

Efficacy of Sucrose and Skimmed Milk in Enhancing Sandy Soil Strength Using the SCU-CP Method

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Abstract The Soybean Crude Urease Calcite Precipitation (SCU-CP) method is a bio-mediated soil improvement approach that promotes calcium carbonate precipitation through enzymatic urea hydrolysis. Although this method has shown potential for sustainable soil stabilization, its efficiency is often limited by the non-uniform distribution of calcite, which affects interparticle bonding and the overall improvement in soil strength. This study aims to enhance the performance of the SCU-CP method through the use of natural organic additives, specifically sucrose and skim milk, to improve the homogeneity of calcite precipitation and increase the strength of the treated sandy soil. Experimental investigations were conducted using soybean extract concentrations of 20, 60, and 100 g/L, combined with sucrose and skim milk additions of 2.0, 4.0, and 6.0 g/L. Experimental tests, including precipitation, hydrolysis, viscosity, water holding capacity, and unconfined compressive strength (UCS), were conducted to examine the influence of these additives on the grouting characteristics and soil performance. The results showed that the addition of sucrose and skim milk increased the solution viscosity and water retention, which facilitated a more uniform distribution of calcite crystals within the soil matrix. This improvement in calcite uniformity strengthened the interparticle bonding and resulted in a substantial increase in the UCS. The optimum performance was obtained using 6.0 g/L skim milk, resulting in an

approximately 90% increase (21.3 kPa) in UCS compared with untreated sand, whereas 6.0 g/L sucrose produced a 49% improvement (18.4 kPa). Overall, the use of natural organic additives improved the microstructural integrity and grouting behavior of the SCU-CP method. These findings provide a reference for improving enzyme-induced soil stabilization techniques and indicate the need for further research on organic content, calcium chloride optimization, and multicycle treatment to support potential field-scale applications.

Keywords Calcite Distribution, SCU-CP, Skim Milk, Soil Stabilization, Sucrose

1. Introduction

The rapid growth of population and infrastructure demand has led to the extensive use of various soil types, including loose sandy soils characterized by high permeability, low cohesion, and limited bearing capacity. These properties make sandy soils vulnerable to shear failure and excessive settlement, posing challenges to geotechnical stability [1]. Therefore, ground improvement methods are essential to enhance their engineering performance.

In recent years, bio-based approaches have gained

attention as sustainable alternatives to chemical stabilization. One such method is Soybean Crude Urease–Calcite Precipitation (SCU-CP), which utilizes crude urease enzymes extracted from soybeans to catalyze urea hydrolysis and form calcium carbonate (CaCO_3) that binds soil particles and improves strength [2]. Several studies have demonstrated significant strength gains through SCU-CP; for example, Pratama et al. [3] reported more than a twofold increase in unconfined compressive strength (UCS) using 20 g/L soybean extract, while Prayodi et al. [4] achieved a peak UCS of 1.3 MPa using the same soybean concentration combined with 1.5 mol/L reagent. These findings confirm the potential of SCU-CP for sandy soil stabilization. However, the method still faces a key limitation, namely the non-uniform CaCO_3 precipitation resulting from rapid urea hydrolysis, which leads to uneven bonding and inconsistent strength within the soil matrix [5].

To address this limitation, several researchers have investigated the addition of organic modifiers such as brown sugar, glutinous rice powder, polyacrylic acid, chitosan, and powdered milk to control precipitation kinetics and improve calcite morphology in SCU-CP systems [6–9]. Among these, skim milk has demonstrated notable improvements in strength performance. Skimmed milk contributes protein compounds, primarily casein, which are known to enhance nucleation and crystal growth of CaCO_3 by binding to calcium ions, leading to stronger and more stable calcite networks within the soil matrix [10, 11]. This mechanism facilitates increased soil bonding and strength. Nevertheless, the relatively slow precipitation rate of skimmed milk, reported to range between 0.5–1 mm/day, limits its distribution effectiveness, especially in saturated soils where rapid treatment is required [9].

In contrast, sucrose works through a different mechanism that enhances the interaction of the solution with water and ions, thereby modifying its viscosity and promoting more efficient and homogeneous CaCO_3 precipitation through the formation of additional nucleation sites. According to Jiang and Soga [12], the inclusion of 6.0 g/L sucrose can increase UCS values by approximately 20%, from 400 to 480 kPa. The interaction of sucrose with calcium ions results in more orderly crystal formation and reduced porosity, leading to improved soil compaction and resistance to infiltration and erosion [13].

Although these additives have been examined individually in other bio-cementation contexts, their comparative performance within the SCU-CP method has not been systematically evaluated. In this study, sucrose and skim milk were each incorporated separately into the SCU-CP process to assess their respective effects on solution viscosity, water holding capacity, hydrolysis rate,

calcite distribution, and unconfined compressive strength (UCS). The investigation aims to clarify how these natural additives influence precipitation uniformity and to support the development of sustainable, bio-based soil improvement methods suitable for various geotechnical applications.

2. Materials and Methods

2.1. Soil and Chemical Materials

The soil used in this study was classified as poorly graded sand (SP) based on the Unified Soil Classification System (USCS), with a particle specific gravity (G_s) of 2.44, coefficient of uniformity (C_u) of 4.44, and coefficient of curvature (C_c) of 0.80. The initial porosity values ranged from 0.49 to 0.58. The sandy soil was air-dried, sieved, and stored in a sealed container before use. The SCU-CP solution was prepared using crude soybean extract at concentrations of 20, 60, and 100 g/L, respectively. The extract was obtained by mixing soybean powder with distilled water and filtering through a No. 400 mesh. Urea and CaCl_2 were added at equal molar concentrations of 1 mol/L. Skimmed milk powder (<0.5% fat) and sucrose (97% purity, 0.35 μm particle size) were used as additives at concentrations of 2.0, 4.0, and 6.0 g/L.

2.2. SCU-CP Solution Preparation and Sample Curing

The SCU CP solution was prepared by separately dissolving soybean powder, urea, and calcium chloride (CaCl_2) in distilled water. Soybean powder was mixed with distilled water for five minutes to produce a soybean extract, which was then filtered using a No. 400 mesh (0.037 mm). The filtered extract was combined with the urea solution and stirred for three minutes using a magnetic stirrer. Calcium chloride solution was then added to the mixture and stirred for an additional two minutes to obtain the SCU CP solution. The solution was subsequently modified by adding skimmed milk or sucrose, as shown in Figure 1. Cylindrical sand specimens (5 cm in diameter and 10 cm in height) were placed in molds and treated by percolating 70 mL of the SCU CP solution through the sample. Each specimen was treated using a single injection (one curing cycle) approach, corresponding to one pore volume (1 PV) of SCU-CP solution. The specimens were then cured at room temperature (25–28 °C) for seven days to allow enzymatic activity and calcium carbonate (CaCO_3) precipitation. The formulations were prepared based on the concentrations listed in Table 1.

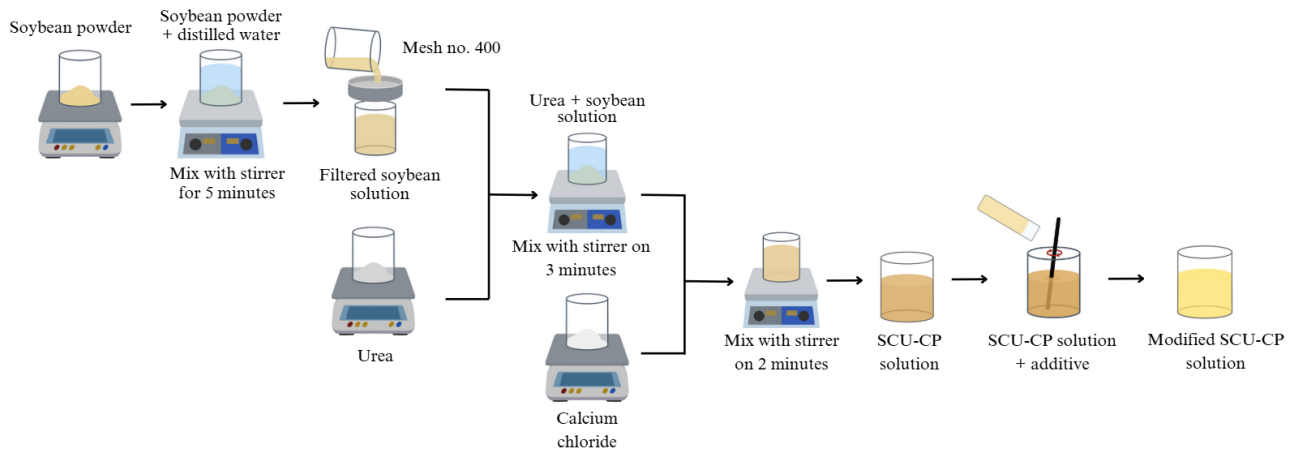


Figure 1. SCU-CP solution preparation procedure

Table 1. Formulation ratio of SCU-CP, milk, and sucrose

Sample	Concentration				
	Soybean (g/L)	Urease (g/L)	CaCl ₂ (mol/L)	Milk (g/L)	Sucrose (g/L)
P1	20	1	1	-	-
P2	40	1	1	-	-
P3	60	1	1	-	-
P4	80	1	1	-	-
P5	100	1	1	-	-
C1	20	1	1	-	-
C2	60	1	1	-	-
C3	100	1	1	-	-
M1	20	1	1	2	-
M2	60	1	1	2	-
M3	100	1	1	2	-
M4	20	1	1	4	-
M5	60	1	1	4	-
M6	100	1	1	4	-
M7	20	1	1	6	-
M8	60	1	1	6	-
M9	100	1	1	6	-
S1	20	1	1	-	2
S2	60	1	1	-	2
S3	100	1	1	-	2
S4	20	1	1	-	4
S5	60	1	1	-	4
S6	100	1	1	-	4
S7	20	1	1	-	6
S8	60	1	1	-	6
S9	100	1	1	-	6

2.3. Precipitation Test

A precipitation test was conducted to evaluate the calcite formation in transparent tubes, adopting the method described by Neupane et al. [14] and Putra et al. [2]. Precipitation was performed using soybean extract at concentrations of 20, 40, 60, 80, and 100 g/L, combined with 1 mol/L urea and 1 mol/L calcium chloride (CaCl_2). The reagent solution was mixed with the soybean extract and transferred into 30 mL transparent tubes. The solution was cured for seven days to allow the formation of calcite. The solutions were then filtered using filter paper with a pore size of 11 μm to remove undissolved particles. The CaCO_3 retained on the filter paper was oven-dried at 60 $^\circ\text{C}$ for 24 h. Each precipitation test was repeated three times, and the two closest results were averaged to obtain the actual precipitated mass (m_p). The precipitation ratio was calculated by comparing the mass of the formed calcite with the theoretical mass, as described by Putra et al. [2], using Equations (1) and (2). The schematic procedure of the precipitation test is illustrated in Figure 2.

$$\text{Precipitation ratio (\%)} = m_p/m_t \quad (1)$$

$$m_t = C V M \quad (2)$$

where m_p is the mass of the precipitated CaCO_3 evaluated from the tests/actual precipitation mass (g), m_t is the theoretical mass of CaCO_3 (g), C is the concentration of the solution (mol/L), V is the volume of the solution (L), and

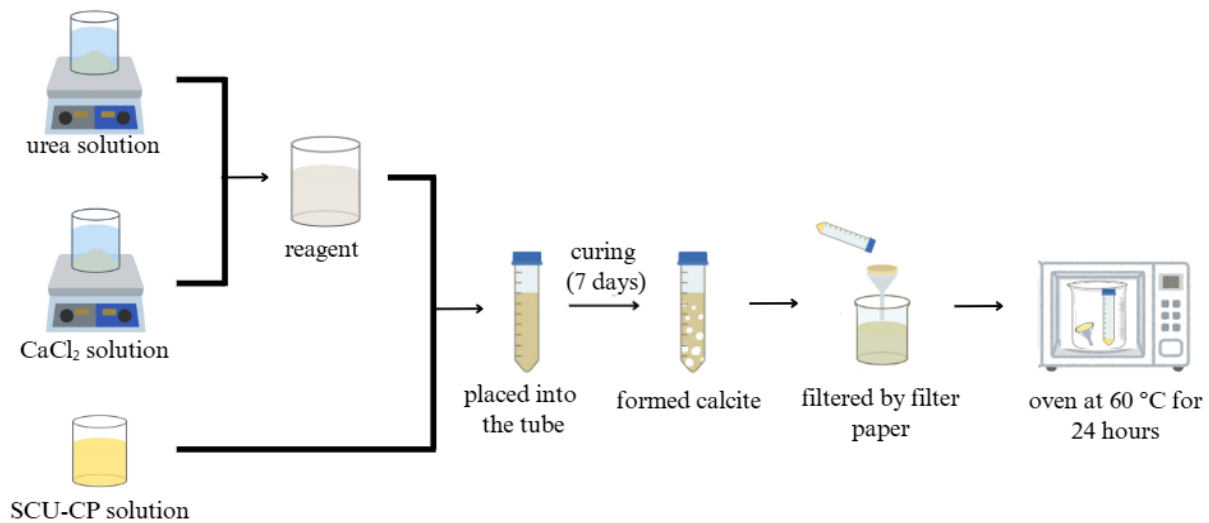


Figure 2. Precipitation test procedure

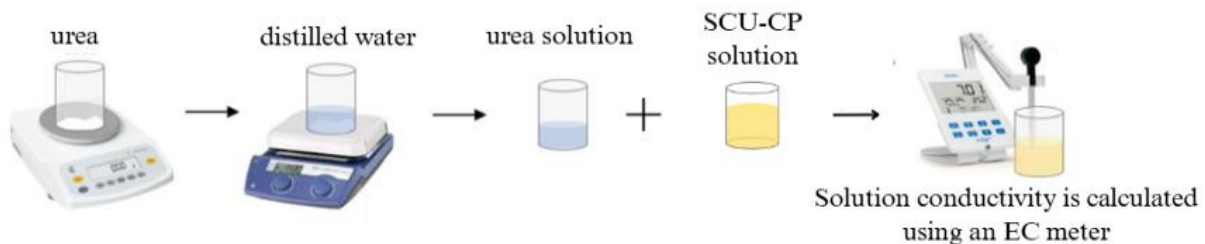


Figure 3. Hydrolysis rate test procedure

M is the molar mass of CaCO_3 (100.087 g/mol).

2.4. Hydrolysis Rate Test

A hydrolysis rate test was conducted to evaluate the reaction rate of urease enzymes in soybean extracts in hydrolyzing urea. Higher urea hydrolysis leads to increased calcite precipitation, as more carbonate ions are produced to bind with calcium ions (Ca^{2+}), forming calcite (CaCO_3). The test involved mixing urea with the SCU CP solution and monitoring the ion conductivity changes over 10 min using a Hanna Edge Multiparameter 230 (EC meter), as shown in Figure 3. The hydrolysis rate was repeated 3 times and calculated using Equation (3). The standard conductivity curve used in the study by Putra et al. [5], is shown in Figure 4. The experimental conditions for hydrolysis rate test were prepared based on the concentrations listed in Table 2.

$$\text{Hydrolysis rate (u/g)} = \theta_{ms} \cdot v \cdot N / (\theta_{sc}) \quad (3)$$

where θ_{ms} is the gradient of the measurement curve, θ_{sc} is the standardized curve gradient, v is the sample volume (L), and N is the final ammonia concentration (mmol/L). Since the sample volume (V) was expressed in liters, the calculated hydrolysis rate (u/L) was multiplied by 1000 to convert it to u/mL. The obtained value was then normalized to the initial soybean mass (g) used for enzyme extraction, resulting in the final hydrolysis rate expressed in u/g.

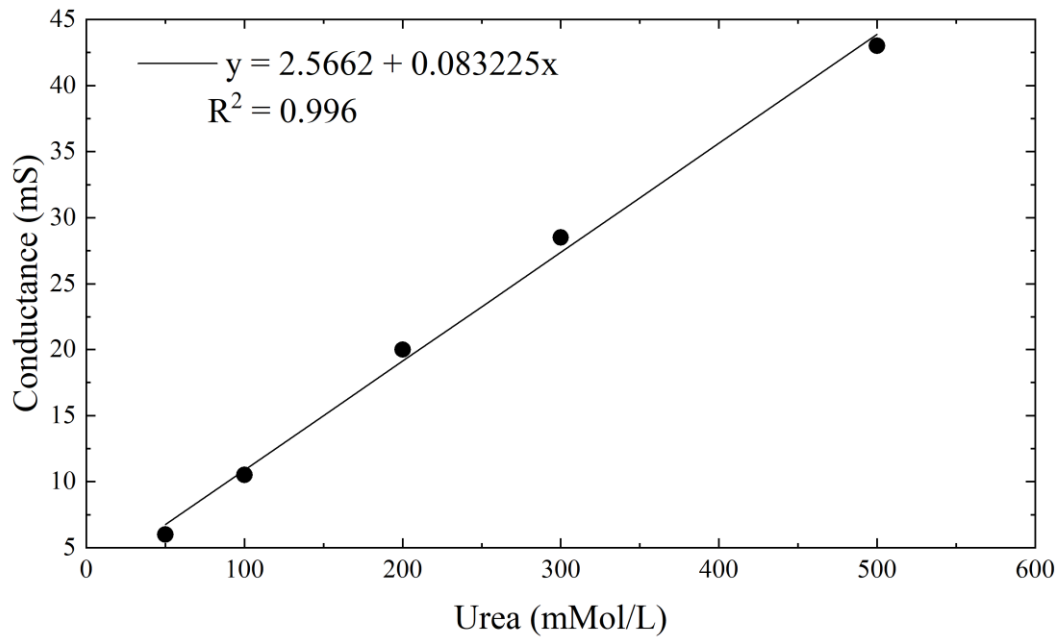


Figure 4. Standard curve of hydrolysis [5]

Table 2. Experimental condition of hydrolysis test

Case	Concentration			
	Soybean (g/L)	Urea (Mol/L)	Milk (g/L)	Sucrose (g/L)
C1	20	0.5	-	-
C2	60	0.5	-	-
C3	100	0.5	-	-
M1	20	0.5	2	-
M2	60	0.5	2	-
M3	100	0.5	2	-
M4	20	0.5	4	-
M5	60	0.5	4	-
M6	100	0.5	4	-
M7	20	0.5	6	-
M8	60	0.5	6	-
M9	100	0.5	6	-
S1	20	0.5	-	2
S2	60	0.5	-	2
S3	100	0.5	-	2
S4	20	0.5	-	4
S5	60	0.5	-	4
S6	100	0.5	-	4
S7	20	0.5	-	6
S8	60	0.5	-	6
S9	100	0.5	-	6

2.5. Viscosity Test

A viscosity test was conducted to measure the flow resistance of the solution used in the SCU-CP method. Viscosity influences the rate at which the solution can distribute and infiltrate the pores of sandy soil, as well as the uniform distribution of ions necessary for calcite precipitation. The viscosity was measured using an Ostwald viscometer, which is a U-shaped glass tube that operates based on the principle of capillary pressure. The procedure followed the Indonesian National Standard (SNI) 0936:2008 [15], which specifies how to measure the viscosity of liquids using a capillary viscometer. A total of 30 mL of the SCU-CP solution was prepared for the tests. The viscometer was placed in a constant temperature water bath and marked with two reference points: Point A (upper limit) and Point B (lower limit). The solution was drawn above Point A. It was allowed to flow freely to Point B. The flow time was recorded using a stopwatch, as illustrated in Figure 5. Each measurement was repeated three times until consistent results were obtained. The viscosity of the solution was calculated based on the flow time and fluid density using Equation 4.

$$\eta = \eta_0(t \rho) / (t_0 \rho_0) \quad (4)$$

where η is the sample liquid viscosity (cP), η_0 is the

distilled water viscosity (cP), t is the sample liquid flow time (s), ρ is the distilled water flow time (s), t_0 is the sample liquid density (g/mL), and ρ_0 is the distilled water density (g/mL).

2.6. Water Holding Capacity Test

The Water Holding Capacity (WHC) test aims to determine the ability of soil to hold water after the formation of calcite crystallization in the pores. An increase in the WHC indicates the precipitation of calcite, which fills the interparticle space and strengthens the bond between soil grains. WHC measurements were performed in triplicate using the hanging water column method, based on ASTM D2980-20 [16]. In this procedure, sand is placed into a porous mold and then SCU-CP solution is added until it reaches a saturated condition. The saturated sample was then suspended so that the water could flow out naturally owing to gravity. The sample was weighed every 24 h until its mass approached the dry initial condition. The degree of saturation was calculated over time to determine the remaining water content, and the test was considered complete when the degree of saturation approached zero, indicating that the water had fully drained. The water holding capacity test procedure is shown in Figure 6.

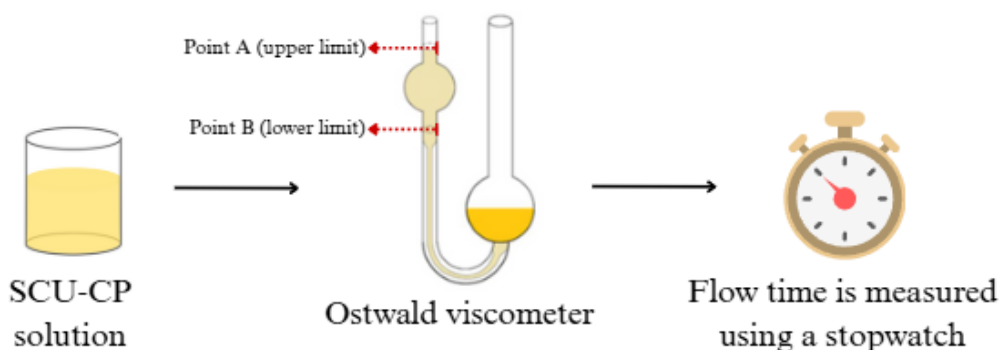


Figure 5. Viscosity test procedure

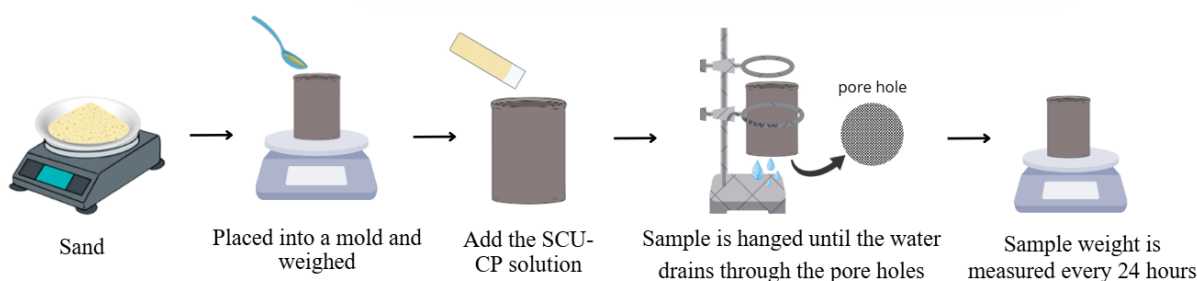


Figure 6. Water holding capacity test procedure

2.7. Calcite Distribution Test

Calcite distribution was analyzed to quantify the mass and distribution of calcium carbonate (CaCO_3) precipitates formed within the sand following treatment with a modified SCU-CP solution. The calcite content was determined using the acid leaching method adapted from the procedure described by Putra et al. [17]. This method enables the dissolution of calcites through its reaction with strong acidic solutions. After seven days of curing, 50 g of soil was collected from each of the three segments (top, middle, and bottom), and each segment was tested three times. The samples were oven-dried at 100°C for 24 h to eliminate water content. Each sample was then washed with 0.1 mol/L hydrochloric acid (HCl) until no more bubbles appeared. This indicated that the reaction between the acid and carbonate was complete. The leaching process was intended to remove the CaCO_3 precipitates formed during the biocementation process. Once the reaction was complete, the samples were re-dried under the same conditions and weighed. The difference in dry mass before and after acid leaching was attributed to the amount of calcite precipitated and retained in the soil. The schematic procedure of the calcite distribution test is illustrated in Figure 7.

2.8. UCS Test

An unconfined compressive strength (UCS) test was conducted to assess the influence of stabilization on the mechanical behavior of sand. The test was performed using a calibrated compression testing machine. Soil samples were prepared in cylindrical molds (5 cm diameter \times 10 cm height), with 70 mL of SCU-CP solution added to each sample. The samples were cured for seven days under controlled conditions. Following the curing period, the samples were demolded and subjected to axial loading at a constant strain rate until failure. Corrections to the cross-sectional area of the loose sand samples were recorded in response to the deformation observed during loading. The sample preparation procedure for the UCS testing is illustrated in Figure 8, and calculated using Equation (5).

$$q_u = \frac{P_u}{A} \quad (5)$$

where q_u is unconfined compressive strength of the soil (kPa), defined as the highest axial stress that the specimen can withstand before failure or rupture occurs; P_u is maximum load at failure (kN); and A is the cross-sectional area of the test specimen (mm^2).

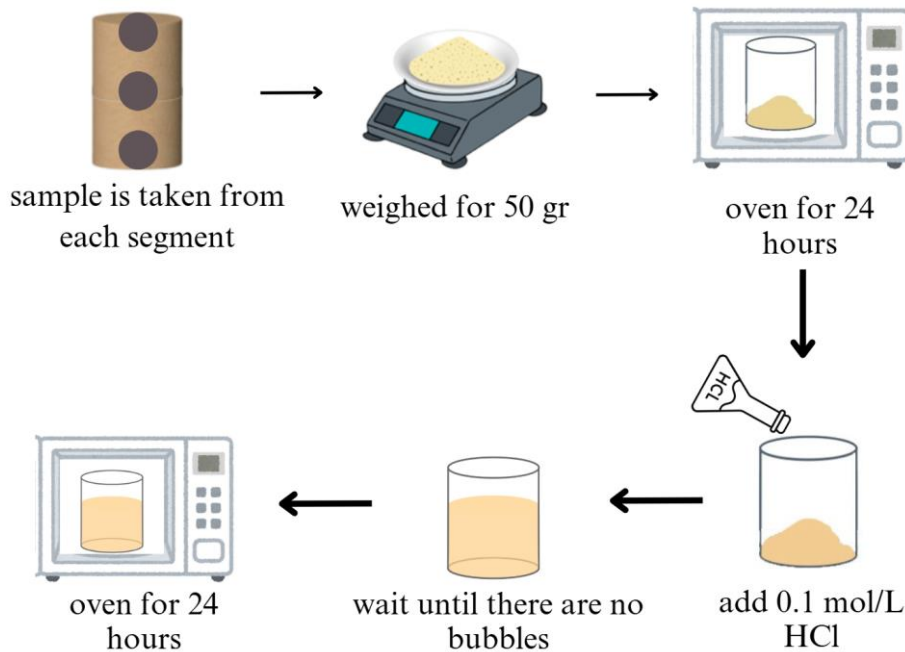


Figure 7. Calcite distribution test procedure

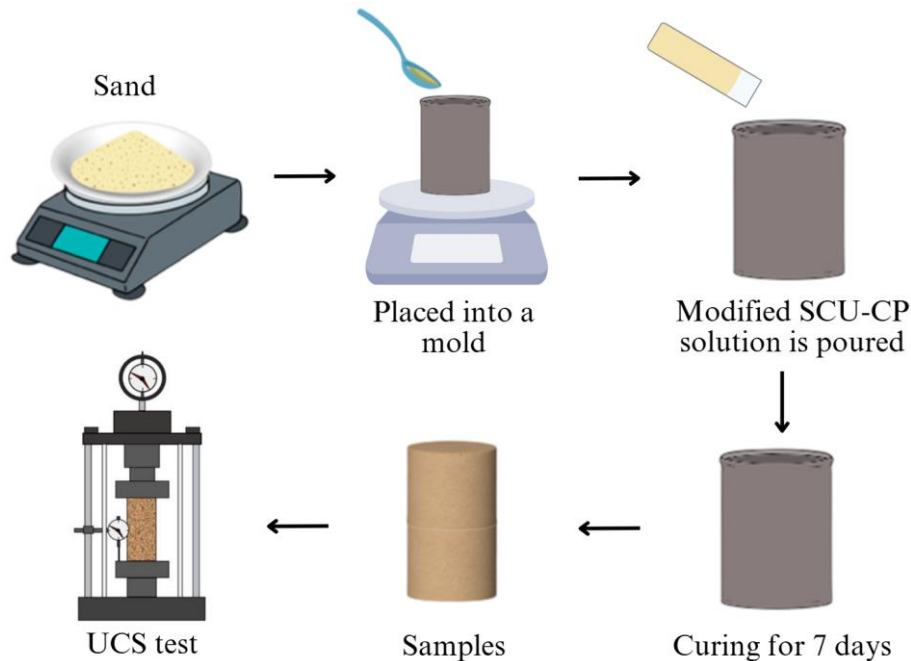


Figure 8. UCS test procedure

3. Results

3.1. Calcite Precipitation and Urease Hydrolysis Rate

Calcite precipitation tests were conducted to quantify the amount of calcite (CaCO_3) formed under different SCU-CP solution compositions. The precipitated calcite binds sand particles through pore filling and cementation, thereby enhancing interparticle contact and increasing soil strength. As shown in Figure 9, the precipitation ratios varied across five soybean extract concentrations: 20 g/L (38.13%), 40 g/L (24.98%), 60 g/L (31.31%), 80 g/L (30.97%), and 100 g/L (33.30%). These findings are consistent with those reported by Putra et al. [5], who demonstrated that the optimum condition was achieved at 1 mol/L reagent and 20 g/L soybean due to the balance between reagent availability (urea and CaCl_2) and urease enzyme activity derived from soybean.

In general, increasing the soybean concentration enhances urease activity, leading to greater calcite formation. However, at higher concentrations, the increase in insoluble organic content may reduce precipitation efficiency, as undissolved particles can interfere with the calcite formation reactions [2]. The reduction observed at 40 g/L is likely due to an imbalance between enzymatic activity and dispersion stability, where proteins or other organic compounds tend to coagulate, thereby hindering crystallization [5]. Conversely, at higher concentrations (60–100 g/L), the dispersion system becomes more stable

as a result of improved enzymatic activity and better homogenization during mixing, which diminishes inhibitory effects. In this study, three concentrations exhibiting the highest calcite precipitation ratios (20, 60, and 100 g/L) were selected as optimal conditions for further analysis.

To evaluate the enzymatic performance of the soybean extract, the rate of urea hydrolysis was assessed. The test aimed to determine the ability of the extract to hydrolyze urea, with conductivity measurements taken over time. The endpoint of hydrolysis was indicated by the maximum conductivity value, which signified the complete conversion of urea. As shown in Figure 10, the conductivity increased with higher soybean extract concentrations, which is consistent with the findings of Prayodi et al. [4], who demonstrated a positive correlation between soybean concentration and hydrolysis rate. SCU-CP solutions containing skim milk exhibited the highest conductivity, indicating enhanced urease activity compared to sucrose or control solutions.

The hydrolysis rate results (Figure 11) confirmed this trend, with the highest activity (1,581.3 U/g) observed in the SCU-CP solution containing 100 g/L soybean extract and 6.0 g/L skim milk. This finding aligns with Yin et al. [18], who reported that milk proteins, such as casein and β -lactoglobulin, act as cofactors that stabilize urease and improve catalytic efficiency. In contrast, sucrose, a disaccharide of glucose and fructose, did not provide a similar enhancement owing to the absence of functional cofactors [19].

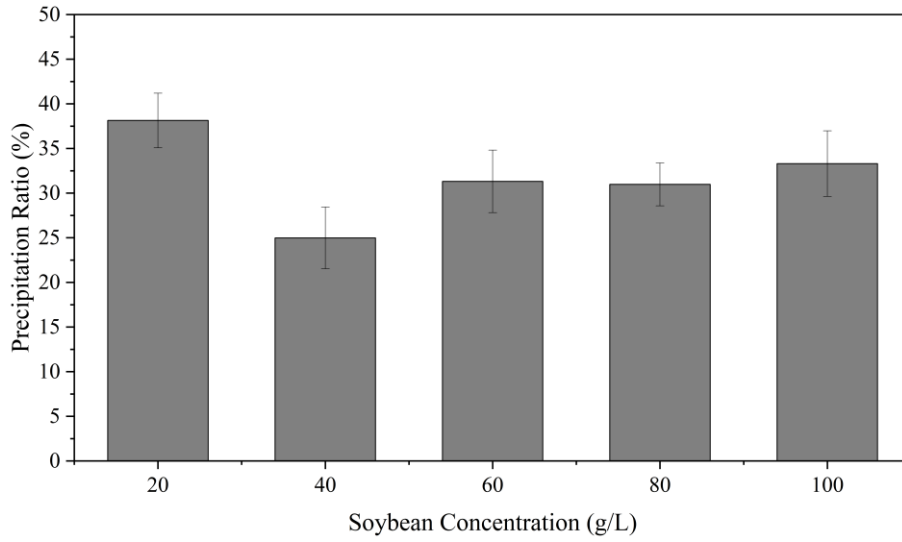
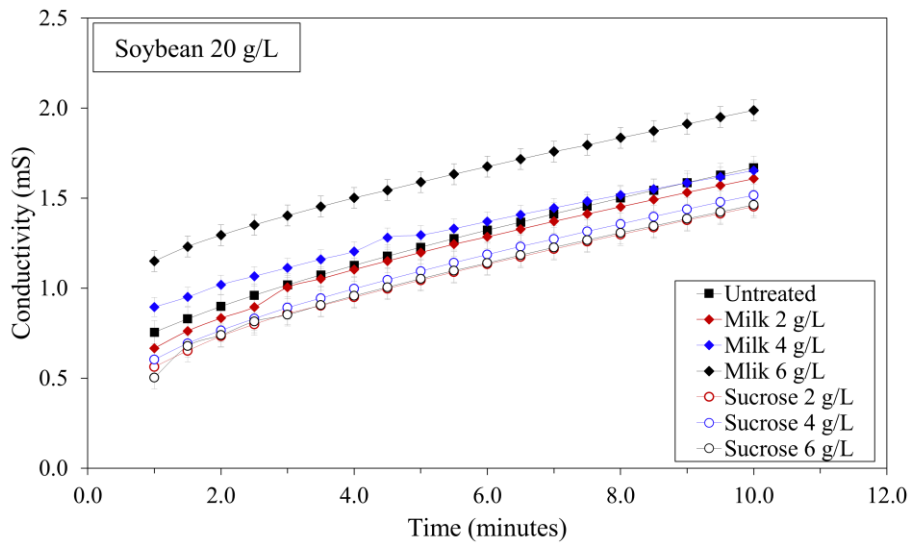
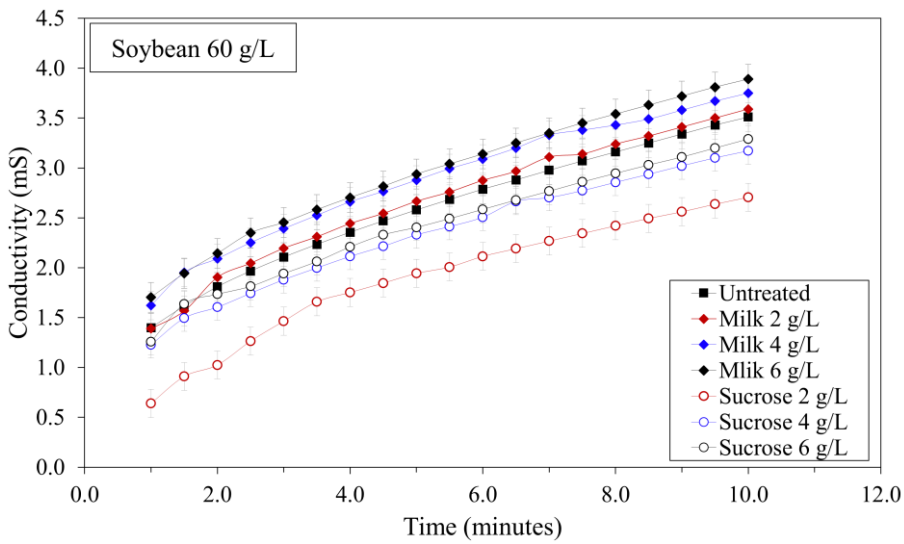


Figure 9. Calcite precipitation ratio of SCU-CP solutions



A



B

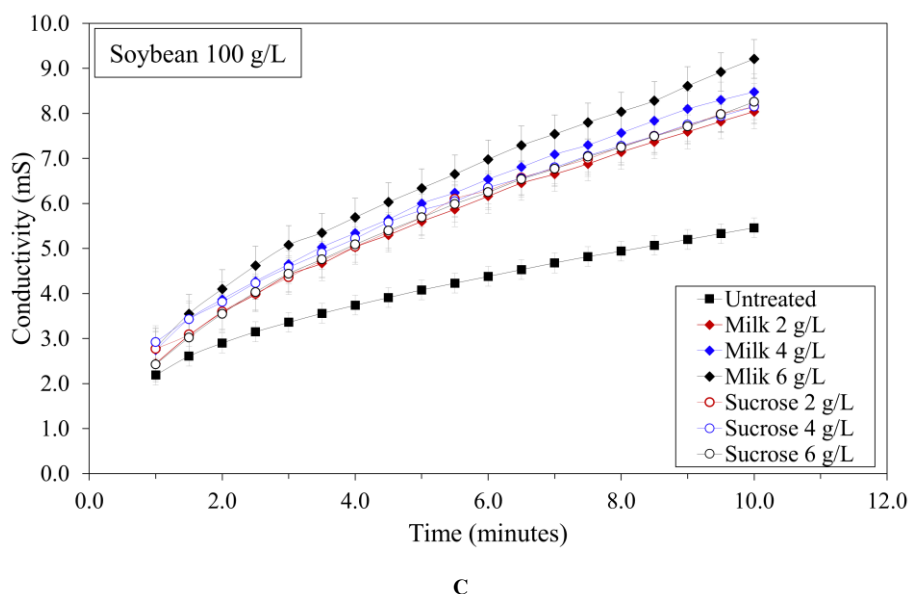


Figure 10. Conductivity of SCU-CP solutions over time at soybean extract concentrations of; (a) 20 g/L, (b) 60 g/L, and (c) 100 g/L

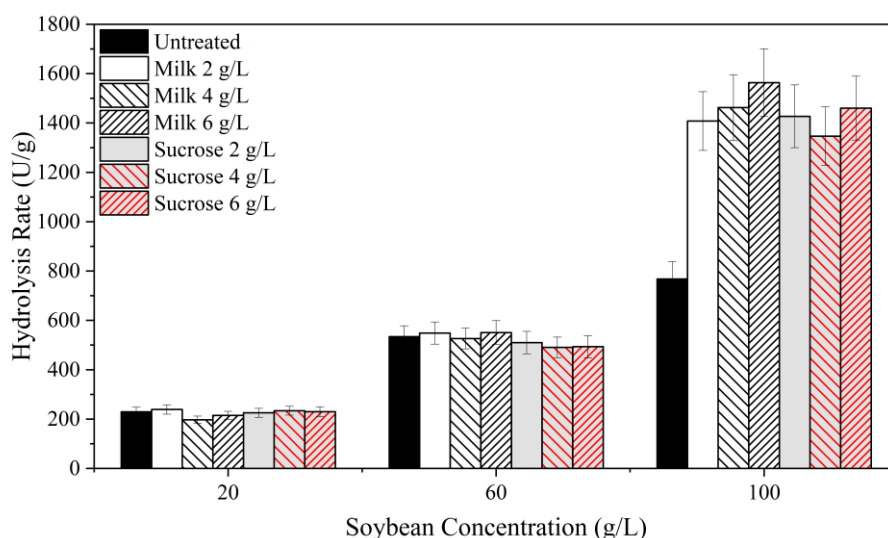


Figure 11. Urease hydrolysis rates with milk and sucrose variations

3.2. Viscosity and Water Holding Capacity

Viscosity significantly influences the spatial distribution of the SCU-CP solution and the efficiency of calcite precipitation within soil pores. The incorporation of skimmed milk and sucrose resulted in a notable increase in solution viscosity compared to that of the control (distilled water, 0.8904 cP). The SCU-CP solution without additives exhibited viscosities between 2.57 and 4.09 cP, while the addition of skimmed milk elevated this range to 3.76–5.60 cP. Sucrose supplementation yielded intermediate viscosities of 3.04–4.97 cP, which were higher than those of the control but lower than those with skimmed milk (Figure 12).

An increase in viscosity enhances the water-holding capacity (WHC) of the soil, thereby promoting sustained

moisture retention and improved dispersion of treatment agents. Prolonged water availability facilitates stronger interparticle bonding, contributing to improved soil mechanical properties [20]. The experimental results (Figure 13) indicate that the skim milk solution exhibited the longest saturation duration, with a marked decline observed on day 26. This prolonged retention is consistent with its higher viscosity compared to sucrose. These findings align with those of Dong and Liu [13], who reported higher WHC in EICP-treated soils using milk (12.54%) than using sucrose (12.23%). This is attributable to the larger molecular size of milk constituents, which increases the intermolecular interactions and imparts greater resistance to flow, thereby enhancing the viscosity and retention capacity [21].

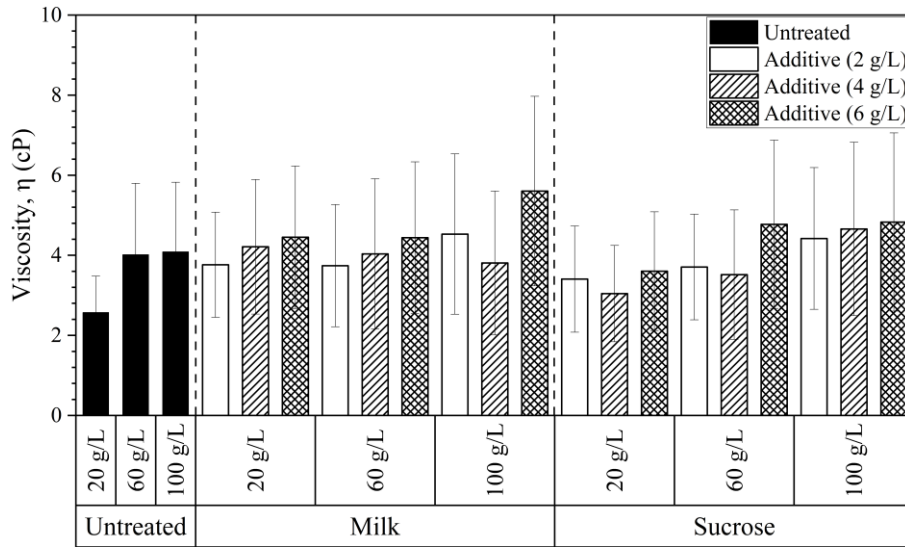
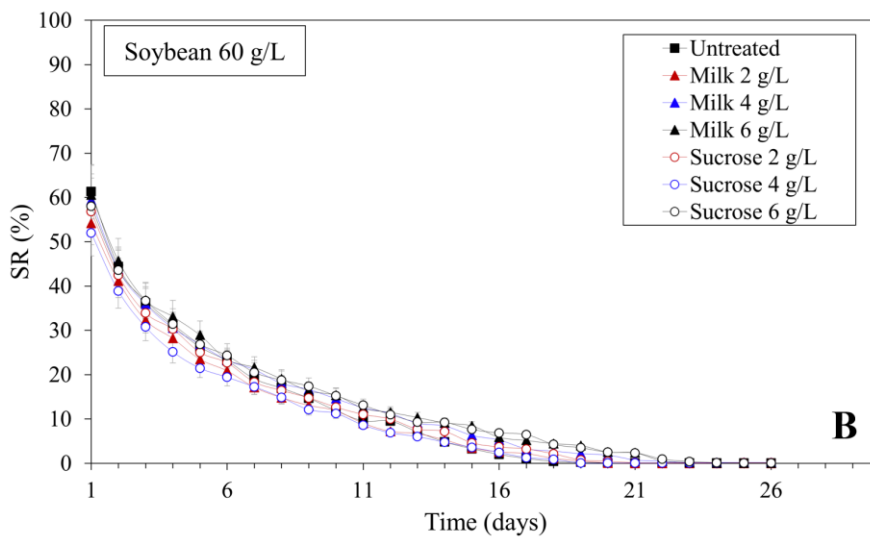
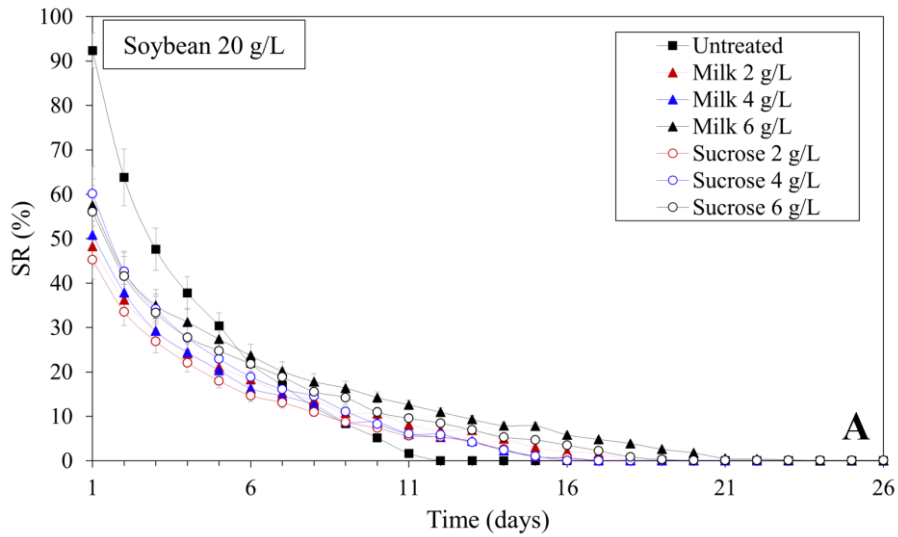


Figure 12. Viscosity of SCU-CP solutions



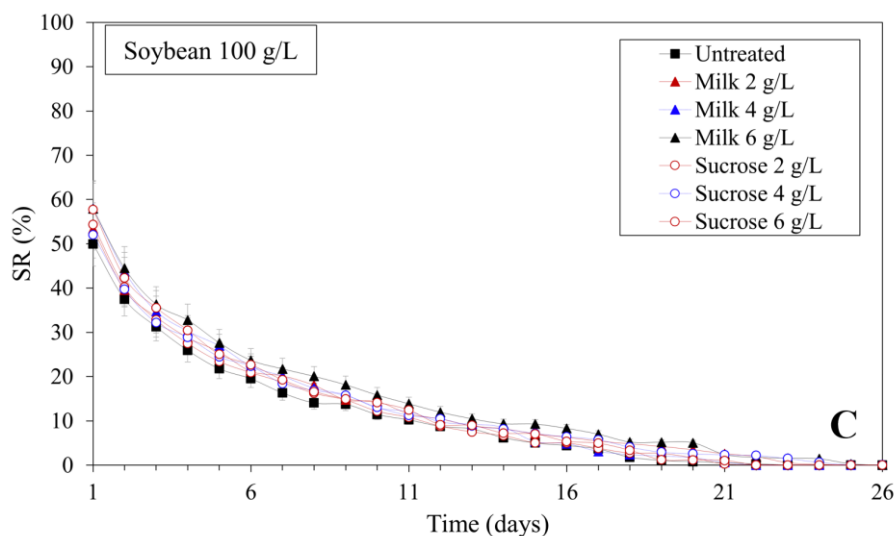


Figure 13. Saturation degree as a function of time for SCU-CP solutions with soybean concentrations of (a) 20 g/L, (b) 60 g/L, and (c) 100 g/L

3.3. Unconfined Compressive Strength (UCS)

An Unconfined Compressive Strength (UCS) test was conducted to determine the unconfined compressive strength (q_u) of sand samples treated with the SCU-CP solution. Testing was conducted using a compression machine after a seven-day curing period. The unconfined compressive strength (UCS) results in Figure 14 show that the addition of milk and sucrose increased the soil strength compared with the control at soybean extract concentrations of 20, 60, and 100 g/L. The UCS values of the control samples were 10.1 kPa (20 g/L soybean), 11.3 kPa (60 g/L soybean), and 13.3 kPa (100 g/L soybean). For the 20 g/L soybean concentration, the addition of 2.0, 4.0, and 6.0 g/L milk resulted in UCS values of 13.26, 11.38, and 19.33 kPa, respectively, whereas sucrose addition yielded 10.90, 11.22, and 10.01 kPa, respectively. At 60 g/L soybean, milk addition produced UCS values of 13.49, 15.73, and 19.07 kPa, whereas sucrose addition resulted in 11.19, 14.39, and 16.24 kPa, respectively. For the 100 g/L soybean concentration, the UCS values were 17.54, 18.18, and 21.34 kPa with milk and 16.25, 16.11, and 17.12 kPa with sucrose. Overall, the addition of 2.0–6.0 g/L milk enhanced UCS by approximately 60–90% (an increase of 7.8–9.2 kPa), whereas sucrose improved UCS by around 8–49% (an increase of 1.1–4.9 kPa).

Tirkolaei et al. [22] demonstrated that supplementing crude jack bean urease with milk powder significantly increased the efficiency of soil strengthening. This improvement was attributed to the organic molecules in milk, which likely act as enzyme-protective agents that maintain catalytic activity and promote a more effective calcite precipitation process. The organic compounds in milk, particularly proteins and long-chain sugars, are

assumed to help protect bacterial cells and extracellular enzymes by acting as nucleation sites and preventing their encapsulation within forming calcite crystals [27–28]. Moreover, sucrose contains hydroxyl groups that act as nucleation agents, promoting the transformation of amorphous or less stable calcium carbonate phases into calcite [25]. This transformation enhances crystal growth and cementation within the soil matrix, thereby improving its strength. Yang et al. [26] confirmed that the presence of nucleation agents such as sucrose reduces the vaterite content from 10.07% to 1.81–3.93%, indicating its role in facilitating calcite formation. Calcite is known to be a more stable and mechanically stronger polymorph than vaterite [27], resulting in denser cementation and stronger interparticle bonding, which contribute to higher soil strength.

Previous studies have reported that milk and sucrose effectively enhance calcite precipitation and soil strength, with strength improvements of approximately 33% (1167.23–1547.95 kPa) and 63% (176.6–287.7 kPa), respectively [8,26]. The lower UCS values compared to those in previous studies are mainly attributed to differences in soil gradation, reagent quality, and extraction methods. Previous studies used well-graded sand ($C_u = 7.48$, $C_c = 1.20$) and oven-dried soybean powder prior to extraction [8] as well as laboratory-grade reagents [26], whereas this study employed poorly graded sand ($C_u = 4.44$, $C_c = 0.80$) and technical-grade reagents with direct soybean extraction to represent practical conditions. Therefore, this study focused on the relative improvement in strength rather than the absolute UCS values, emphasizing the comparative effects of milk and sucrose on SCU-CP performance.

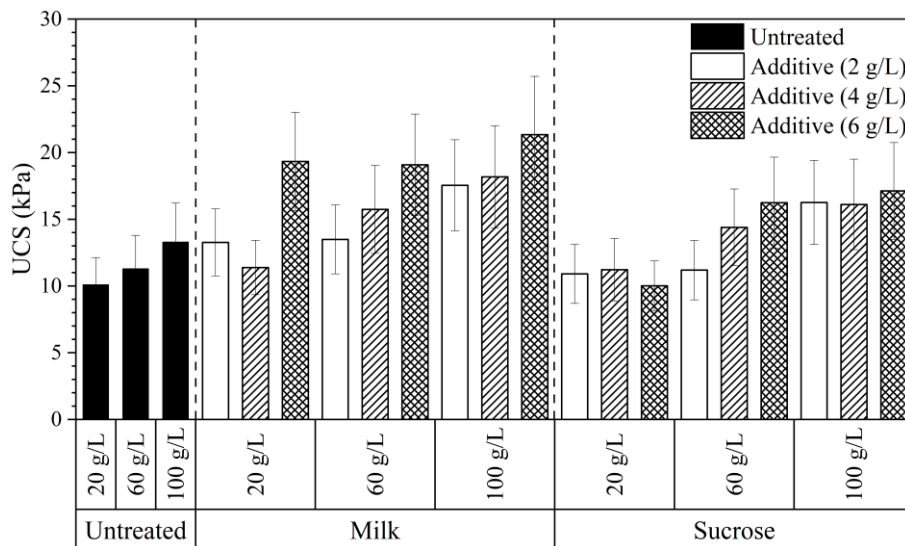


Figure 14. Unconfined compressive strength of untreated and treated samples

The improvement in the UCS was consistent with the results of the viscosity and hydrolysis rate tests. The addition of skim milk increased the viscosity of the SCU-CP solution, facilitating a more uniform distribution of calcium carbonate (CaCO_3) precipitates within soil pores, leading to a denser structure and higher strength. Furthermore, increased urease activity due to protein content enhances the rate of urea hydrolysis, accelerating CaCO_3 precipitation, which acts as a natural cementing agent [28]. Although sucrose contributed to increased nucleation sites, its relatively lower effect on solution viscosity rendered calcite distribution in the soil matrix less efficient than that in skimmed milk.

3.4. Calcite Distribution

Calcite distribution testing was conducted to quantify the amount and distribution of the calcite precipitate formed within the soil samples. The distribution of calcite at each soybean extract concentration is illustrated in Figure 15. A homogeneous distribution of calcite results in a more uniform presence throughout the soil matrix, thereby contributing to enhanced soil strength [14]. The calcite mass was analyzed at the top, middle, and bottom sections of each test specimen. The results indicated that at a concentration of 20 g/L, the calcite distribution tended to be uneven, with dominant accumulation in the bottom layer, particularly in the control and sucrose treatment samples. In the control (0.58% top, 1.12% middle, and 1.72% bottom) and sucrose 2 g/L (1% top, 1.06% middle, and 1.14% bottom) treatments, the calcite distribution was as follows: These findings are consistent with those of Pratama et al. [29], who used the SCU-CP method and reported calcite percentages of 3.3% in the bottom, 1.5% in the middle, and 0.9% in the top section. The addition of 6.0 g/L skim milk

began to produce a more balanced distribution, with a significant increase of up to 2.27-fold in the top layer (1.9% top; 1.98% middle; 1.94% bottom layer).

At a soybean concentration of 60 g/L, the calcite distribution improved further, indicated by near-uniform values, as seen in the 6.0 g/L sucrose treatment (1.62% top; 1.6% middle; 1.64% bottom), which showed a notable improvement compared with that of the control sample (0.68% top; 0.96% middle; 1.40% bottom). The top, middle, and bottom layers increased by 1.38-fold, 66.67%, and 17.14%, respectively. The most uniform distribution was observed at a soybean extract concentration of 100 g/L, especially with the addition of 6.0 g/L skim milk (2.16% top; 2.22% middle; 2.22% bottom), with increases in the top, middle, and bottom layers of 2.17, 1.58, and 0.85 times, respectively, compared to the control (0.68% top; 0.86% middle; 1.20% bottom).

Similarly, the addition of 6.0 g/L sucrose resulted in increases of 1.47, 1.00, and 0.41 times in the respective layers (1.68% top; 1.72% middle; 1.7% bottom). Higher concentrations of soybean extract enhance urease activity, facilitating the urea hydrolysis reaction and accelerating CaCO_3 precipitation throughout the soil pore volume [30]. Xu et al. [31] reported that urease activity increased from 3.18 IU/mL at 20 g/L to 4.23 IU/mL at 100 g/L, then declined to 3.55 IU/mL at 120 g/L. This indicates the existence of an optimal soybean extract concentration that maximizes enzyme effectiveness before the increase in viscosity hinders extraction efficiency. Elevated viscosity impedes solvent–substrate diffusion, slows mass transfer, and limits the contact surface between the enzyme and extraction medium. Consequently, although more raw material is present, the amount of active urease extracted is reduced [31].

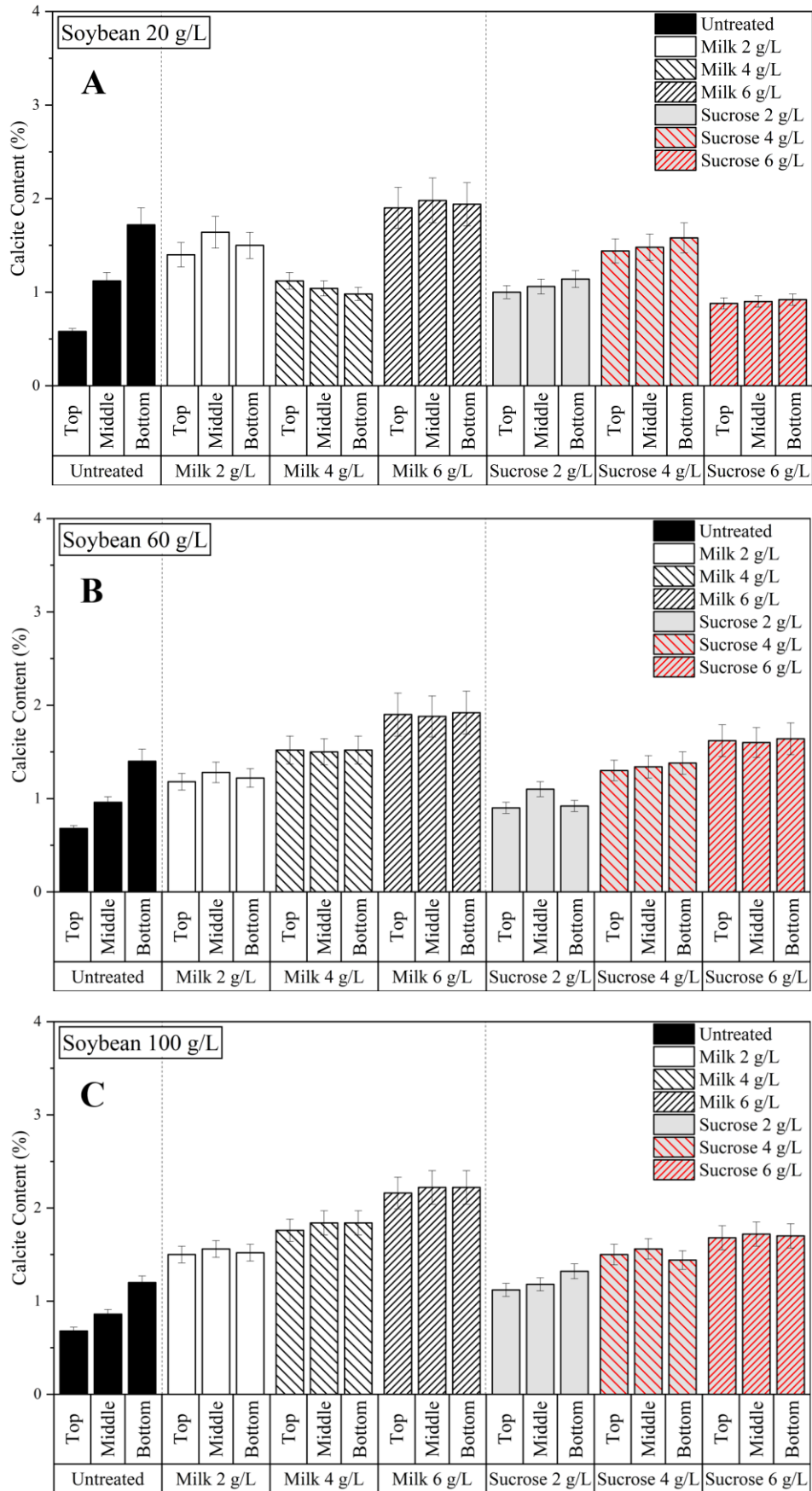


Figure 15. Calcite distribution with different soybean extract concentrations; (a) 20 g/L, (b) 60 g/L, (c) 100 g/L

The observed calcite distribution with sucrose addition aligns with the findings of Yang et al. [26], where sucrose addition through the EICP method increased the calcite content by 0.6–1.5%. The enhancement in calcite deposition was attributed to sucrose providing nucleation sites during CaCO_3 precipitation due to its hydroxyl ($-\text{OH}$) groups. These groups facilitate hydrogen bonding with calcium (Ca^{2+}) and carbonate (CO_3^{2-}) ions, forming active surfaces that stabilize the crystal precursors and promote nucleation [26]. Nucleation sites serve as the initial locations for the aggregation of Ca^{2+} and CO_3^{2-} ions, enabling the formation of calcite crystal nuclei [32]. Arab et al. [33] demonstrated that nucleation sites form active layers that direct CaCO_3 crystal growth into more compact and organized structures, in contrast to random and dispersed growth in the absence of such sites.

The calcite distribution results with milk addition in this study were higher than those reported by Almajed et al. [34], who recorded calcite percentages of 0.82% (top), 0.79% (middle), and 1.17% (bottom) in the cake. This variation was attributed to the use of higher calcium chloride concentrations in the current study. Yuan et al. [8] found that increased CaCl_2 concentrations enhance CaCO_3 precipitation ratios, although this effect diminishes beyond the optimal point. At high concentrations, excess Ca^{2+} inhibits urease activity, reduces urea hydrolysis, and subsequently lowers carbonate ion availability, which diminishes CaCO_3 precipitation [8].

A higher CaCl_2 concentration introduces more Ca^{2+} ions into the solution, increasing the likelihood of a reaction with carbonate ions and promoting CaCO_3 precipitation [8]. The observed enhancement in calcite precipitation is attributed to casein proteins in milk, which bind with calcium ions to form nucleation sites for calcite precipitation [11].

The distribution results were consistent with those obtained from the viscosity, water holding capacity (WHC), and unconfined compressive strength (UCS) tests. The solution with 6.0 g/L milk exhibited the highest values for all three parameters tested. The incorporation of additives increased the viscosity of the solution, which retarded calcite sedimentation and yielded a more uniform distribution. Furthermore, increased viscosity improved the soil WHC, prolonging moisture retention and extending the precipitation process. With a more homogeneous calcite distribution and better moisture preservation, the interparticle bonding was enhanced, contributing to the increased UCS of the treated soil.

4. Discussion

The results of calcite precipitation showed that the precipitation efficiency varied with soybean extract concentration, where 20 g/L produced the highest ratio (38.13%), decreased at 40 g/L (24.98%), and increased again at 60–100 g/L (31–33%). This pattern indicates that

increasing the soybean extract concentration does not necessarily increase the precipitation efficiency. At moderate concentrations, excessive insoluble organic matter may interfere with the nucleation and growth of calcite crystals, as undissolved residues can cover reactive surfaces and restrict ion interactions during the formation process. In contrast, at higher concentrations (60–100 g/L), improved homogeneity during mixing may reduce particle aggregation, allowing urease activity to remain effective and leading to more stable precipitation.

A high accumulation of organic residues may also reduce the quality of the resulting calcite by introducing impurities or altering the crystal morphology, which in turn affects the interparticle bonding strength within the treated soil. Therefore, further evaluation of the organic content, such as the measurement of total organic matter or insoluble residue, is necessary to confirm this hypothesis and determine the relationship between organic content and precipitation efficiency.

Calcium ions from CaCl_2 were the main reactants for calcite formation. Yuan et al. [8] reported that an increase in Ca^{2+} concentration initially led to a higher CaCO_3 precipitation rate owing to the greater availability of calcium ions reacting with carbonate ions produced via urea hydrolysis. Although the concentration of CaCl_2 was not independently varied in this study, the relatively higher CaCl_2 concentration used may have contributed to the improved precipitation efficiency observed compared to previous research. However, this assumption requires experimental verification because an excessive concentration of Ca^{2+} can inhibit urease activity. Further research should systematically vary the CaCl_2 concentration while maintaining a constant urease activity to identify the optimal balance between calcium ion availability and enzymatic performance.

Overall, the results indicate that the accumulation of organic residues in the soybean extract is a critical factor influencing both the efficiency and quality of calcite precipitation. Therefore, controlling the organic content in natural urease sources is essential for optimizing the SCU-CP process and ensuring consistent biocementation performance.

5. Conclusions

This study examined the influence of skim milk and sucrose on soil improvement using the Soybean Crude Urease–Calcite Precipitation (SCU-CP) method. The addition of these additives enhanced soil strength, with milk increasing the UCS by up to 90% and sucrose by up to 49%. The increased viscosity from milk and sucrose promoted a more uniform calcite distribution and improved water holding capacity, allowing complete urea hydrolysis and calcite formation throughout the soil matrix. These mechanisms resulted in denser cementation and stronger interparticle bonding.

Although the UCS values achieved in this study (a maximum of 21.3 kPa) remain relatively low for structural applications, they are sufficient for light geotechnical purposes, such as surface stabilization, erosion control, or dust mitigation. This demonstrates that the SCU-CP process, enhanced with natural additives, has practical potential for eco-friendly soil improvement, where moderate strength and environmental compatibility are prioritized. Future research should initially assess the organic content of the SCU-CP solution to clarify its role in calcite formation, followed by the optimization of the calcium chloride concentration to improve the calcite yield and bonding uniformity. Multiple treatment cycles may also be explored to further enhance soil strength and support potential field-scale applications.

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