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Microbially Induced Calcium Carbonate Precipitation (MICP) of Nature Expansive Soil to Evaluated Unconfined Compression Strength Parameter of Soil

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ABSTRACT:

Expansive soil is a type of soil that has a high potential for swelling and shrinkage. As a tropical country, Indonesia has two distinct seasons: the rainy and dry seasons. This condition affects expanded clay and make some infrastructure distress since decades. The shrinkcage may causes tilting, differential settlement, cracking, and failure of utility lines. This study aims to determine the effect of Bio Grouting or MICP using Bacillus subtilis bacteria on changes in the mechanical properties of expansive soils. Expansive soil stabilization was carried out by adding bacterial solutions ranging from 3%, 4.5%, and 6%, where the bacterial cultures used were three days and six days of culture. Based on the study's results, it was found that the MICP method using the bacterium Bacillus subtilis could increase the value of unconfined compression strength. The optimum unconfined compression strength value was obtained in soil samples with the addition of 4.5% bacterial culture solution for six days with a curing period of 28 days of 16.46 kg/cm^2 or 51 times higher than the unconfined compression strength value of soil without stabilization.

1. Background

In the general technical sense, the soil consists of aggregates (granules) of non-cemented (chemically bound) solid minerals and decomposed organic matter (including solid particles), which is defined as a material with liquids and gases that fills the space of solid particles [1].

Soil is an aggregate of mineral particles, air and water in a vacuum, they form a three-phase system. Soil stabilization can be accomplished by several methods [2][3]. All these methods fall into two broad categories, namely mechanical stabilization and chemical stabilization [4]. Expansive soil is a type of soil that has a high potential for swelling and shrinkage. Expansive soil will experience expansion when there is an increase in water content, whereas when the water content decreases, there will be shrinkage [5][6].

Indonesia, as a tropical country, has two seasons, namely, the rainy season and the dry season. This condition will significantly affect expansive soil [6][7]. During the dry season, the soil will experience shrinkage and cracks due to reduced water, while during the rainy season, the soil will experience expansion due to increased water content in the soil [8][9][10].
Soil stabilization is a way to improve soil properties which is done by mixing other materials [11]. Soil stabilization is an effort to improve the parameters of the soil shear strength so that the carrying capacity of the soil increases [12].

Firoozi A.A et al. (2017) explained that soil stabilization is an action to improve the engineering properties or characteristics of the soil (soil properties) [13]. Zada et. all (2023) states that Soil stabilization is a term for physical, chemical, or biological methods which can be used to improve specific properties of the soil to suit the proper engineering purposes [14]. Based on the addition of certain additives, soil stabilization processes are grouped into two, namely soil stabilization without additives (compaction) and soil stabilization with additives (cement, lime, bitumen, etc) [15][16][17][18][19][20][21][22][23]. One of the environmentally friendly soil improvement methods is Bio Grouting [24][25][26]. The influence of microorganisms on many minerals, such as carbonates, sulfates, phosphates, and silicates, has been proven. One of the standard processes in nature is Microbially Induced Calcium Carbonate (Calcite) Precipitation (MICP) [27][28][29][30][31][32].

MICP is a biologically driven calcium carbonate (calcite or CaCO3) deposition technology, which includes two biologically controlled and biologically induced CaCO3 deposition mechanisms. In nature, biomineralization is a common phenomenon that occurs where mineral precipitation is formed by microbial activity [33][34][35]. Among the various mechanisms involved in biomineral production, MICP has attracted the attention of engineers and microbiologists. Microorganisms, which contain the enzyme urease, facilitate the precipitation of carbonates (by hydrolysis) [36][37]. One of the MICP systems is based on the urea hydrolysis process catalyzed by ureolytic bacteria, which can produce the enzyme urease. The bacteria that can be used is Bacillus subtilis bacteria [38][33][31][29]. The use of Bacillus subtilis bacteria with a culture age of 6 days. The results showed that the California Bearing Ratio (CBR) and Unconfined Compressive Strength tests with the addition of 2%, 4%, and 6% bacteria showed that the compressive strength values tended to increase and decrease with the addition of 8% bacteria. The compressive strength curve also increased with the curing time of 3, 7, 14, and 28 days. This study's results indicate that using Bacillus subtilis as a stabilizing agent increases the carrying capacity of clay with high plasticity [28].

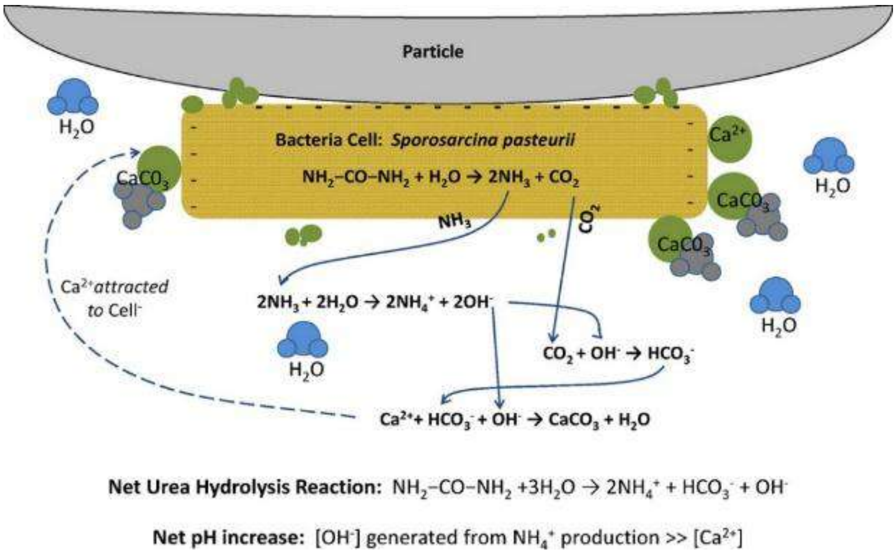

Figure 1. Biocementation Reaction Mechanism (Dejong et al., 2010) [39]

Based on this, this research was conducted to explore the use of MICP as an environmentally friendly solution for research, especially in improving the mechanical properties of expansive soils [40][41].

2. Metodology

a. Location and Time of Research

All the samples were tested in the soil mechanics laboratory, Faculty of Engineering, Hasanuddin University, South Sulawesi. The samples were treated with the bacteria Bacillus subtilis and tested with several mechanical and physical characteristics.
The intervals and durations established using the testing criteria are referred to as the research time.

b. Expansive Soil Identification

There are several ways to identify expansive soil: direct and indirect. Direct identification is made using a free expansion test and an oedometer test. Indirect identification can be used using soil parameters such as Chen, Skempton, and Seed Method.

2.2.1. Chen (1988)
Chen uses a single index, namely the Plasticity Index (PI) [42].

Table 1. Correlation of Plasticity Index Value with Level of Swelling Potential

Plasticity Index (PI) %	**Swelling Potential**
0 – 15	Low
10 – 35	Medium
20 – 55	High
>55	Very High

2.2.1. Skempton (1953)

Identification of expansive clay is also often carried out by taking into account its activity value. Skempton (1953) defines activity as [43]:

$$Ac = \frac{PI}{C} \quad (1)$$

2.2.3. Seeds (1962)

$$Ac = \frac{PI}{C-10} \quad (2)$$

Seed et al. (1962) also proposed another empirical relationship between swelling potential and soil plasticity index.

$$S = 60K(PI)^{2,44} \quad (3)$$

c. Method of Collecting Data

Data collection is carried out on the materials to be used for the manufacture of test objects. The first step is the selection of materials by taking into account their characteristics visually, then testing the characteristics of these materials to ensure their suitability with the required stabilizing agent.

The tests carried out in this study were to analyze the expansive soil behavior due to the bacterial stabilization process. The mechanical characteristics resulting from the Unconfined Compression Strength (UCS) were analyzed qualitatively to determine the function of the mixture composition and curing time. The mechanical test results are then used to determine the soil's effective expansive and bacterial composition.

Table 2. Physical and Mechanical Testing Standards

Test Type	**ASTM**
Specific Gravity	D854–14
Water Content	D2216–71
Atterberg Limits	D4318–05, D4943–08
Sieve Analysis and Hydromter	D422–63
Compaction (*Standard Proctor*)	D698–07
UCS (*Unified Compression Strength*)	D2166–06

d. Material

2.4.1. Expansive Soil

The soil used in this study is nature expansive soil from South Sulawesi Province in Indonesia. Severe damage occurs every year at the location in the form of damaged and bumpy roads and the results of the soil test obtained which have certain levels of kaolinite and ontmorillonite minerals as shown in Table 3.

Figure 2. Nature Expansive Soil

2.4.2. Bacillus Subtilis

The bacterial culture process of Bacillus subtilis in this test was carried out on B4 medium with the formula Urea 20 gr; Nutrient Broth 3 gr; NaHCO3 2.12 gr; CaCl2.2H2O 4.14 gr; and NH4Cl 10 gr.

Then these ingredients are mixed into an Erlenmeyer flask with 1 liter of distilled water. Bacillus subtilis is cultivated with a culture age of 3 and 6 days, which will later be used as a stabilizing agent according to variations in the design of the test object.

Figure 3. *Bacillus subtilis*

Limitations and challenges can arise during the experimental process, particularly in the context of soil sample preparation and MICP. To overcome those situation optimizing bacterial strains and growth conditions for enhanced resilience were conducted with developing better injection and treatment protocols for uniform distribution in the labarotory.

2.5. Unconfined Compression Strenght

Unconfined Compression Strength (UCS) is the axial pressure of the test object when it collapses or when the axial strain reaches 20%. An Unconfined Compression Strength test is one way to determine soil shear. The independent compressive strength test aims to determine the free compressive strength of a type of cohesive soil, both in its undisturbed, remolded, and compacted soil. UCS (q_u) is the maximum axial stress value that a cylindrical specimen (soil sample) can be withstood before it collapses. UCS value is obtained from the reading of the proving ring dial with the maximum stress.

$$q_u = \frac{k \times R}{A} \quad (4)$$

3. Result and Discussion

a. Characteristics of Physical and Mechanical Properties of Nature Expansive Soil

Testing the physical and mechanical characteristics of the soil was carried out to classify the type of soil used in the study. Based on the results and testing in the laboratory, the following data were obtained:

To overcome

Table 3. Characteristics of Physical and Mechanical Properties of Soil

No.	Test Type	Unit	Test Result
Physycal Properties			
1.	Specific Gravity (Gs)	-	2.70
2.	Water Content (ω)	(%)	72.00
3.	Atterberg Limits		
	Shrinkage Limit	(%)	13.88

	Plastic Limit	(%)	26.77
	Liquid Limit	(%)	82.75
	Plasticity Index	(%)	55.98
4.	*X-Ray Diffraction* (XRD) Kaolinite Montmorillonite	 (%) (%)	 34.1 1.7
5.	Sieve Analysis and Hydrometer Test		
	Gravel	(%)	0.40
	Sand	(%)	7.20
	Silt	(%)	22.40
	Clay	(%)	70.00
Classification			
USCS			CH
AASHTO			A-7-6
Mechanical Properties			
5.	Compaction (Kompasi)		
	Maximum Dry Density ($\gamma_{dry\ max}$)	gr/cm^3	1.37
	Optimum Moisture Content (ω_{opt})	%	29.74
6.	UCS (*Unconfined Compression Strength*)	kg/cm^2	0.323
7.	Elastic Modulus	kg/cm^2	8.730

Noted : 1 kg/cm2 = 0.098 MPa

Several methods are used to identify expansive soil indirectly.

Chen

This method uses a single index, namely the Plasticity Index (PI). From the Atterberg boundary test, the plasticity index value is 55.98%. Based on Table 1, the soil has a high swelling potential because it has a plasticity index of >55%, so it can be said to be expansive soil.

Skempton

Skempton identified expansive soils with activity values, namely the ratio between the plasticity index (PI) and the percentage of clay fraction (C). The activity value obtained was 0.8. Soil is included in the active category with moderate development potential, so it can be said to be expansive soil.

Seed

Using equation (3) a potential swelling value of soil is 39.77%.

b. The Result of Unconfined Compression Strength test of Expansive Soil

3.2.1. Samples with Addition of Bacterial Culture 3 Days

a. Sample with 3% Bacterial Mix

Figure 4 shows based on variations in curing time for samples with the addition of 3% bacteria, there was an increase in UCS values during each curing period, namely 6.47 kg/cm^2 for 3 days curing, 7.90 kg/cm^2 for 7 days curing, 11.80 kg/cm^2 for 14 days curing, and 13.29 kg/cm^2 for 28 days curing.

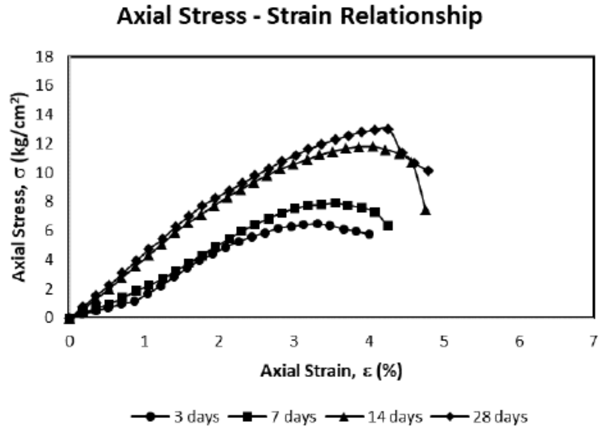

Figure 4. Graphics of Unconfined Compression Strength Test with the Addition of 3% Bacterial Culture 3 Days

b. *Sample with 4,5% Bacterial Mix*

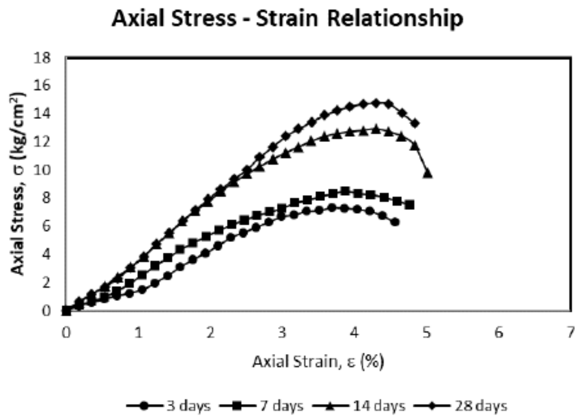

Figure 5. Graphics of Unconfined Compression Strength Test with the Addition of 4.5% Bacterial Culture 3 Days

Based on variations in curing time for samples with the addition of 4.5% bacteria, there was an increase in UCS values during each curing period, namely 7.34 kg/cm^2 for 3 days curing, 8.54 kg/cm^2 for 7 days curing, 12.94 kg/cm^2 for 14 days curing, and 14.78 kg/cm^2 for 28 days curing.

c. *Sample with 6% Bacterial Mix*

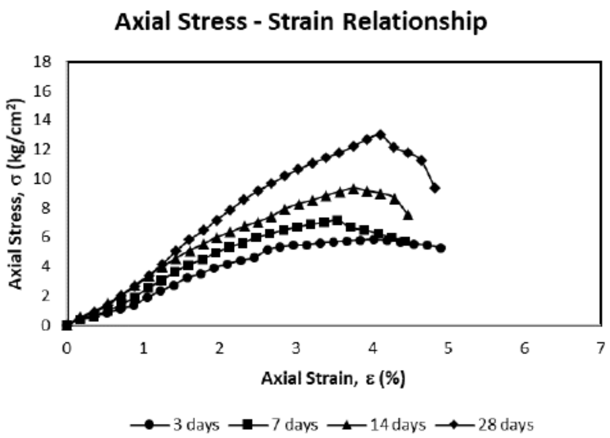

Figure 6. Graphics of Unconfined Compression Strength Test with the Addition of 6% Bacterial Culture 3 Days

Based on variations in curing time for samples with the addition of 6% bacteria, there was an increase in UCS values during each curing period, namely 5.83 kg/cm^2 for 3 days curing, 7.17 kg/cm^2 for 7 days curing, 9.34 kg/cm^2 for 14 days curing, and 13 kg/cm^2 for 28 days curing.

3.2.2. Samples with Addition of Bacterial Culture 6 Days

a. Sample with 3% Bacterial Mix

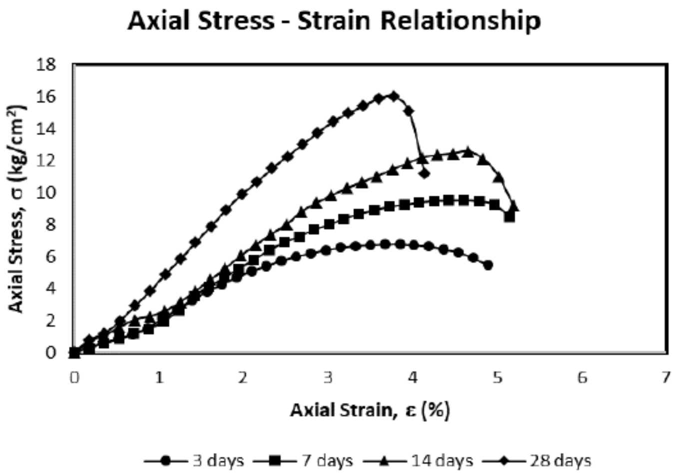

Figure 7. Graphics of Unconfined Compression Strength Test with the Addition of 3% Bacterial Culture 6 Days

Based on variations in curing time for samples with the addition of 3% bacteria, there was an increase in UCS values during each curing period, namely 6.79 kg/cm^2 for 3 days curing, 9.50 kg/cm^2 for 7 days curing, 12.58 kg/cm^2 for 14 days curing, and 16.02 kg/cm^2 for 28 days curing.

b. Sample with 4,5% Bacterial Mix

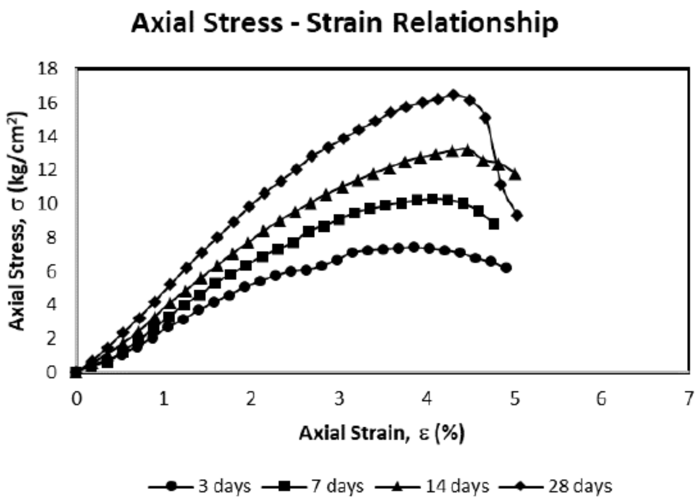

Figure 8. Graphics of Unconfined Compression Strength Test with the Addition of 45% Bacterial Culture 6 Days

Based on variations in curing time for samples with the addition of 4.5% bacteria, there was an increase in UCS values during each curing period, namely 7.44 kg/cm2 for 3 days curing, 10.27 kg/cm2 for 7 days curing, 13.23 kg/cm2 for 14 days curing, and 16.46 kg/cm2 for 28 days curing.

c. Sample with 6% Bacterial Mix

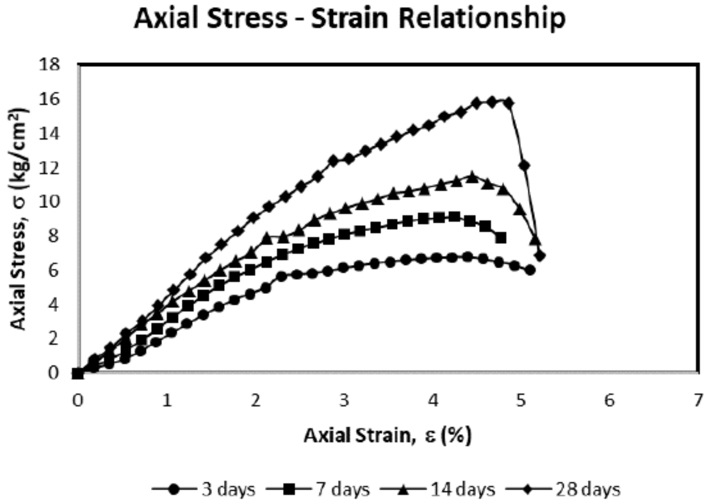

Figure 9. Graphics of Unconfined Compression Strength Test with the Addition of 6% Bacterial Culture 6 Days

Based on variations in curing time for samples with the addition of 6% bacteria, there was an increase in UCS values during each curing period, namely 6.77 kg/cm^2 for 3 days curing, 9.12 kg/cm^2 for 7 days curing, 11.51 kg/cm^2 for 14 days curing, and 15.85 kg/cm^2 for 28 days curing.

3.2.3. Recapitulation of the Effect of Bacterial Mix on Unconfined Compression Strength of Expansive Soil

Based on Table 4, it is found that the curing time affects the value of the UCS in the sample for each addition of the bacterial solution. Of the three variations of adding bacterial solution, namely 3%, 4.5%, and 6% with 3 and 6 days culture, it was found that the highest unconfined compression strength value was in the addition of 4.5% bacterial solution for 6 days culture.

Table 4. Summary of Unconfined Compression Strength Test Results of Nature Expansive Soil Stabilized by Bacillus Subtilis

Sample	**Culture**	**Bacterial Solution** (%)	**Unconfined Compression Strength, q_u** (kg/cm^2)			
			3 Days	7 Days	14 Days	28 Days
	3 Days	3	6.47	7.90	11.80	13.29
		4.5	7.34	8.54	12.94	14.78
Soil		6	5.83	7.17	9.34	13.00
	6 Days	3	6.79	9.50	12.58	16.02
		4.5	7.44	10.27	13.23	16.46
		6	6.77	9.12	11.51	15.85

The increase in unconfined compressive strength (UCS) due to microbial-induced calcium carbonate precipitation (MICP) involves several intricate mechanisms tied to the activity of Bacillus subtilis. The precipitated calcium carbonate fills the pores of soil or other materials, effectively binding particles together. This leads to several changes in the material properties such as increased cohesion, reduc inporosity, and improving load-bearing capacity.

4. Conclusion

The addition of a stabilizing agent, namely a solution of Bacillus subtilis bacteria, can increase the unconfined compression strength of expansive soils. Of the three variations of the addition of bacterial solutions, namely 3%, 4.5%, and 6% with 3 and 6 days of culture, it was found that the highest UCS value was in the addition of 4.5% 6 days of bacterial culture solution. The effect of the curing period on stabilized samples of Bacillus subtilis is directly proportional, where the longer the curing time, the value of the UCS will also increase. From the results of the study, it was found that the optimum free compressive strength value was obtained during the 28 day curing period at 4.5% mixed bacterial culture 6 days of 16, 46 kg/cm^2 or 51 times higher than the soil without stabilization. Over time, the stabilized soil or material maintains its improved mechanical properties, as calcium carbonate is highly stable under typical environmental conditions. This makes MICP a promising technique for geotechnical applications like soil stabilization, erosion control, and construction.

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