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Bearing Capacity and Strength of Bacterial Soil Columns Full-Scale Tests

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Abstract

Infrastructure development often faces challenges due to soils with low bearing capacity, which can potentially cause instability and subsidence and threaten the safety of structures. Therefore, an efficient and environmentally friendly stabilization method is required. This study aims to evaluate the effectiveness of Microbial Induced Calcite Precipitation (MICP) in improving bearing capacity and soil strength through the formation of bacterial soil columns. This study employed a full-scale physical model test using 40 cm diameter and 200 cm deep soil columns filled with soil mixed with Bacillus subtilis, compacted, and cured for 56 days. The results showed significant improvements in the geotechnical characteristics of the soil, with CBR values increasing from 5.5% to over 12%, unconfined compressive strength reaching 345 kPa, and modulus of elasticity increasing to 12.5 MPa. Soil cohesion increased to 65 kPa, while internal friction angle increased from 10° to 34°. The novelty of this research is the application of MICP technology in the form of bacterial soil columns as an innovative, effective, and sustainable stabilization method to improve the mechanical properties of soft soils.

Keywords: Soil Stabilization; MICP; Biocementation; Bacterial Soil Column.

1. Introduction

Soils are fundamental in construction as the primary support medium for structural loads. Soil geotechnical properties, such as shear strength, compressibility, and plasticity, largely determine the capacity of the soil to withstand loads and the stability of overlying structures [1]. However, soft soils with low bearing capacity often cause geotechnical problems, such as subsidence and instability, which impact infrastructure reliability [2]. To overcome these problems, effective soil stabilization methods are necessary. Conventional methods in soil stabilization generally involve using additives such as cement, lime, and fly ash to improve soil strength and stability. Previous studies have shown that these additives can significantly improve the bearing capacity of soils, especially in high-salinity soils [3-5]. However, this method has negative environmental impacts, such as high carbon emissions due to cement and lime production and exploitation of non-renewable natural resources [6-8]. Therefore, recent research has begun to turn to more sustainable solutions, one of which is *microbial-based* soil stabilization through *Microbial-Induced Calcite Precipitation* (MICP).

MICP is an innovative technique that uses microorganisms such as *Sporosarcina pasteurii* and *Bacillus subtilis* to induce calcium carbonate ($CaCO_3$) precipitation in soil pores. The precipitated $CaCO_3$ serves as an adhesive between soil particles, thereby increasing the cohesion, stiffness, and shear strength of the soil [9-13]. Recent studies have shown that MICP can improve soil mechanical parameters several times compared to conventional stabilization methods [14-16]. In addition, MICP has environmental advantages as it produces no hazardous waste and can be

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applied to a wide range of soil types and environmental conditions [17, 18]. In recent studies, this technique has also been shown to reduce soil permeability, contributing to long-term soil stability [7, 19]. The effectiveness of microbial-based soil stabilization depends on various factors, such as the type of soil, the concentration of the bacterial solution, and the duration of curing. Some studies show that the optimal curing time for bacterial stabilization is around 28℃, during which bacterial biomineralization activity is at its peak [20, 21]. In addition, soil moisture content also plays a vital role in the effectiveness of MICP, as it affects nutrient diffusion as well as the survival of the bacterial community [22, 23].

A notable field application of MICP technology is the use of bacterial soil columns, designed to improve soft soils' bearing capacity. This method is based on the concept of soil improvement with columnar elements, such as stone columns and sand columns, which have been widely used in geotechnical engineering [24, 25]. Stone columns can significantly reduce settlement in soft clay soils but have the disadvantages of limited reliance on natural aggregates and environmental impacts from material extraction [26]. Meanwhile, sand columns can increase soil-bearing capacity by up to 30% under certain conditions but are susceptible to internal cohesion degradation due to increased water table [27]. In contrast to these conventional methods, MICP-based bacterial soil columns offer a more environmentally friendly and sustainable approach. This method involves mixing a bacterial solution into the soil, which is then inserted into a borehole (bore pile) and compacted to form a stable column. The biomineralization process by bacteria will produce $CaCO_3$ precipitates, which increase soil strength and cohesion [7, 9].

Although various studies have addressed the effectiveness of MICPs in soil stabilization, there are still some gaps that need to be addressed. Most previous studies focused on laboratory-scale or small physical models, limiting validation under complex field conditions [13]. In addition, factors such as variations in soil type, environmental conditions, and duration of curing have not been fully assessed in full-scale applications [11]. This study aims to fill the gap by conducting an experimental evaluation of a full-scale MICP-based bacterial soil column. The study will evaluate how various soil geotechnical parameters, such as unconfined compressive strength (UCS), modulus of elasticity, soil cohesion, and internal friction angle, change after applying bacterial soil columns with varying curing times up to 56 days. With this approach, this research provides a deeper understanding of the mechanism of microbial-based soil improvement and experimental data that can be used in the design and implementation of MICP-based stabilization methods in real construction projects. Given the growing awareness of the environmental impact of conventional construction practices, developing more environmentally friendly and sustainable solutions is becoming increasingly important. MICP-based bacterial soil columns are a promising alternative to improve the bearing capacity of soft soils without causing significant negative impacts on the environment.

2. Materials and Methods

2.1. Materials

The bacterium used in this study was *Bacillus subtilis*, produced in the Microbiology Laboratory, as shown in Figure 1. *Bacillus subtilis* is a type of Gram-positive bacteria that is rod-shaped (bacillus) and can form oval endospores in the center. Endospores are a survival phase produced by some bacteria, such as Bacillus and Clostridium, when environmental conditions are unfavorable. These endospores resist extreme conditions, including high temperatures, drought, toxic chemical compounds (disinfectants, antibiotics), and UV radiation. Endospores represent the dormant phase, allowing survival under harsh conditions until environmental conditions become more favorable. *Bacillus subtilis* is 2-3 µm long and 0.7-0.8 µm wide. *Bacillus subtilis* can live in conditions with or without oxygen, so it is called a facultative anaerobic microorganism. Figure 1 displays the samples used in this study. (a) The original soil sample was tested to determine its physical properties, including water content, specific gravity, Atterberg limits, sieve analysis, compaction, and mechanical characteristics through Unconfined Compression Test (UCT), Direct Shear Test, and California Bearing Ratio (CBR) test. (b) The bacterial solution containing Bacillus subtilis was prepared. (c) The growth medium (B4) consisted of 20 g urea, 3 g Nutrient Broth, 2.12 g $NaHCO_3$, 4.14 g $CaCl_2$, and 10 g NH_4Cl.

(a) (b) (c)

(d)

(e)

Figure 1. Testing Sample, (a) media material B4, (b) bacteria Bacillus subtillis, (c) bacteria culture equipment, (d) original soil, (e) soil after mixing with bacteria

2.1.1. Characteristics of Soil

Based on Table 1, the physical and mechanical properties of untreated soil were analyzed. The specific gravity of 2.72 suggests a high-density mineral composition, typical of clay-dominated soils (48%). The moisture content (w) of 50% and degree of saturation (Sr) of 89% indicate that the soil is close to saturation. This is relevant to environments that have high rainfall or shallow groundwater conditions. The soil composition is dominated by the clay fraction at 48%, with a small fraction of sand at 24% and silt at 28%. This indicates that the soil has high cohesive characteristics that tend to be plastic and difficult to consolidate. The liquid limit (LL) of 61% and plastic limit (PL) of 27% resulted in a plasticity index (PI) of 34%. This value indicates a high plasticity clay-type soil according to the CH soil classification (USCS). These expansive properties are critical considerations for construction.

Table 1. Soil Characteristics

Testing	Testing Results	Unit	Testing Standards
Physical Properties Testing			
Water Content	50.1	%	ASTM D-2216-98
Specific Gravity (*GS*)	2.72		ASTM 0854-14
Sieve Analysis			
a. *Gravel*	0	%	ASTM D7928 - 17 ASTM C117 - 13
b. *Sand*	24,0	%	
c. *Silt*	27.9	%	
d. *Clay*	48.1	%	
Atterberg Limits			ASTM D4318 - 10
a. *Plastic Limit* (*PL*)	27	%	
b. *Liquid Limits* (*LL*)	61	%	
c. *Plastic Index* (*PI*)	34	%	
d. *Shrinkage Limit* (SL)	18	%	
Soil Classification			
AASHTO Classification	A-7-6		M 145-91 (2004)
USCS Classification	CH		ASTM D 2487 - 17
Mechanical Properties Testing			
Compaction			ASTM D1557-02
a. Maximum dry density	13.2	kN/m^3	
b. Optimum Water Content	31	%	
CBR Test			ASTM D-1883
CBR Unsoaked	5,5	%	
CBR Soaked	2,7	%	
Unconfined Compression Test			ASTM D2166-06
UCS	66.4	kN/m^2	
Modulus of elasticity (E)	4.43	MPa	
Direct Shear Test			ASTM D3080M-11
Cohesion (C)	26.5	kPa	
Internal friction angle of soil	10	°	

The particle size distribution curve is depicted in Figure 2.

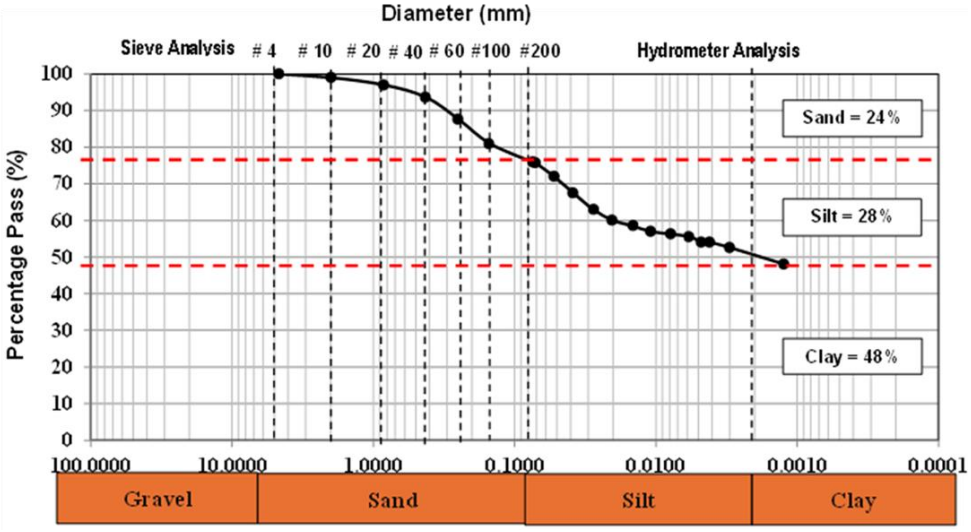


Figure 2. Particle size distribution curve

2.1.2. B4 Media and Bacterial Growth

B4 medium is the medium required for bacterial growth. The materials needed to make 1 liter of B4 media are 1 liter of water mixed with 20 grams of urea, 3 grams of nutrient broth, 2.12 grams of $NaHCO_3$, 4.14 grams of $CaCl_2$, and 10 grams of NH_4Cl in an Erlenmeyer flask. The conical flask was covered with cotton, wrapped with aluminium foil paper, and then tied with rubber. The flask was then placed in a semi-automatic autoclave machine for sterilization. This machine works as a steam sterilizer, so water must be added to work correctly. The sterilization process is performed at a temperature of 121ºC for 15 minutes at a pressure of 1 atm. After sterilization, the bacteria are inoculated by mixing the bacterial isolate into the B4 media liquid. This inoculation must be performed in a Laminar Airflow unit with UV light. This is to prevent bacterial contamination and maintain sterility. Once inoculation is complete, the shaking process is performed. This process is performed in a special shaking room. It takes 72 hours or 3 days.

2.2. Research Methods

The research employed a quantitative method based on field data from physical model tests. The research was designed and implemented systematically and thoroughly, as shown in Figure 3. Soil physical and mechanical properties were tested according to ASTM testing standards. Likewise, mechanical tests for soil-bacteria column samples, such as Dynamic Cone Penetrometer (DCP), Unconfined Compression Test (UCT), and Direct Shear Test (DST), were performed according to ASTM standard procedures.

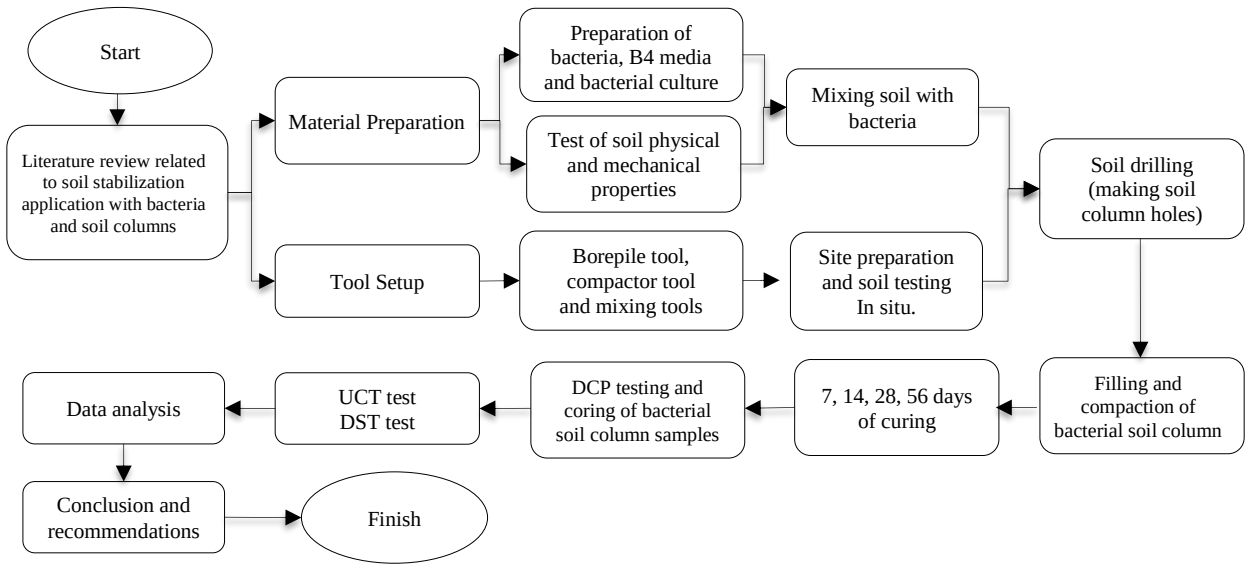


Figure 3. Research process flow

2.2.1. Mixing Soil with Bacteria

Mixing the soil with the bacterial solution was carried out in several steps. Tools and materials were prepared in advance, including a 50 kg capacity molen, a 16-liter sprayer, scales, and other needed materials. The materials needed for a mixture consisted of 2.1 kg of bacteria with a 3-day-old bacterial culture, 43.8 kg of soil with a moisture content of 25%, and additional water if the soil moisture content was less than 25%. The 2.1 kg of bacteria was weighed and added to the sprayer as needed. The molen was made sure to be clean before the soil was gradually added until it reached 43.8 kg. The molen was then turned on, and the mixture of bacteria and water was sprayed slowly and evenly onto the stirred soil until all the bacteria solution in the molen was used up. The molen was allowed to rotate for 15 minutes to ensure that the mixture was evenly distributed, and the results were checked to ensure no lumps or unmixed parts of the soil.

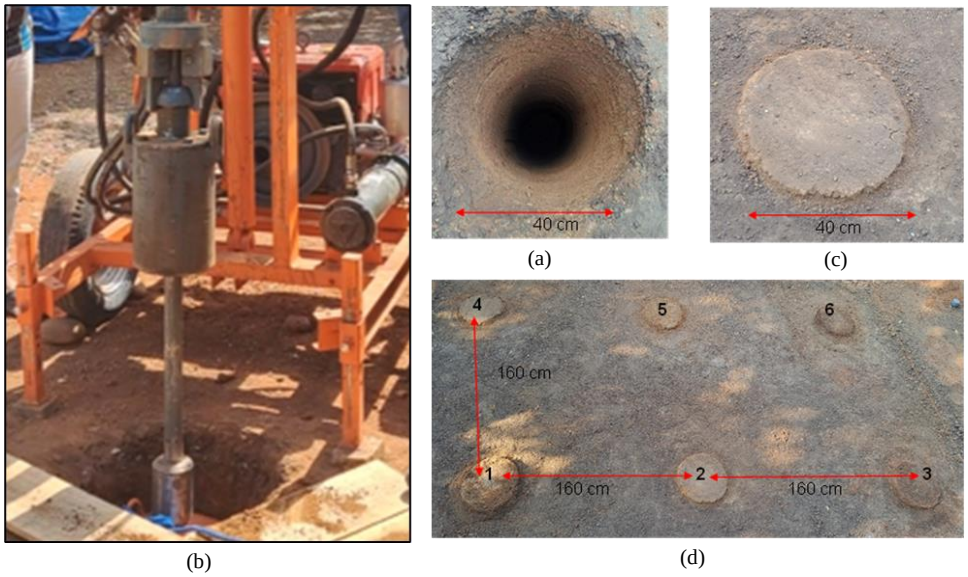
2.2.2. Making Boreholes/Columns (Drilling)

The drilling process for the soil-bacteria column was performed using a drillpile rig machine tool with a 40 cm diameter drill, as shown in Figure 4. The drill site was prepared with the drill points marked according to the plan. Then, the drill was placed over the point in a stable and aligned position. Drilling was performed from the ground surface to a depth of 200 cm. Upon completion, the borehole was cleaned of any remaining soil material to ensure a clean borehole. The depth and diameter of the borehole were again checked with a gauge to ensure it was in accordance with the plan.

Figure 4. Drilling process

2.2.3. Filling and Compaction of Bacterial Soil into the Borehole

The process of filling and compacting the bacterial soil in the column was performed using a 63.5 kg compactor equipped with an impact mat and a compactor root, as shown in Figures 5 and 6. Filling the borehole with soil-bacteria material was done in layers, each filled with 22.95 kg of soil-bacteria. The soil bacteria was placed in the column, leveled, and compacted with a compactor until the thickness of each layer reached 10 cm and the soil no longer shrank significantly when compacted. This process was repeated for each subsequent layer until a total depth of 200 cm was reached, ensuring that each layer had the appropriate thickness and density.



(a) (c)

(b) (d)

Figure 5. The compaction process of column

Figure 6. Coring for bacterial soil sampling

2.2.4. *Dynamic Cone Penetrometer* Testing and Coring of Samples in the Bacterial Soil Column

Dynamic Cone Penetrometer (DCP) tests to determine field CBR were conducted at 7, 14, 28, and 56-day intervals after burial. The DCP test was placed on top of the soil-bacteria column, and the penetrometer rod was inserted into the soil according to ASTM procedures. The impact tool was dropped from a specified height, and the number of impacts was recorded for each specified depth until it reached 100 cm, as shown in Figure 7. The measurement results at each depth were recorded to evaluate the bearing capacity of the column, and the data were analyzed to determine the field CBR value of the bacterial soil column. Sampling (coring) with a core drill tool, as shown in Figure 7, with the core drill tool positioned above the soil-bacteria column to be sampled. The sampling of the soil-bacteria column is divided into three sections: the upper section with a depth of 0-65 cm, the middle section with a depth of 65-130 cm, and the lower section with a depth of 130-195 cm, as shown in Figure 7. Undisturbed samples are carefully collected from each depth to maintain their integrity for further testing.

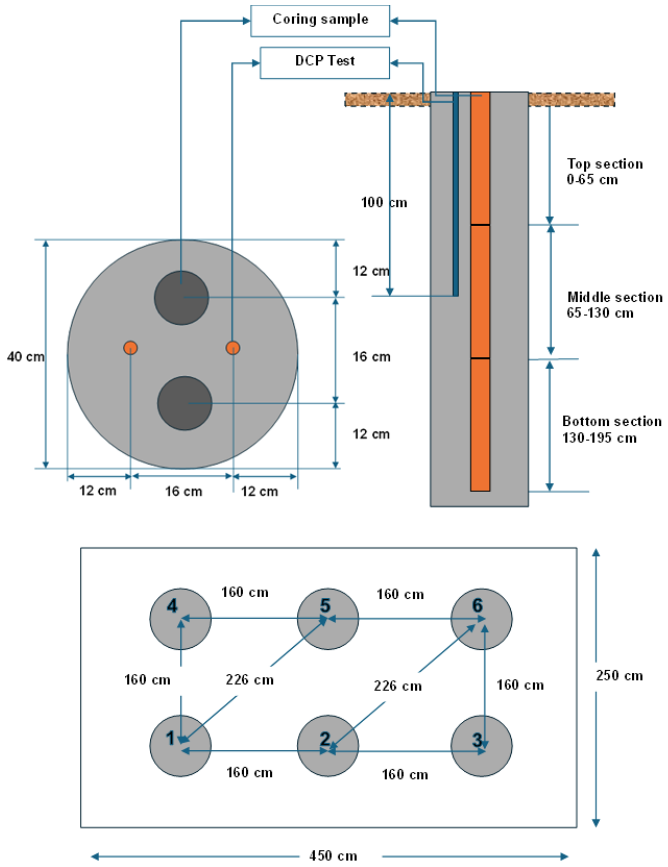


Figure 7. Details on DCP testing and sampling locations

3. Results and Discussion

3.1. Dynamic Cone Penetrometer Test Results

A summary of the Dynamic Cone Penetrometer (DCP) test results is shown in Figure 8. The figure shows the relationship between the cumulative number of blows and cumulative penetration in the soil-bacteria column tests at 7, 14, 28, and 56 days of curing compared to the untreated soil. The curve for the untreated soil showed high cumulative penetration with relatively few impacts, reflecting low bearing capacity and weak resistance to penetration. In contrast, the soil-bacteria column showed an increase in penetration resistance with increasing curing time. At the 7-day curing period, the soil resistance began to increase compared to the untreated soil, indicating that the initial biomineralization process had improved the mechanical properties of the soil. The resistance became more significant during the 14-day curing period, indicating improved bonding between soil particles through calcium carbonate precipitation. The 28-day curing curve shows a much higher increase in resistance, reflecting the active phase of biomineralization where calcium carbonate precipitation reaches a significant volume. At the 56-day curing period, the curve becomes steepest, indicating maximum resistance to penetration, reflecting optimal soil stabilization. These results indicate that bacterial soil stabilization effectively improves the bearing capacity and mechanical strength of soils. The progressive increase in penetration resistance with increasing curing time indicates that the biomineralization process significantly strengthens the soil structure, making it more suitable for construction applications.

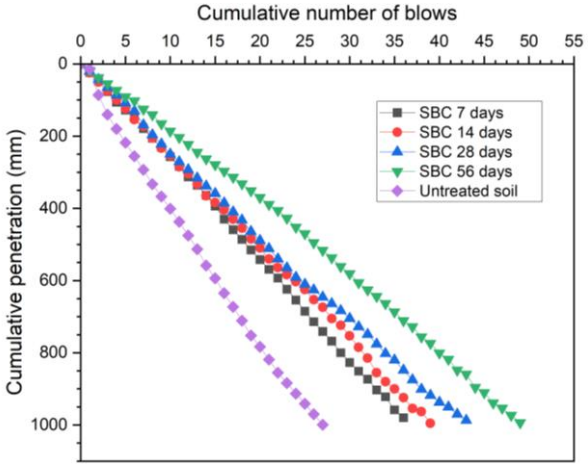


Figure 8. The relationship between the number of blows and the decrease based on the curing time

Figure 9 shows that the bacterial stabilization of the soil column significantly increased the California Bearing Ratio (CBR) value compared to the untreated soil. The CBR value of the untreated soil stabilized at 5.5%, while the soil-bacteria column showed an increase in CBR value from approximately 8% at 7 days curing to more than 12% at 56 days curing. The most significant increase occurred between 7 and 28 days, which is the active period of biomineralization, during which bacteria produce calcium carbonate ($CaCO_3$) that strengthens soil structure. After 28 days, the increase is slower and reaches its optimum state at 56 days. With an increase in bearing capacity of more than twice that of the original soil, bacterial stabilization proved effective for applications such as lightweight foundations and pavements on sites with soft soil conditions. Sufficient curing time is an important factor in the success of the stabilization process, and further research is needed to evaluate the long-term stability and optimization of this method for different environmental conditions.

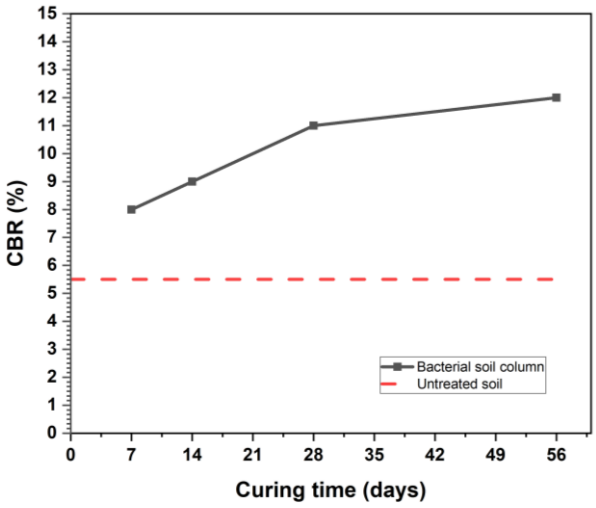


Figure 9. Relationship between curing time and CBR value of bacterial soil column

3.2. Unconfined Compression Test Result

Table 2 shows a recapitulation of the unconfined compressive strength (q_u) and modulus of elasticity (E) test results of bacteria-stabilized soil columns with curing times of 7 days, 14 days, 28 days, and 56 days, compared to untreated soil.

Table 2. Recapitulation of Unconfined Compression Test Results

Sample			Parameters	
	Curing time (days)	Sample depth (cm)	q_u (kN/m^2)	E (MPa)
Soil Bacterial Column	7	0-65	219	9.94
		65-130	222	10.12
		130-195	230	10.00
		Average	224	10.02
	14	0-65	288	11.07
		65-130	301	11.17
		130-195	301	10.76
		Average	297	11.00
	28	0-65	324	12.02
		65-130	319	11.84
		130-195	345	12.78
		Average	330	12.21
	56	0-65	334	12.39
		65-130	347	12.41
		130-195	354	12.66
		Average	345	12.49
Untreated Soil			66	4.43

Figures 10 to 12 show the relationship between Axial Strain (ε) and Axial Stress (σ) for various curing times, namely 7 days, 14 days, 28 days, and 56 days. In general, it can be seen that the longer the curing time, the more the value of axial stress tends to increase. This is shown by the higher peak value of Axial Stress at 56 days of curing compared to shorter curing. In addition, the graph shows a consistent pattern, i.e., Axial Stress increases along with the increase in Axial Strain until it reaches a peak, then decreases after passing the peak point, which indicates the material begins to collapse. At 7 days of aging, the peak value of Axial Stress is still relatively low, indicating that the material has not fully matured. Twenty-eight days of curing showed a significant increase in strength, while 56 days provided optimal results with the highest peak Axial Stress value. In addition, the longer curing time also allows the material to withstand more significant deformation (strain) before reaching collapse, as seen from the rightward shift of the graph peak. Practically speaking, these results indicate that sufficient curing time (at least 28 to 56 days) is highly recommended to achieve optimal material performance. The tested materials have characteristics suitable for construction applications that require maximum strength and long-term stability. With adequate curing, the materials can perform better in resisting axial loads.

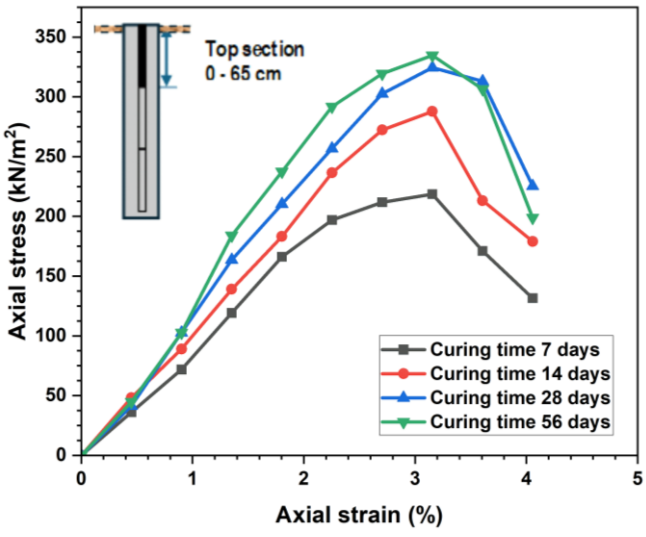


Figure 10. Relationship between axial stress vs. deformation when applied on the bacterial soil column

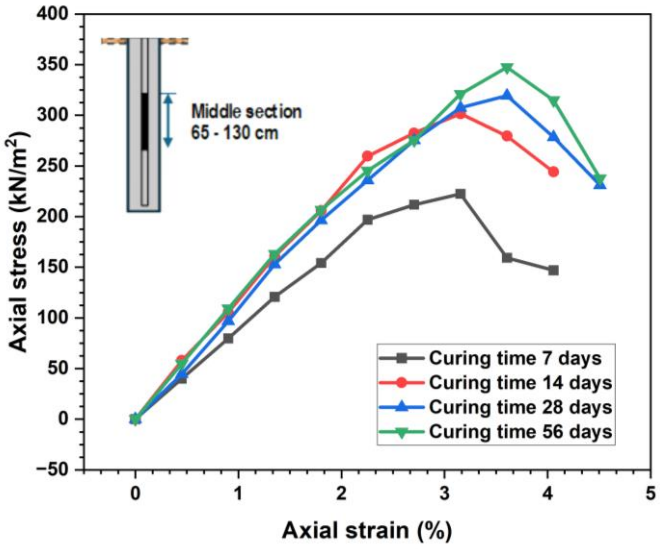


Figure 11. Relationship between axial stress vs. deformation when applied on the bacterial soil column

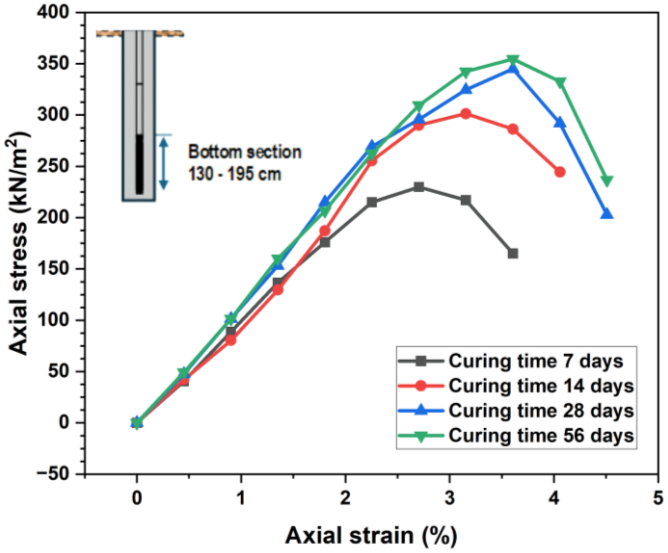


Figure 12. Relationship between axial stress vs. deformation when applied on the bacterial soil column

Figure 13 shows the relationship between curing time (in days) and the unconfined compressive strength (qu value of the bacterially stabilized soil compared to the untreated soil. On the 7th day, the average q_u column value of the bacteria-stabilized soil reached about 224 kPa, showing a significant increase compared to the untreated soil, which was only 66 kPa. This indicates the initial effect of bacterial activity in producing calcium carbonate ($CaCO_3$) through the biomineralization process. On day 14, q_u increased to 297 kPa, indicating that biomineralization was actively taking place, with the formation of calcium carbonate further strengthening the soil structure. The significant increase continued until day 28, when qu reached 330 kPa, reflecting the improved mechanical strength of the soil. On day 56, qu peaked at 345 kPa, close to the optimal condition for soil stabilization, with the rate of increase slowing down, indicating that the biomineralization process was approaching saturation.

Compared to the untreated soil, which only had a qu of 66 kPa, the bacteria-soil column at day 56 showed an almost five-fold increase in strength. This proves the success of the bacterial stabilization method in strengthening the soft soil, making it more capable of bearing loads. The graph also shows a significant increase in qu from 7 to 28 days, the active period of biomineralization. After 28 days, the increase slows down, indicating that the stabilization has reached a saturation level. Bacterial activity results in calcium carbonate precipitation that strengthens the bonds between soil particles, thus directly increasing soil strength. These findings demonstrate the effectiveness of bacterial stabilization as an innovative solution to enhance soft soils and improve their bearing capacity.

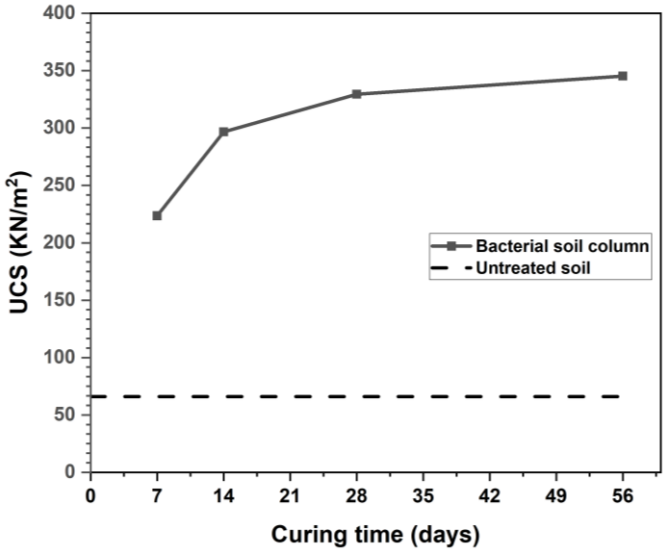


Figure 13. Relationship between curing time and the average value UCS of the bacterial soil column

Figure 14 shows the relationship between the curing time and the modulus of elasticity (E) value of the bacteria-stabilized soil column compared to the *untreated* soil, illustrating the effectiveness of the bacteria biomineralization process in increasing soil stiffness. On day 7, the average modulus of elasticity (E) value of the bacterial soil column reached 10.02 MPa, significantly improving over the untreated soil with an E of 4.43 MPa. This marks the beginning of the successful biomineralization process by bacteria, which produces calcium carbonate ($CaCO_3$) to strengthen the soil structure. On day 14, the E value increased further to 11 MPa, indicating that microbial activity continued to strengthen the soil. The E value continued to increase until it reached 12.21 MPa on day 28, reflecting a significant increase in soil stiffness during the curing period. On day 56, the E value reached 12.49 MPa, close to the optimal stabilization condition, with the increase beginning to slow down after day 28.

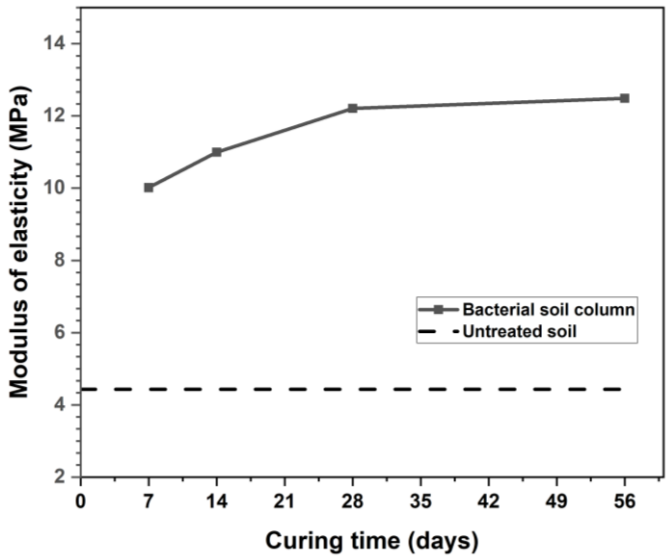


Figure 14. Relationship between curing time and average modulus of elasticity of bacterial soil column

The *untreated* soil, with a modulus of elasticity of 4.43 MPa, had a low elastic capacity and was prone to deformation under load. In contrast, the bacterially stabilized soil column showed an almost threefold increase in modulus of elasticity compared to the untreated soil at day 56, proving the effectiveness of this stabilization method. The graph also shows a significant increasing trend from 7 to 28 days, reflecting the active phase of bacterial biomineralization. After 28 days, the rate of increase slowed down, approaching stability at day 56. The biomineralization process produced by bacteria strengthens the bonds between soil particles, thus making the soil more rigid and resistant to elastic deformation. These results prove that bacterial stabilization can be used as an effective solution to increase the stiffness of soft soils in construction applications such as lightweight foundations and pavements.

3.3. Direct Shear Test Result

The results of testing the shear strength parameters of bacterial soil columns at various curing times (7, 14, 28, and 56 days), compared to untreated soil, can be seen in Table 3. The parameters tested include cohesion (C), internal friction angle (ϕ), and shear stress (τ) at three normal stress levels (35 kPa, 70 kPa, and 140 kPa). The results of this test provide an overview of the increase in soil shear strength due to bacterial stabilization.

Table 3. Recapitulation of Direct Shear Test results

Sample			Parameters		Normal stress, σ (kN/m²)		
	Curing time (days)	Sample depth (cm)	C (kPa)	ø (°)	35	70	140
Bacterial Soil Column	7	0-65	33	17	45	52	76
		65-130	36	18	46	60	80
		130-195	35	14	45	51	70
		Average	35	16	45	54	75
	14	0-65	50	22	66	73	106
		65-130	50	24	64	84	111
		130-195	49	19	63	71	98
		Average	50	22	64	76	105
	28	0-65	61	29	80	99	138
		65-130	60	32	85	99	148
		130-195	64	30	87	99	146
		Average	61	30	84	99	144
	56	0-65	67	33	93	108	160
		65-130	65	37	94	111	170
		130-195	64	32	85	108	151
		Average	65	34	91	109	160
Untreated soil			26	10	34	38	52

Figure 15 shows the increase in the average cohesion (C) value of the bacterial soil compared to the untreated soil over the curing period of up to 56 days. The untreated soil had a low cohesion value of 26 kPa, reflecting weak interparticle bonding and an inability to resist shear forces. After bacterial stabilization, the cohesion value increased to 35 kPa on day 7, indicating the initial effect of the biomineralization process in improving soil structure. This increase continued until day 14, when the cohesion value reached 50 kPa, reflecting microbial activity that continued to produce calcium carbonate ($CaCO_3$) to strengthen the bonds between soil particles. On day 28, the cohesion value increased to 61 kPa, more than double that of the untreated soil. On day 56, the cohesion value peaked at 65 kPa, indicating that the stabilization process had reached optimal. The figure also shows that the most significant increase in cohesion occurred during the 7 to 28 days of curing, the active phase of biomineralization. After the 28th day, the rate of increase began to slow down, approaching optimal stability on the 56th day. The results of this study prove that bacterial stabilization significantly increases soil cohesion, which makes the soil better able to withstand shear forces. This significant improvement makes the stabilized soil suitable for various engineering applications such as slope stabilization, lightweight foundations, and pavements. The optimum curing time for best results is between 28 and 56 days, making this method an effective and sustainable solution for improving soft soils.

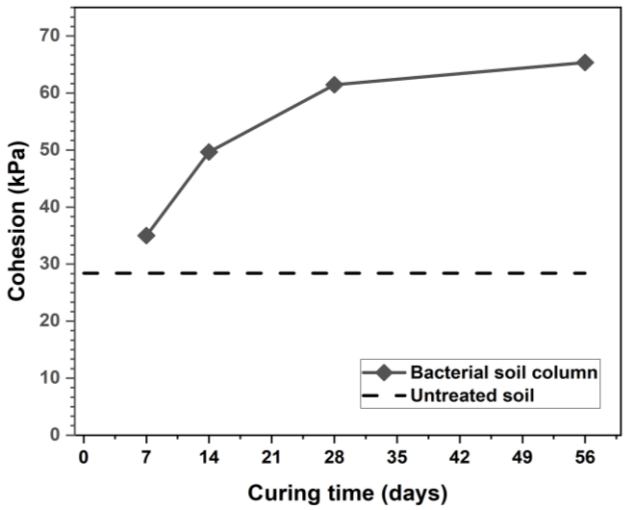


Figure 15. Relationship between curing time and average cohesion value of bacterial soil column

Figure 16 shows the increase in the internal friction angle (ϕ) value of the bacterially stabilized soil compared to the untreated soil during the curing period of up to 56 days. The untreated soil had a low internal friction angle value of 10°, reflecting its limited ability to resist shear before collapse. In the bacterially stabilized soil, the ϕ value increased to 16° on day 7, indicating the initial effect of the biomineralization process, which improved the bonding between soil particles. On day 14, the ϕ value increased further to 22°, reflecting microbial activity that continued strengthening the soil structure by forming calcium carbonate ($CaCO_3$). A significant increase occurred until day 28, when ϕ reached 30°, while on day 56, the ϕ value peaked at 34°, which is close to optimal conditions. This graph shows that the most significant increase in the internal friction angle occurs from 7 to 28 days, which is the active phase of biomineralization. After the 28th day, the rate of increase slowed down, indicating that the stabilization process was approaching saturation. These results show that bacterial stabilization significantly increased the internal friction angle of the soil from 10° to 334°, more than four times the value of the untreated soil. With this increase, the stabilized soil has a much greater ability to resist shear loads, making it highly suitable for applications such as slope stabilization, lightweight foundations, and pavements. This research confirms the importance of curing time, especially up to 28 days, to achieve optimal results in the bacterial stabilization process.

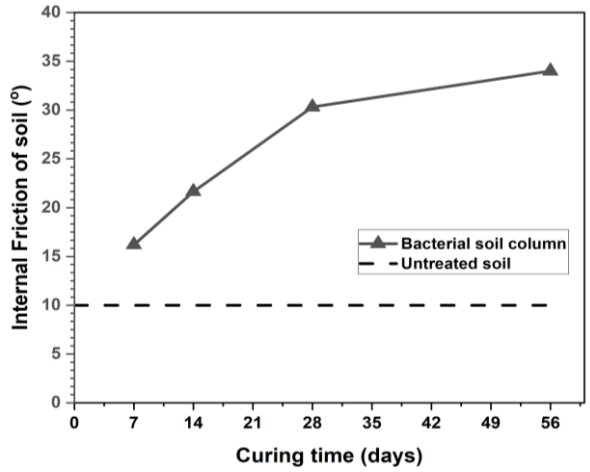


Figure 16. Relationship between curing time and average internal friction angle of the bacterial soil column

Figure 17 shows the relationship between curing time and shear stress in a soil-bacteria column consisting of three sections: top section, middle section, and bottom section, under three loading conditions (Load 1 = normal stress 35 kN/m^2, Load 2 = normal stress 70 kN/m^2, and Load 3 = normal stress 140 kN/m^2). The results showed that the shear stress increased significantly as the curing time increased from 7 to 56 days, with the greatest increase occurring at the bottom of the column, which received the highest load. The bottom of the column reached a maximum shear stress of more than 160 kN/m² after 56 days of curing under load 3. This reflects the successful biomineralization process by bacteria producing calcium carbonate ($CaCO_3$) to strengthen the soil structure. The most significant increase occurred up to 28 days of curing, after which the rate of increase slowed, indicating that stabilization had reached optimal conditions. In addition, the figure shows that the shear stress increases with increasing load, indicating that the soil-bacteria column can withstand greater loads as the curing time increases. This research demonstrates the effectiveness of the bacteria-based soil stabilization method in improving the shear strength and capacity of the soil to support infrastructure loads, making it a sustainable solution for soft soil reinforcement.

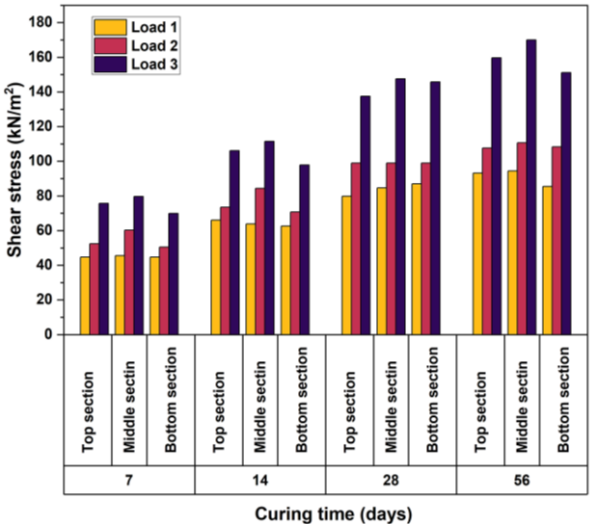


Figure 17. Relationship between curing time and shear stress in bacterial soil columns divided into three sections under three different loading conditions

Figure 18 shows the relationship between curing time and shear stress of bacterial soil column (SBC) and untreated soil (US) under three loading conditions (Load 1 = normal stress 35 kN/m^2, Load 2 = normal stress 70 kN/m^2 and Load 3 = normal stress 140 kN/m^2). The results showed that the shear stress of the bacterial soil column increased significantly as the curing time increased, with the greatest increase occurring between 7 and 28 days, which is the active phase of the bacterial biomineralization process that produces calcium carbonate ($CaCO_3$). At day 56, the maximum shear stress of the bacterial soil column for load 3 reached more than 160 kN/m², much higher than that of the untreated soil, which came only about 52 kN/m² for the same load. The significant difference in shear stress between the bacterial soil column and the untreated soil confirms the effectiveness of the bacterial stabilization method in improving soil shear strength, making it an efficient solution for improving soft soils. The optimal curing time for maximum results was up to 28 days, during which the most significant increase in shear stress occurred, with further stability achieved by day 56.

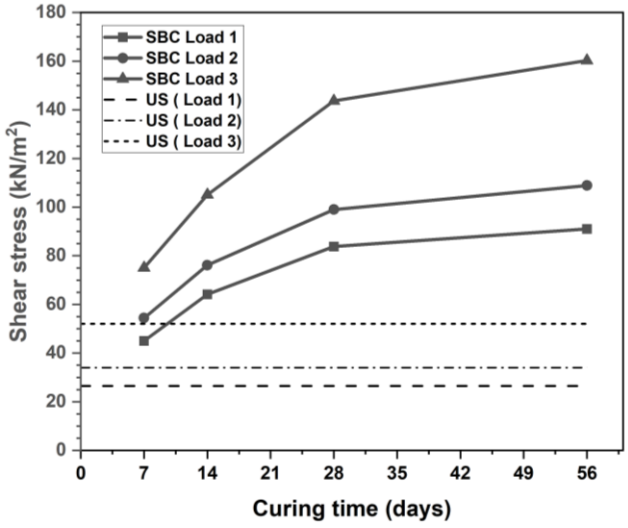


Figure 18. Relationship between curing time and average shear stress in the column of bacterial soil and untreated soil under three different loading conditions

4. Discussion

This study showed that soil stabilization using the Microbial Induced Calcite Precipitation (MICP) method through soil-bacteria columns significantly improved various soil mechanical parameters compared to *untreated* soil. This improvement is in line with previous studies, which confirmed that the MICP technique could effectively improve the bearing capacity, shear strength, and elastic modulus of soil [14, 28].

4.1. Improved Soil Bearing Capacity (CBR)

Dynamic Cone Penetrometer (DCP) test results showed that the California Bearing Ratio (CBR) value increased from 5.5% in the original soil to more than 12% after 56 days of curing. This indicates a more than twofold increase in bearing capacity. This increasing trend is similar to the results of Liu et al. (2021), who found that the MICP method can increase the CBR value up to 200% compared to untreated soil [28]. In this study, the most significant increase occurred between 7 to 28 days, the active phase of biomineralization, before finally reaching stability after 56 days. Compared to conventional stabilization methods using lime and cement, the MICP method is more environmentally friendly and produces more sustainable stabilization without high carbon emissions than chemical-based methods [29].

4.2. Increase in Free Compressive Strength (qu) and Modulus of Elasticity (E)

Unconfined Compression Test (UCT) showed that the free compressive strength (qu) increased from 66 kN/m^2 in the original soil to 345 kN/m^2 after 56 days of curing, which is more than a 4-fold increase. A similar increase was also seen in the modulus of elasticity (E), which rose from 4.43 MPa to 12.49 MPa. This increase indicates that the MICP technique successfully strengthened the bond between soil particles through the precipitation of calcium carbonate ($CaCO_3$), which functions as a natural binder in soil. This is in line with the research of Hasriana et al. (2018), which showed that bacterial stabilized soil had an increase in elastic modulus up to 3 times compared to the original soil [30]. However, compared to the results of Zheng et al. (2022), who found that sandy soils showed an increase in elastic modulus of up to 15 MPa, this study showed a more moderate increase. This difference could be attributed to the difference in soil type, where sandy soils are more responsive to calcium carbonate precipitation than clay soils as in this study [14].

4.3. Increased Soil Shear Strength

Direct Shear Test showed a significant increase in the shear strength parameter of the soil, i.e., cohesion (c) increased from 26 kPa to 65 kPa after 56 days of curing: The cohesion value (c) increased from 26 kPa to 65 kPa after 56 days of curing. The inner shear angle (φ) increased from 10° to 34°, showing an increase of more than three times compared to the original soil. The maximum shear stress increased more than four times from 52 kN/m² in the native soil to more than 160 kN/m² in the soil-bacteria column under a normal load of 140 kN/m². This increase is more significant than the results of Xiao et al. (2019), who found that the inner shear angle increased from 15° to 28° with the MICP method in coarse-grained soil [31]. This difference may be due to the characteristics of the clay soil in this study, which has higher cohesive properties and thus is more responsive to the increase in cohesion due to calcium carbonate precipitation. Compared to conventional methods, such as the use of sand or stone columns, the soil-bacteria column in this study shows the advantage of increasing cohesion without the risk of losing stability due to groundwater level rise, as is often the case with sand columns [32].

4.4. Effect of Curing Time and Bacterial Activity during the 7-28 Day Period

The results showed that the optimal aging time was between 14 and 28 days, where the most significant increase occurred in the first 28 days, while afterward, the rate of increase slowed down. This is in line with the research of Hu et al. (2022), who found that MICP stabilization reached its peak effectiveness after 28-35 days before experiencing mineralization saturation [19]. However, compared to the results of Shahin et al. (2020), who showed that sandy soils reached optimal stabilization in 21-28 days, this study indicates that clay soils take longer, up to 56 days, to reach optimal strength [33]. This is likely due to the smaller pore structure of clay soils, which inhibits the diffusion of calcium carbonate solution and slows the formation of bonds between soil particles.

This study showed that the most significant improvement in soil properties occurred between day 7 and day 28 after hardening. This is closely related to the biomineralization activity of Bacillus subtilis bacteria, which is the main microorganism in the Microbial-Induced Calcite Precipitation (MICP) process. In the early stages (0-7 days), the bacteria begin to adapt to the soil environment and enter an exponential phase of growth, during which they begin to produce significant amounts of the enzyme urease. This enzyme hydrolyzes urea into carbonate (CO_3^{2-}) and ammonium ions (NH_4^+), which then react with calcium (Ca^{2+}) in solution to form calcium carbonate ($CaCO_3$) precipitation. On days 7 to 28, calcium carbonate production reaches its peak, strengthening the soil structure by increasing the bonds between particles. After day 28, the deposition rate begins to decrease as the soil pore space decreases and the amount of available substrate decreases, as confirmed by the research of Liu et al. (2021) [28].

To optimize the hardening process faster without compromising the quality of stabilization, several strategies can be applied, namely *first*, increasing the initial bacteria concentration: The study by Qiao et al. (2024) [34] showed that a higher concentration of bacteria can improve the efficiency of $CaCO_3$ formation and accelerate soil hardening. Second, modification of the nutrient solution: By adjusting the composition of the B4 medium used for bacterial growth, such as increasing the urea ($CaCl_2$) ratio, the biomineralization process can be accelerated. *Second*, controlling moisture content and pH: Keeping soil moisture content within the optimal range (around 20-30%) and environmental pH of 7.5-8.5 will increase enzymatic activity and accelerate the hardening process [35]. *Third*, gradual injection: Instead of a one-time application of bacteria and calcium solution, a stepwise injection approach can maintain biomineralization activity over a shorter time [19].

4.5. Comparison with Conventional Soil Stabilization Techniques

MICP has several advantages over conventional methods such as cement or lime stabilization. In this study, the increase in CBR from 5.5% to more than 12% and free compressive strength from 66 kN/m^2 to 345 kN/m^2 prove the effectiveness of this method. The advantages of MICP compared to conventional methods are *first*, environmentally friendly: Soil stabilization using cement and lime results in high carbon emissions. In contrast, MICP is a more sustainable biological process [29]. *Second*, for improved soil structure, MICP increases cohesion (from 26.5 kPa to 65 kPa) and inner shear angle (from 10° to 34°) without drastically changing the basic soil properties, in contrast to cement, which tends to increase soil stiffness excessively [36]. Third, resistance to degradation, although $CaCO_3$ may leach in high rainfall environments or low pH soils, research by Xiao et al. (2019) [31] showed that combining MICP with silicate or other additives can improve the soil's resistance to chemical erosion. However, conventional methods still have advantages in several scenarios including *first*, short time requirements, if soil stabilization is needed in a short time, conventional methods such as lime and cement harden faster than MICP which requires a minimum of 28 days [22]. Secondly, application on extreme soils, on sites with unfavorable geochemical conditions (e.g., very low pH or very alkaline), lime stabilization may be more effective as it can directly change the chemical properties of the soil [37].

4.6. Performance under Loading Conditions and Scalability of MICP in Field Applications

The significant increase in shear strength, cohesion, and internal friction angle positively impacts soil durability in real infrastructure applications. In *Heavy traffic*, the increase in modulus of elasticity from 4.43 MPa to 12.49 MPa

indicates that the soil stabilized with MICP has higher deformation resistance to repeated loads from heavy vehicles [1]. *Seismic resistance*, with increased cohesion and deep shear angle, MICP-reinforced soils are more stable in the face of earthquakes, reducing the risk of liquefaction [19]. *For lightweight pavements and foundations*, a study by Hu et al. (2022) [19] showed that MICP can be used as a road subbase layer or lightweight foundation, which minimizes deformation and improves the bearing capacity of soft soil. Further tests with cyclic loading can be conducted to understand how the stabilized soil behaves under repeated dynamic loads [31].

Large-scale implementation of MICP faces several challenges, including cost, implementation time, and labor requirements. *Cost*, production of bacteria and urea-$CaCl_2$ solution is still more expensive compared to conventional methods. Solution: Using industrial waste as a calcium source can reduce costs [38, 39]. *Implementation time*, the biomineralization process takes longer than cement or lime. Solution: Modifying bacterial formulation and gradual injection can accelerate hardening [40]. *The distribution of bacteria in soil and* infiltration of bacterial solution should be uniform for even stabilization. Solution: Sensor-based automatic injection technology can improve efficiency [41].

4.7. Advantages and Limitations of the Column Method

Based on the results of this study and comparison with previous studies, the MICP-based soil-bacteria column method has several key advantages, namely *first*, a significant increase in bearing capacity without the need to add external materials such as stone or sand. *Second*, it is an environmentally friendly method compared to lime- or cement-based stabilization, resulting in high carbon emissions. *Third*, it has proven effective in improving soil's shear strength and modulus of elasticity under various conditions. However, this method also has some limitations, including first, dependence on environmental conditions, such as temperature and soil moisture, which can affect the effectiveness of biomineralization. Second, there is a relatively long curing time (up to 28 days) compared to faster conventional stabilization methods. Third, lower effectiveness in soils with very low permeability, such as highly plastic clays, which inhibit diffusion of the bacterial solution.

The results of this study indicate that the MICP-based soil-bacteria column method is an innovative solution to improve the bearing capacity of soft soil in a sustainable and environmentally friendly manner. For further research, some recommendations that can be developed include a long-term investigation of the stability of soil-bacteria columns after more than 56 days of burial. Experiments with varying bacterial concentrations need to be conducted to determine the optimal dosage in various soil types. The vulnerability of bacterial soil columns to water requires further investigation of geomembrane-wrapped bacterial soil columns and their application in road construction over subgrade using geosynthetics [42, 43]. Furthermore, numerical simulations to evaluate the potential application of this method in large-scale projects. Further research needs to be conducted on cyclic loading to understand how the stabilized soil behaves under repeated dynamic loads.

5. Conclusion

Based on the results, the bacterial soil column was shown to significantly improve the mechanical parameters of the soil compared to the untreated soil. The California Bearing Ratio (CBR) increased from 5% in the untreated soil to 12% after 56 days of curing, indicating an almost threefold increase in the soil's bearing capacity. Unconfined compressive strength (UCS) increased from 66 kPa to 345 kPa after 56 days, a more than fivefold increase. The modulus of elasticity (E) of the soil increased from 4.43 MPa in the untreated soil to 12.49 MPa, reflecting a significant increase in soil stiffness. Shear strength parameters also increased significantly, with the cohesion (C) value increasing from 26 kPa in the untreated soil to 65 kPa after 56 days. The internal friction angle (ϕ) increased from 10° to 34°, more than three times that of the untreated soil, while the shear stress (τ) reached 160 kN/m^2 at a normal stress of 140 kN/m^2, more than four times that of the untreated soil. The most significant increase occurred between 7 and 28 days, the active period of bacterial biomineralization, with the increase slowing down after day 28 to reach optimal stability at day 56.

The soil-bacteria column is a very effective method for improving the mechanical properties of soft soils. The biomineralization process by bacteria significantly improves bearing capacity, shear strength, stiffness, and soil cohesion, making it suitable for various engineering applications such as slope stabilization, lightweight foundations, and pavements. The study also confirmed the importance of curing time to optimize stabilization performance, with optimal results achieved at curing times between 28 and 56 days. In addition, this method offers a sustainable and environmentally friendly solution to the challenges of ground improvement on sites with soft soil conditions.

6. Declarations

6.1. Author Contributions

Conceptualization, R. and T.H.; methodology, R.; software, R.; validation, T.H., A.B.M., and A.A.; formal analysis, R.; investigation, R.; resources, R.; data curation, R.; writing—original draft preparation, R.; writing—review and editing, R.; visualization, R.; supervision, T.H., A.B.M., and A.A, project administration, R.; funding acquisition, R. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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