was the same as that of Taiyu et al. [28]. As shown in Figures 4–6, when the confining pressure is fixed, the greater the maximum skew stress of the specimen with better curing effect, and the more uniform the curve. The uncured specimen reaches the maximum bias stress at about 8%, and the maximum strain of the cured specimen reaches 16%, nearly doubled, and the curing effect is very obvious. As shown in Figures 7–9, the slope and intercept of the fitted shear strength clad line of the specimen after curing are increased to a certain extent, and the changes in the adhesion force and internal friction angle of the cured specimen can be deduced.

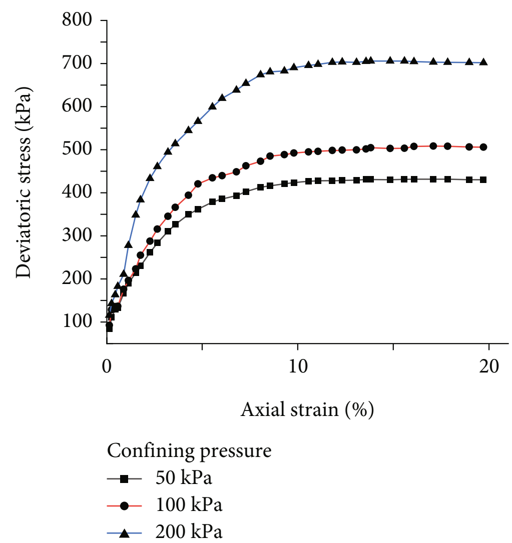

Figure 4: Deviatoric stress-axial strains of plain soil samples under different confining pressures.

For the samples with calcium chloride and calcium acetate as the calcium sources of the cementing solution, the curing effect showed a negative increase with the increase in the concentration. The maximum deviatoric stress was

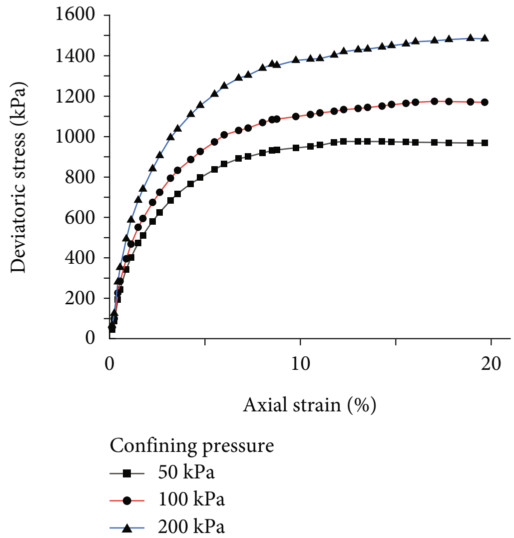

Figure 5: Deviatoric stress-axial strains of solidified soil samples with 0.6 mol/L calcium chloride under different confining pressures.

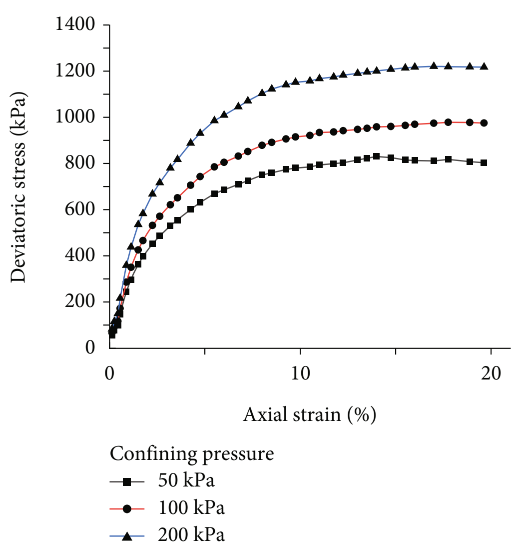

Figure 6: Deviatoric stress-axial strains of solidified soil samples with 1.0 mol/L calcium gluconate solidified under confining pressures.

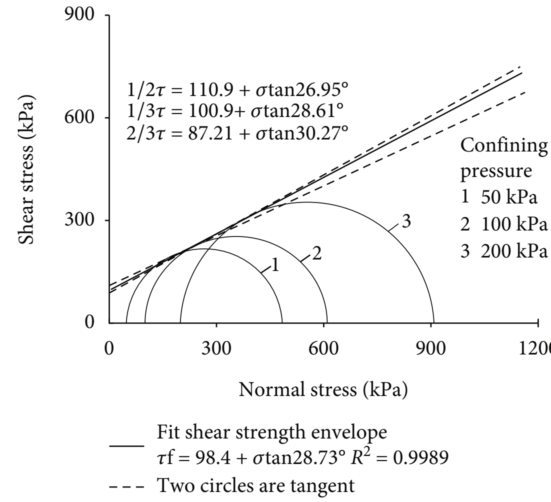

Figure 7: Mohr's stress circles for triaxial tests of plain soil samples.

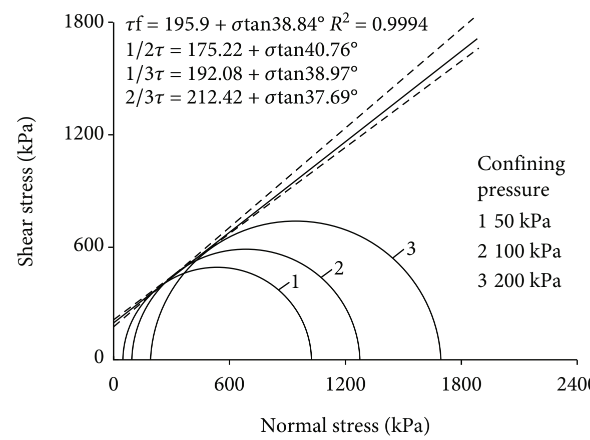

Figure 8: Mohr's stress circles for triaxial tests of solidified soil samples with 0.6 mol/L calcium chloride.

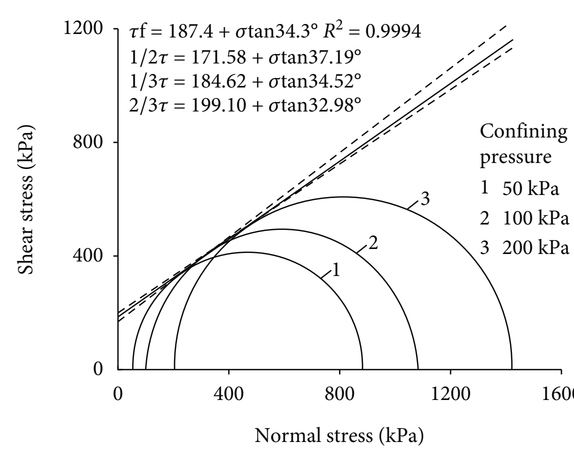

Figure 9: Mohr's stress circles of triaxial tests of solidified soil samples with 1.0 mol/L calcium gluconate.

obtained for the calcium chloride sample with a concentration of 0.6 mol/L; the internal friction angle c and cohesion φ of the sample were increased by 35.19% and 99.1%, respectively, compared with the plain soil sample. The optimal reinforcement concentration of calcium gluconate was 1.0 mol/L, and the internal friction angle and cohesion increased by 19.39% and 90.44% compared to those of the plain soil samples, respectively. There were two reasons for the improvement of the strength: one was the formation of calcium carbonate crystals on the soil particles, which changed the particle size and surface roughness of the soil and increased the friction angle in the soil. Calcium carbonate precipitates gradually formed to cement individual soil

Table 4: Deviatoric stress values and strength indices of specimens under different confining pressures.

Sample	Deviatoric stress at failure (kPa)			Internal friction angle (°)	Cohesion (kPa)
	50 kPa	100 kPa	200 kPa		
T0	431.6	508.2	705.7	28.73	98.4
L1	975.3	1173.1	1484.7	38.84	195.9
L2	622.4	735.6	927.8	30.18	151.3
L3	426.5	508.6	694.5	28.26	99.7
Y1	681.4	773.2	988.0	30.5	164.0
Y2	450.7	547.6	733.4	28.99	105.4
Y3	346.0	414.6	532.2	22.41	96.1
P1	694.0	794.7	1009.8	30.9	166.2
P2	831.2	979.3	1221.8	34.3	187.4
P2	479.7	556.4	714.7	26.1	124.9

(a) Cured sample (b) Plain soil

Figure 10: Comparison of samples after strength tests.

particles, thereby enhancing the cohesion [29]. Based on the increase in the internal friction angles and cohesion of the samples, the increase in the cohesion was much larger than that of the internal friction angle. Therefore, the microbial reinforcement of gravel-containing silty clay was mainly dominated by cementation and cohesion.

Compared with the solidified sand of Qabany and Soga's team [19] after changing the calcium source concentration, the sand sample had the best reinforcement effect at a calcium source concentration of 1.0 mol/L. However, the reinforcement effect of silty clay containing crushed stone with a 1.0 mol/L concentration of the calcium source was less than that with a 0.6 mol/L concentration. When calcium chloride and calcium acetate concentrations exceeded 0.6 mol/L and the calcium gluconate concentration exceeded 1.0 mol/L, the production of urease produced by the metabolism of microorganisms had an inhibitory effect, so that the curing effect at high concentrations was not as good as that at low concentrations. High concentrations of calcium sources not only inhibited the activity of microorganisms but also reduced the synthesis effect of calcite, and the types of calcium crystal precipitation generated by different concentrations of calcium sources were also different. Based on the optimal reinforcement concentration of the three calcium sources, deviatoric stress, internal friction angle, and cohesion, the curing effects were in the order of calcium chloride (0.6 mol/L) > calcium gluconate (1.0 mol/L) > calcium acetate (0.6 mol/L).

3.2. Unconfined Compressive Strength Test. The unconfined compressive strengths were measured using an ultimate strength test in which only an axial load was applied without a lateral pressure. Broken traces were visible on the sides when the samples were subjected to axial forces. The plain soil control and nine test groups that had been cured for 28 d were analyzed by a strain-controlled unconfined instrument (YYW-2 type) to analyze the failure type and peak strength. The test instrument was hand-cranked and unconfined, allowing the dynamometer and axial deformation to be read. The strain rate was controlled to 1 mm/min, and the test was stopped when the axial deformation reached 15 mm or the soil sample was noticeably damaged.

In the plain soil sample shown in Figure 10, an oblique section failure was evident from one-third of the bottom corner to the top edge, and the damage was very noticeable. This plain soil was prone to large-area collapse and complete fracture. Although the strain test sample in the left picture was damaged, there was only a certain degree of cracking, and the overall shape was relatively complete. During the curing process of the soil samples, under the action of gravity, bacterial and cementitious liquid were gradually deposited below the sample, so the reinforcement effect of the lower half of the sample was better than that of the upper half. The test used an unconstrained instrument, and after the compression test of the sample, the cracks in the soil sample were in the upper half, and the lower half was basically intact.

After the unconfined compressive strength test, the peak strength of the uncured soil sample was 126.28 kPa. As shown in Figure 11, calcium chloride and calcium acetate had the highest strength at the concentration of 0.6 mol/L. Compared with the plain soil sample, calcium chloride increased the strength by 37.94%, and calcium acetate only increased it by 25.75%. Zhang et al. [15] found that the strength with calcium acetate as a calcium source in sandy soil was 140% of that of other calcium sources. However, the strength improvement of calcium acetate in gravel-containing silty clay was only two-thirds of that of calcium chloride, and the curing effect of calcium acetate in cohesive soil was not ideal. Calcium chloride and calcium acetate had the highest peak clay strength at a concentration of 0.6 mol/L when used as calcium-based additives. Calcium gluconate had the best effect at the concentration of 1.0 mol/L, increasing the peak strength by 33.27%, and the microbial curing effect was also ideal. During the test, when the concentration of calcium gluconate exceeded 1 mol/L, the solution became more viscous. The microorganisms in the highly viscous cementitious solution could inhibit the induction of calcium carbonate precipitation; although there was a certain solidification ability, the curing effect gradually decreased. The peak strengths of the three calcium sources were in the following order: calcium chloride (0.6 mol/L) > calcium gluconate (1.0 mol/L) > calcium acetate (0.6 mol/L). The concentrations of the three calcium sources should not be too high, and the soil strength showed a downward trend when the concentration was greater than 1.0 mol/L. This was basically consistent with the results of the triaxial consolidation undrained strength tests.

4. Strength Change Mechanism

The amount of calcium carbonate formed in the curing test was closely related to the curing effect. The more calcium carbonate was generated, the better the reinforcement effect was to a certain extent. After testing the unconfined compressive strength, the soil sample was directly tested for calcium carbonate generation, and the unconfined compressive peak strength was used to compare with the calcium carbonate generation to explore the mechanism of its strength change.

During the microbial reinforcement process, the soil only formed calcium carbonate precipitates, so the acid washing method was used to determine the amount of calcium carbonate produced. The samples that had undergone the unconfined compressive strength test were dried and crushed to make the calcium carbonate more soluble in the acid solution. After drying again, 20 g of the soil sample was removed and placed in a beaker, an excess of 2 mol/L hydrochloric acid was added, and the sample was soaked

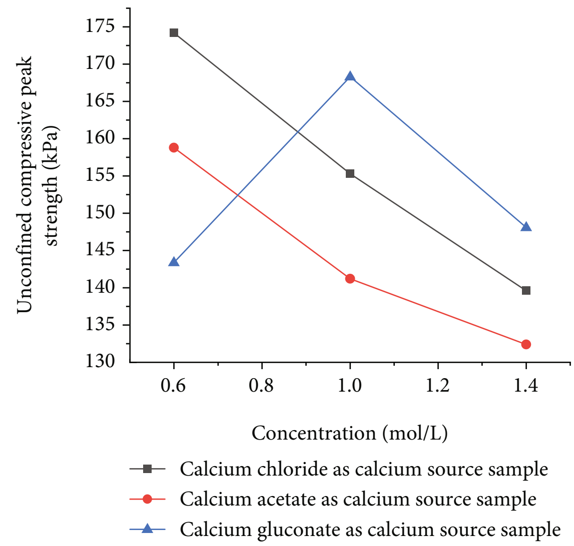

Figure 11: Unconfined peak intensity curves of samples with different calcium sources and concentrations.

until no bubbles were formed. To make the reaction more thorough, the soil sample was allowed to stand for 24 d, and then, the mixed solution was poured into a funnel with filter paper. The material collected on the filter paper was rinsed with clean water three to five times, and the remaining residue and filter paper were dried at 105°C until the weight was constant [30]. For calcium carbonate production (C), the calculation formula is

$$C = \frac{M_{S+C} - M_S}{M_{S+C}} \times 100\% - C_0, \qquad (4)$$

where M_{s+c} is the drying mass of the soil sample before pickling (20 g), M_s is the dry mass of the soil sample after pickling (g), and C_0 is the initial calcium carbonate content of silty clay containing crushed stone (2.90%).

Figures 12–14 show the amounts of calcium carbonate generated and the peaks of the unconfined compressive strength for different calcium sources and concentrations. The generation of calcium carbonate in the soil samples with calcium chloride and calcium acetate as calcium sources decreased with increasing concentration, which was basically consistent with the curve of the unconfined peak compressive strength. However, when calcium gluconate was used as the calcium source, the amount of calcium carbonate produced was the highest when the concentration was 1.0 mol/L. Based on the comparison between the unconfined compressive strength and the calcium carbonate production, the calcium gluconate sample had a lower calcium carbonate production than the calcium acetate sample, but the unconfined strength was higher than that of the calcium acetate sample. Gorospe et al. [16] conducted research with *Pasteurella* and found the microscopic pattern of vaterite when calcium gluconate was the calcium source, while the precipitated crystals were mostly spherical when calcium acetate was the calcium source. The reinforcement effect was better in the silty clay containing crushed stone, so the calcium

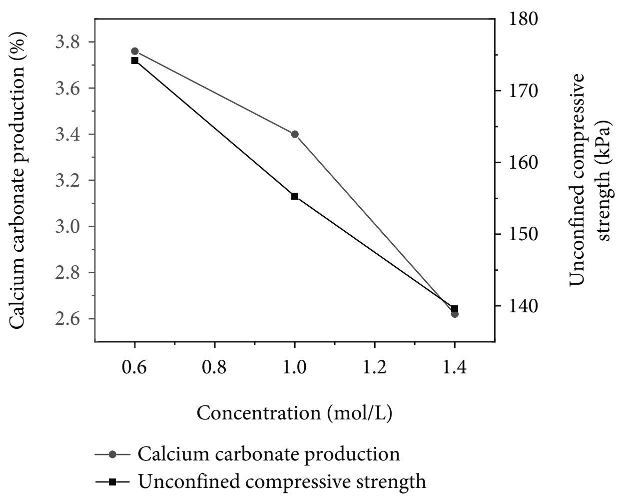

Figure 12: Comparison of calcium carbonate production and unconfined strengths of calcium chloride-cured samples.

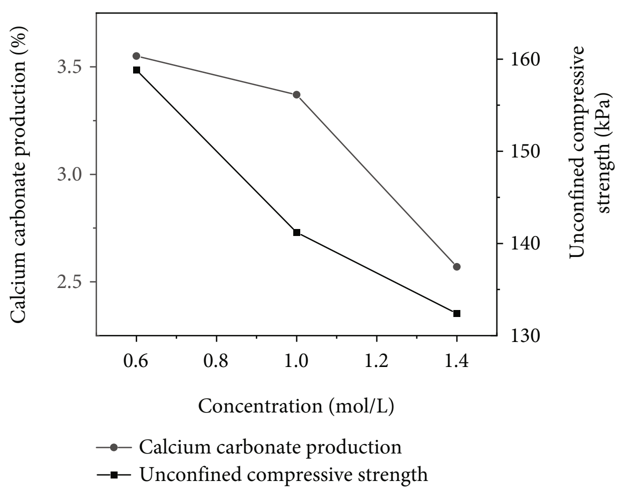

Figure 13: Comparison of calcium carbonate formation and unconfined strengths of calcium acetate-cured samples.

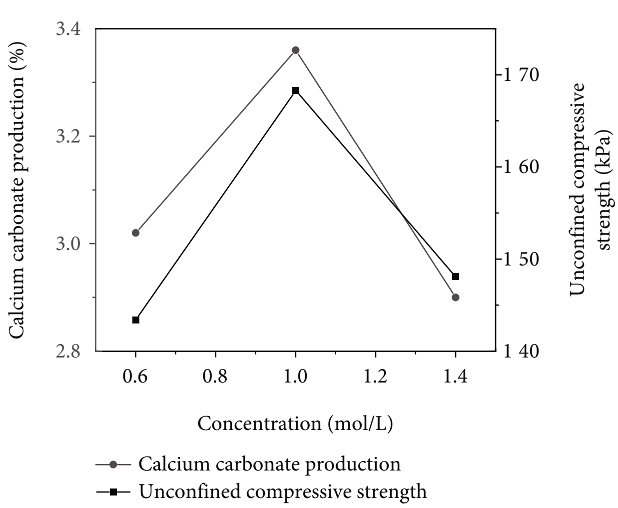

Figure 14: Comparison of calcium carbonate production and unconfined strengths of calcium gluconate-solidified samples.

gluconate sample was better than the calcium acetate sample, although the amount of calcium carbonate generated was lower.

The microorganisms acted as catalysts to hydrolyze urea ($CO(NH_2)_2$) into NH^{4+} and CO_3^{2-}, and the CO_3^{2-} and Ca^{2+} from the calcium source formed calcium carbonate precipitates. The type and quantity of microorganisms and the activity of urease affected the degree of urea hydrolysis to a certain extent, thereby changing the amount of calcium carbonate produced, but this was not a decisive factor. The mass ratio of the bacterial solution and cementation solution, the ratio of urea to the calcium source, and the selection of different calcium sources all had significant influences on the CO_3^{2-} generated by urea hydrolysis, changing the amount of calcium carbonate generated and finally changing the microbial reinforcement effect.

When the concentration of the cementitious solution was too high, the activity of urease was inhibited, the decomposition of urea was reduced, or the conditions of microbial growth changed. The calcium carbonate production decreased, and the microbial reinforcement was also affected [10]. The unconfined compressive strength and the amount of calcium carbonate produced basically showed similar trends, and the reinforcement effect varied with the proportion of the amount of calcium carbonate produced, which indicated that the curing effect would vary with the content of biological enzymes, which was affected by the different calcium sources and concentrations.

5. Conclusions

(1) Reinforcing the silty clay containing crushed stone by mixing and curing could solve the problems of the soil containing small pores and being easily dissolved in water, and the strength of the soil could be effectively improved

(2) After the triaxial consolidation undrained test of the test group, it was found that microbial reinforcement of crushed powdered clay was mainly used to increase cohesion and improve the strength of cured specimens. Calcium chloride and calcium acetate inhibit the production of urease produced by microbial metabolism when exceeding 0.6 mol/L and calcium gluconate exceeding 1.0 mol/L

(3) The unconfined compressive peak strength was tested. The peak strengths of the calcium chloride and calcium acetate were the highest at the concentration of 0.6 mol/L. During the test, the bacterial fluid and cement solution are gradually deposited under the specimen, so that the reinforcement effect of the lower part of the specimen is better than that of the upper half. The cured soil sample was dried and then pickled and then dried to test the amount of calcium carbonate, and it was found that the concentration of cement solution was too large to inhibit urea activity, reduce

the decomposition of urea, and change the conditions for microbial growth

(4) Microbial solidification of gravel-containing silty clay was feasible in the indoor tests, the soil strength was effectively improved, and calcium-based additive selection of 0.6 mol/L calcium chloride has the most obvious effect; the test results can provide a reference for selecting different calcium sources for reinforcement according to different outdoor construction environments

Data Availability

Some of the experimental test data used to support the findings of this study are included within the article. The other data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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