# Improvement of the California Bearing Ratio of Peat Soil Using Soybean Crude Urease Calcite Precipitation

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## Abstract

Due to its high organic matter, moisture content, and low bearing capacity, peat soil needs to be stabilized for use as a subgrade. The soybean crude urease calcite precipitation (SCU-CP) method is a grouting technique using carbonate precipitation and soybean as a biocatalyst. This study aims to analyze the effect of the SCU-CP method and soil density on the California bearing ratio (CBR) value to obtain the best stabilization alternative for reducing the field's compaction energy. The CBR test was conducted in both soaked and unsoaked conditions. The study was conducted with variations of 50%, 70%, and 90% density of Standard Proctor and used grouting treatment with a combination of optimum SCU-CP solution for the treated samples. The results showed a significant increase in CBR, with an average increase of more than two times compared to untreated samples. In terms of compaction effort, a density of 70% Proctor in unsoaked conditions with SCU-CP treatment is the best alternative. However, considering the soil saturation level and the swelling of the subgrade layer, 90% proctor density with SCU-CP treatment can be recommended as a stabilization method without dewatering. This research concluded that the SCU-CP method could improve the CBR value of peat soil.

*Keywords:* Calcite Precipitation; CBR; Peat Soil; Soybean; Subgrade.

## 1. Introduction

The physical properties of the soil and its low bearing capacity frequently cause problems in road infrastructure development. One of the soils with a low bearing capacity is peat or organic soil. The subgrade is a soil layer that supports the road pavement. In highway construction, subgrade can be local native soil or road fill soil. Soil bearing capacity as a subgrade is vital in road pavement engineering for flexible and rigid pavements [1]. Peat soil has high organic content, moisture content, and compressibility, as well as low shear strength, so if used as a subgrade without stabilization, it can cause structure failures such as excessive settlement [2]. Peat soil has been stabilized mechanically, physically, and chemically using techniques such as the replacement method, mini woodpile, corduroy, preloading, and surcharge [3]. However, these methods have several problems, including the need for a large volume of fill and the production of large volumes of dry peat.

Additionally, easily combustible peat requires large amounts of wood and is uneconomical due to high construction costs, and it can lead to carbon release from the subsidence of water content at the bottom of the embankment [4]. Based on these problems, an environmentally friendly method for improving peat soil that has excellent potential for application is the precipitation of calcium carbonate ($CaCO_3$) [5]. Soil improvement technique using $CaCO_3$ can be done by calcite precipitation method. The calcite that settles in soil pores can bind soil particles, limit movement, and improve soil properties [6]. $CaCO_3$ precipitation for soil improvement can reduce permeability and compressibility while increasing soil shear strength [7–10].

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Enzyme-mediated calcite precipitation (EMCP) can be used as an alternative in soil stabilization by breaking down urea into carbonate ions ($CO_3^{2-}$) using the urease enzyme. Carbonate ions will react with calcium ions ($Ca^{2+}$) to form calcite ($CaCO_3$) [6, 8, 11]. Putra et al. [12] stated that an increase in the value of unconfined compressive strength (UCS) in the range of 200 kPa–1.6 MPa had been achieved in sandy soils by the EMCP method. However, pure urease enzyme is less economical if used on a large scale in the field. EMCP requires multiple injections to improve large volumes of soil; the price of the urease enzyme, which can reach >90% of the price of other materials, requires a substitute for the enzyme without reducing the effectiveness of the EMCP method [13]. Soybean has been reported as a potential urease alternative, with enzyme reaction rates reaching 93–104 U/g, whereas the reaction rate for pure urease is 2950 U/g [14]. Based on this, the use of soybeans can increase 60% of the theoretical mass of precipitated calcium carbonate with a lower reaction rate than pure urease. Research conducted by Putra et al. [9] regarding the increase in shear strength of peat soil with the calcite precipitation method using soybean extract (SCU-CP) resulted in a 50% increase in shear strength and an increase in UCS and cohesion of 148 kPa and 50 kPa, respectively. According to Oktafiani et al. [15], regarding the effect of dissolved organic carbon (DOC) on the effectiveness of the SCU-CP method in improving peat soils, it was discovered that high organic soils obtained a UCS value of 178.81 kPa, or a 76.47% increase compared with that of the control sample, while low organic soil resulted in a UCS value of 226.49 kPa, or a 137.50% increase. Hardiyatmo [16] stated that an increase in the UCS value of 200–400 kPa indicates that the soil has a very stiff consistency.

According to the problem of bearing capacity of peat soil and the results of research that have been carried out in stabilizing, soybean crude urease calcite precipitation (SCU-CP) is used for peat soil improvement as a subgrade to improve California bearing ratio (CBR). The CBR is a critical parameter for evaluating the behavior and performance of a subgrade [17, 18]. Furthermore, it is an essential parameter in assessing the serviceability of the subgrade layer [19]. According to the Directorate General of Highways [20], the recommended practical CBR value as a subgrade is not less than 6%. Laboratory CBR testing was conducted to evaluate the effect of calcite formation on CBR parameters based on variations in soil density in soaked and unsoaked conditions. This study aims to analyze the increase in the CBR value of peat soil as a result of soil improvement, investigate the effect of variations in soil density on increasing the value of the adjusted CBR parameter for the subgrade, and obtain the best alternative from the method of improving peat soil as a subgrade.

## 2. Materials

The materials used in this study included peat soil samples passed through sieve no.16, reagents in the form of urea ($CO(NH_2)_2$) with detailed laboratory-grade specifications (ACS, Reng. Ph Eur) and calcium chloride dihydrate ($CaCl_2.2H_2O$) dihydrate with detailed laboratory-grade specifications (ACS, Reag. Ph Eur), soybean powder with Food Grade (Gasol) label having 100% purity specifications, and distilled water as solvent. The reaction for calcite formation is shown in Equations 1 to 3. Figure 1 depicts the materials used in the study.

$$CO(NH_2)^2 + 2H_2O \xrightarrow{catalyst} 2NH_4^+ + CO_3^{2-} \tag{1}$$

$$CaCl_2 \rightarrow Ca^{2+} + 2Cl^- \tag{2}$$

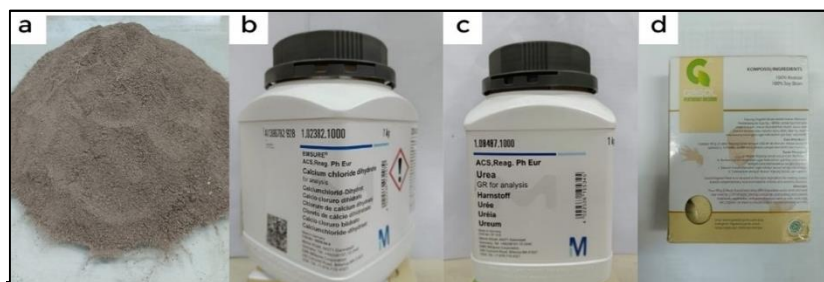$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \text{ (precipitated)} \tag{3}$$



**Figure 1. The material used in this study, (a) Peat soil passed through sieve No. 16, (b) Calcium chloride dihydrate, (c) Urea, and (d) Soybean with 100% purity levels**

Soil properties were tested to investigate the characteristics of peat soil. Based on the test results, the peat soil of the test sample has a specific density (Gs) of 1.13; thus, the soil is classified as peat or organic soil [21]. The liquid limit (LL) of the test soil is 237.38%, where the liquid limit is the percentage of soil water content when the soil begins to change from a plastic state to a liquid state. The ash content (%) of the tested soil sample is <5%, and its organic content is >67%; thus, it is classified as low ash peat soil and fabric peat [22]. The field water content of the peat is 310.04%; thus, it is classified as moderately absorbent peat [22]. The soil sample's properties and grain-size distribution are shown in Table 1 and Figure 2, respectively. The gradation condition of the peat soil sample was determined based on the

uniformity coefficient (Cu) and the gradation coefficient (Cc). Cu and Cc values based on the gradation test results are 2.67 and 1.04, respectively, based on the relationship between D10, D30, and D60. The peat soil used as the test sample does not have a plastic limit because it does not meet the requirements of the plastic limit test, where the soil sample is cracked before milling up to ±3 mm in diameter.

**Table 1. Physical properties of the peat soil used in this study**

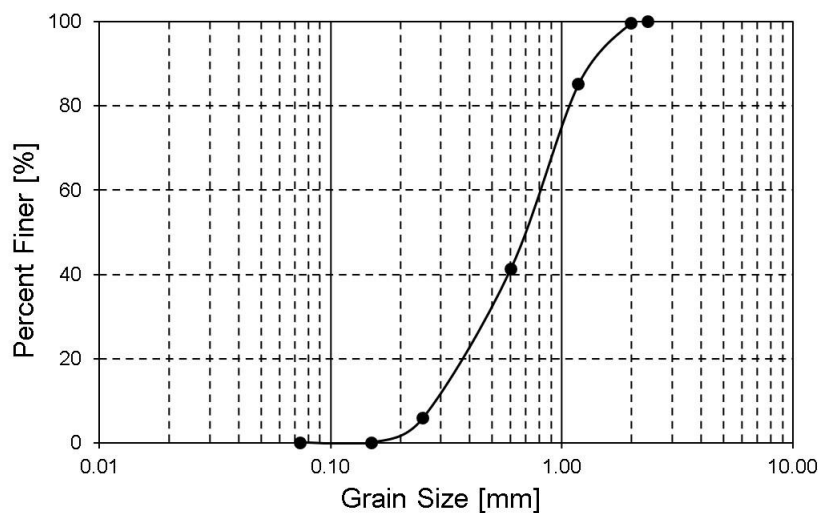| Soil Properties | Value | Unit |
|---|---|---|
| Specific Gravity, *Gs* | 1.13 | - |
| Liquid Limit, *LL* | 237.38 | % |
| Ash Content | 4.66 | % |
| Organic Content | 95.34 | % |
| Field Moisture Content | 310.04 | % |
| Uniformity Coefficient, *Cu* | 2.67 | - |
| Curvature Coefficient, *Cc* | 1.04 | - |
| Soil Type | Pt | - |



**Figure 2. Grain-size distribution of the peat soil used in this study**

# 3. Experimental Methods

The research was conducted in several steps, including soil properties test to identify the physical parameters, preparation of the optimum SCU-CP grouting solution using reagents (urea and CaCl$_2$) and soybean concentration based on precipitation test results from Putra et al. [9], and preparation of soil samples with 50%, 70%, and 90% density of Standard Proctor. Soaked and unsoaked CBR tests were performed to analyze the effect of the SCU-CP method and density on the bearing capacity of the soil as a subgrade

## 3.1. Preparation of Soybean Crude Urease Calcite Precipitation (SCU-CP) Solution

The procedure for preparing the SCU-CP solution was adopted from the research conducted by Putra et al. [9], which uses the concentration of reagent (R) (Urea and CaCl$_2$) and soybeans that produce optimum conditions based on the results of the precipitation test shown in Figure 3. Based on Figure 3, the results of the precipitation test show that the precipitation ratio (%) produced increases with the use of soybean (5–20 g/L) with variations in the use of reagent concentration of 0.5–1.5 mol/L, reaching a stable condition when using soybean concentration of 20–40 g/L, and decreasing when using soybean concentrations of 40–50 g/L. Based on this, an SCU-CP solution was prepared using reagents and soybean under optimum conditions, with CaCl$_2$ and urea concentrations of 1 mol/L and a soybean concentration of 20 g/L. The volume of the SCU-CP grouting solution was calculated based on the needs of water volume from the optimum moisture content (OMC) obtained from the Proctor density test, stirred for 5 min using a stirrer, then the soybean solution was filtered using a filter No. 200 to separate soybean granules in aqueous extracts. The water volume comparison ratio of the reagent (Urea and CaCl$_2$) and soybean composition was determined to be 1:1:2. Figure 4 depicts the scheme for preparing SCU-CP grouting solution based on the optimum combination. The calculations for reagent (R) and soybean (according to the optimum combination) based on the volume of OMC from the Proctor test results in making SCU-CP grouting solution are shown in Equations 4 and 5, respectively. *Mr* is the relative atomic mass of urea and CaCl$_2$, and V$_{OMC}$ is the water volume of the OMC results in the Proctor test.

$$\text{Mass of reagent} = \frac{\text{Conc. of reagent} \times Mr \times V_{OMC}}{1000 \text{ ml}} \tag{4}$$

$$\text{Mass of soybean} = \frac{\text{Conc. of soybean} \times V_{OMC}}{1000 \text{ ml}} \tag{5}$$
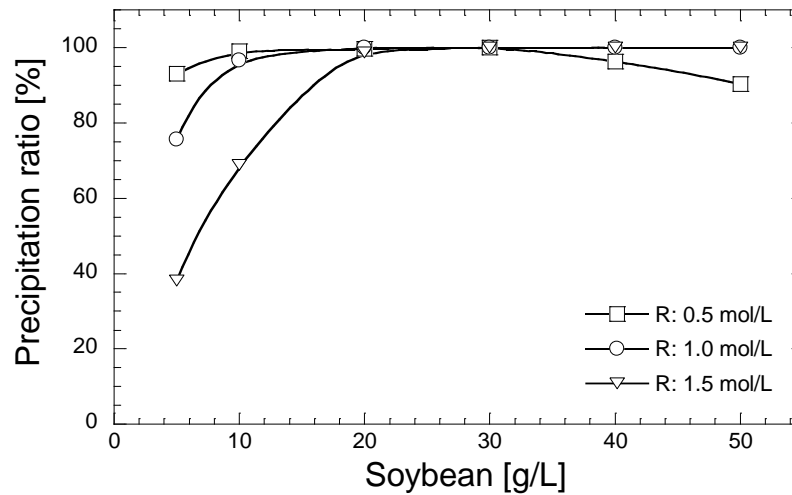
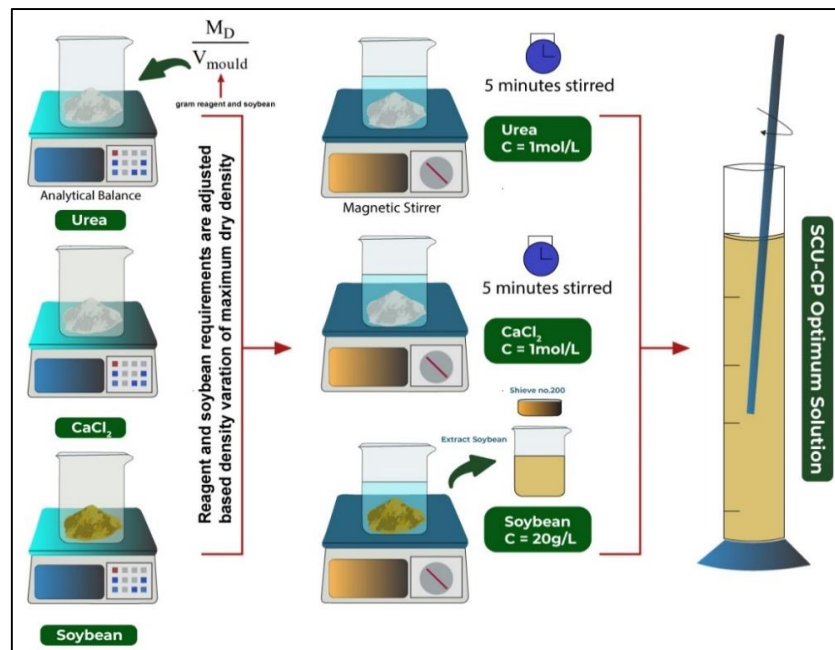**Figure 3. Precipitation test results with variations in reagent and soybean concentrations [9]**

**Figure 4. Procedure for preparing an optimum combination SCU-CP grouting solution**

### 3.2. Preparation of Soil Samples with Density Variation of Maximum Dry Density (MDD)

Preparation of soil samples with variations in density was carried out based on the MDD ($\gamma_{dmax}$) obtained from the Proctor test. The Proctor test is based on ASTM D698-07—the Light Density Test Method for Soil [23]. The test sample has several alternatives: the treated condition, with grouting treatment with the SCU-CP method and compaction, and the untreated condition, with density variations based on the Proctor density. The variations found that will be made for the treated condition with compaction and addition of SCU-CP solution and untreated conditions are 50%, 70%, and 90% Proctor densities. The detailed experimental conditions related to soil condition, SCU-CP solution, and compaction effort are shown in Table 2. First, soil samples were prepared according to the test method, including peat soil with high water absorption and material for mechanical testing CBR parameters. Then, compaction of the soil sample was performed in three layers, and the sample was compacted in a mold with a drop height of 30.5 cm. The OMC (%) and MDD (g/cm$^3$) were obtained based on the curve of the relationship between water content (%) and dry density (g/cm$^3$); thus, the density variations to be carried out were varied based on 50%, 70%, and 90% maximum density for CBR testing based on the water content in a specific range. Sample preparation based on variations of dry density ($\gamma_d$) obtained from in Proctor standard.

**Table 2. Experimental condition of peat soil density**

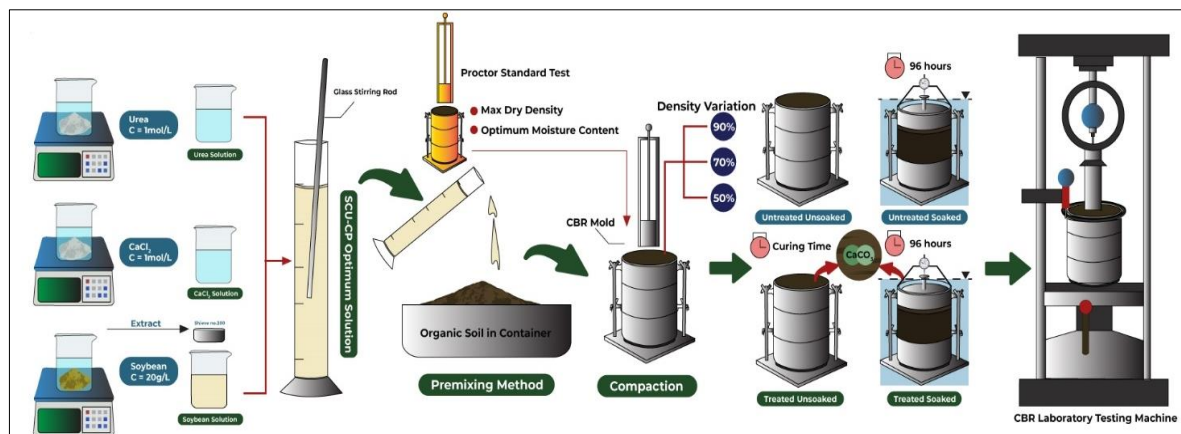| *Case | % Density |
|-------|-----------|
| UT90  | 90.0      |
| UT70  | 70.0      |
| UT50  | 50.0      |
| TE90  | 90.0      |
| TE70  | 70.0      |
| TE50  | 50.0      |

* Untreated condition with Proctor standard density variation (UT); Treated conditions with SCU-CP treatment and Proctor standard density variation (TE)

### 3.3. Soaked and Unsoaked CBR Tests

Soil samples with optimum calcite concentration were prepared in sample molds according to the variation in Proctor density and then injected with the optimum combination of the previous test results. The samples analyzed in the test were in treated conditions with the SCU-CP method of grouting treatment and compaction, as well as in untreated conditions with density variations, to obtain several alternatives. After treatment with the premixing method, the soil sample was cured for 7 days before the unsoaked CBR test was performed. Unsoaked CBR testing was conducted following the ASTM D4429-04 [24] regarding laboratory CBR test methods, as illustrated in Figure 5.
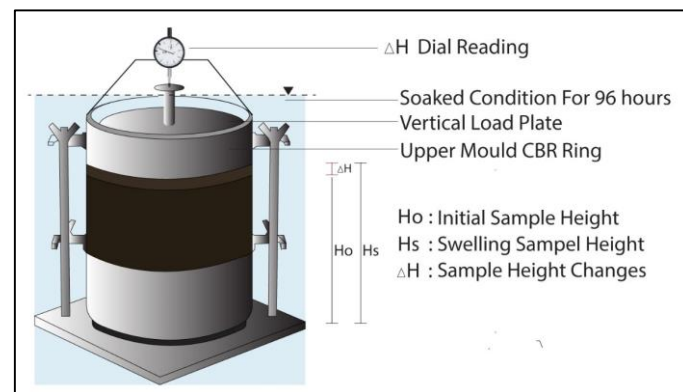


**Figure 5. Potential swelling measurement on soaked CBR laboratory test**

For the soaked CBR test, soil samples will be soaked for 96 h or 4 days for untreated conditions to leave the soil in a saturated condition; for treated samples before the soaking period, soil samples that have been treated with premixing will be left for one day to obtain formation effectiveness of calcite. The soaking will also be carried out for 96 h, including the curing time. In the soaked CBR test, the swelling potential is measured based on the height changes of the soil sample by reading dial measurements every 24 h, enabling the swelling potential to be analyzed based on the degree of expansion. The schematics of swelling potential based on the soaked CBR test are depicted in Figure 5. The schematic of the CBR test according to the experimental conditions is shown in Figure 6. CBR values for penetration pressure at 0.254 cm (0.1") and 0.508 cm (0.2") against standard loads are shown in Equations 6 and 7, respectively. P1 is the pressure at 0.1-inch penetration in kgf/cm$^2$ against standard loads, and P2 is the pressure at 0.2-inch penetration in kgf/cm$^2$ against standard loads.



**Figure 6. CBR laboratory test sample based on the experimental condition**

$$\text{CBR } 0.1" = \frac{P1}{70.37} \times 100\% \tag{6}$$

$$\text{CBR } 0.2" = \frac{P2}{105.56} \times 100\% \tag{7}$$

## 4. Results and Discussion

### 4.1. Density Variation with Standard Proctor Compaction Test

The Standard Proctor test was conducted to obtain the maximum dry density (MDD) (g/cm$^3$) and OMC (%) values for preparing samples of density variations under experimental conditions. The density variations are 90%, 70%, and 50% of the maximum dry density based on the relationship curve between MDD and OMC, as shown in Figure 7. The MDD is 0.504 g/cm$^3$, and the OMC is 134.0%. Ahmad et al. [25] reported that the high value of OMC in peat soil (>100%) was due to the large pore size of the soil and high organic content; hence it promoted significant water absorption. According to Sidhi et al. [26], peat soil's low volume weight value correlates with a high-water content value because the weight of soil grains is replaced by water, which has a lower density than the soil. Zulkifli et al. [27] stated that the high OMC and low MDD in peat soils were due to the high organic fraction, so the bulk density value of peat soils was 0.8–1.0 g/cm$^3$. The results of the Standard Proctor's compaction will be used to determine the gram of soil and milliliter of water and solution required based on a function of dry volume weight (g/cm$^3$) and water content (%) for density variations.
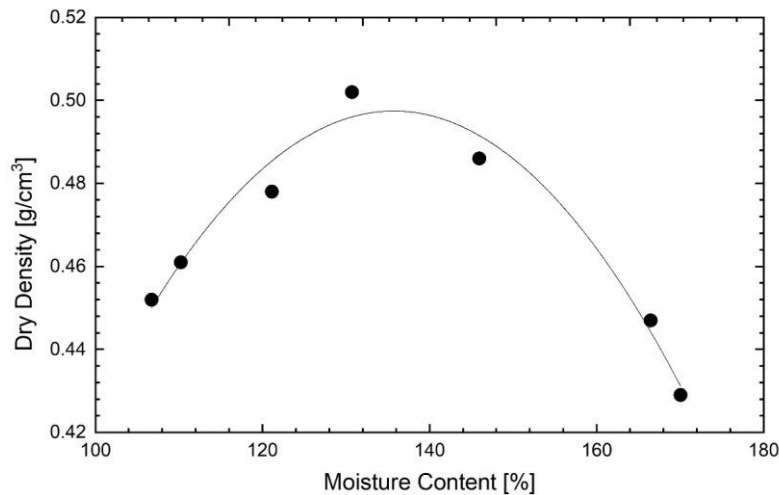


**Figure 7. Proctor standard compaction test results of peat soil sample**

Samples of density variations in untreated and treated conditions will be made based on % OMC results from the Standard Proctor test to examine the effect of the SCU-CP solution on the CBR value of peat soil. The results of the density variation based on the Standard Proctor compaction test are given in Table 3. Density variations made from the MDD in samples treated with optimum SCU-CP solution and untreated from Proctor compaction will be used to obtain alternative stabilization of peat soils. The premixing method was used for mixed solution treatment of soil samples. This method effectively applies to samples with variations in density. The formation of calcite in the voids of high organic soils can increase the soil bearing capacity [28]. Almajed et al. [29] demonstrated that using the premixing method in the EMCP method can improve sandy soil because the number of pores does not limit it. The premixing method for samples of density variations is also supported by research from Rowshanbakht et al. [30], which shows that an increase in density can reduce the amount of calcite formed in the soil using the injection method because the distance between compacted particles is shortened. The optimum volume of SCU-CP solution to use in the premixing method was selected based on the OMC value for each density variation so that the correlation to the CBR value parameter as an alternative for soil improvement can be considered by compaction effort.

**Table 3. Density variation value based on Proctor standard compaction test**

| Case | Dry Density (g/cm$^3$) | CaCl$_2$ (mol/L) | Urea (mol/L) | Soybean (g/L) |
|------|------------------------|------------------|--------------|---------------|
| UT90 | 0.499 | - | - | - |
| UT70 | 0.489 | - | - | - |
| UT50 | 0.478 | - | - | - |
| TE90 | 0.499 | 1.00 | 1.00 | 20.00 |
| TE70 | 0.489 | 1.00 | 1.00 | 20.00 |
| TE50 | 0.478 | 1.00 | 1.00 | 20.00 |

### 4.2. Improvement of CBR in Unsoaked Condition

The CBR parameter on the pavement structure is used to determine the bearing capacity of a subgrade in pavement design. Based on Nagaraj et al. [31], in the design of the pavement on a highway, the CBR value of the subgrade significantly affects the thickness requirement of the pavement, where the lower the CBR value of a subgrade, the greater the need for pavement structure thickness. The Directorate General of Highways stated that the recommended practical CBR value is not less than 6% for use as a subgrade layer [20]. The unsoaked CBR test was used as a simulation to represent the typical soil bearing capacity in the field. Based on the results of CBR testing of peat soil samples in untreated conditions (UT50, UT70, and UT90), the CBR values of all test samples were less than 6%, including 1.76%, 3.66%, and 4.10%, respectively; thus, they did not achieve the effective CBR value for subgrade. According to the correlation between CBR value and density variation, treated samples with 90% Proctor density had higher CBR value than those with 70% and 50% Proctor densities. Soil density affects soil bearing capacity, with increased soil density increasing the shear strength and reducing compressibility [32]. The compressibility value is very influential for compaction treatment and highly correlates with the CBR value. Bharath et al. [33] revealed that the dry density of the soil and compaction effort have a significant influence on the CBR value, where the compaction effort with light compaction treatment has the highest MDD value of 2.10 g/cm$^3$ with a CBR value of 2.40%, while for the heavy compaction treatment, the highest MDD obtained was 2.87 g/cm$^3$ with a CBR value of 16%. This study also discovered that untreated (UT) and treated (TE) samples at 90% Proctor density have a higher CBR value due to a higher MDD value than the other samples.

Mahmood et al. [2] used palm oil fuel ash (POFA) to stabilize the peat soil and reported that density has a significant effect on the CBR value, where the silica content as an added material increases the volume weight and decreases the void ratio due to bonding between soil particles so that the soil density increases four times greater than the untreated sample in the range of 2.08–2.16 g/cm$^3$. Based on this, the grouting treatment in increasing the CBR value of peat soil using the SCU-CP method has a similar concept in that it results in soil particle bonding to change the level of soil consistency. However, the fundamental difference is that calcite is not a composite material but a grouting material Hence, the soil density has been determined as an initial density for an alternative stabilization treatment in the field. A comparison of CBR values before and after treatment is shown in Figure 8.
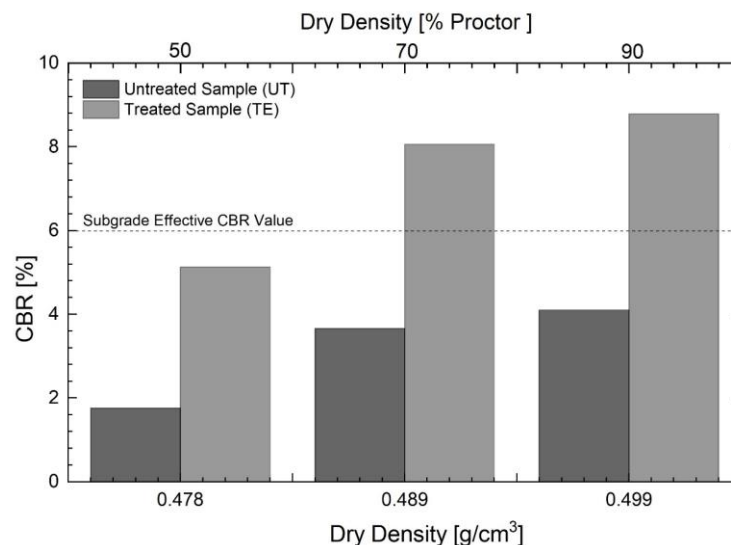


**Figure 8. Results of unsoaked CBR value improvement of peat soil used in this study**

The CBR values for the treated soil samples (TE50, TE70, and E90) were 5.13%, 8.06%, and 8.79%, respectively, increasing more than two times on average for untreated samples (UT). Samples with 70% (TE70) and 90% (TE90) Proctor densities obtained a CBR value greater than 6%, while the sample with a density of 50% Proctor (TE50) obtained a CBR value less than 6% but had the highest improvement valueThe higher increase in the TE50 sample was due to the TE70 and TE90 having a high density than TE50, so the calcite formed to increase soil cohesion in the soil pores was more effective in increasing the CBR value in the TE50 sample. The highest increase in 50% Proctor density correlated with Ramadhan and Putra's research [34] using EMCP grouting treatment with density variations of 50%, 70%, and 90% Proctor densities. Compared to other density variations, 50% Proctor density had the highest increase in UCS value, which is 48%, with an increase from 114.63 kPa to 170.06 kPa.

According to Rowshanbakht et al. [30], an increase in soil density can reduce the amount of calcite formed because crystals function as a binder of particles formed at short distances. The increase in CBR value observed in the treated sample due to the increase in soil cohesion correlated with a study conducted by Pratama et al. [35] regarding the use of

the EMCP method in increasing the shear strength of peat soil, which succeeded in increasing the value of undrained cohesion, with the cohesion value increasing from 34 kPa to 49 kPa. Mackevičius et al. [36] stated that the bond between peat soil particles and calcite caused an increase in soil cohesion due to increased reagent reaction in the presence of a soybean catalyst. Alternatives that can be obtained, 70% and 90% Proctor densities, are selected by providing an SCU-CP solution based on the optimum combination with the resulting CBR value that meets the requirements (>6%). These alternatives must be considered based on the parameters of the compaction effort. Based on this, the 70% Proctor density can be an alternative with a CBR value >6% as a subgrade layer by stabilizing with SCU-CP solution according to the optimum combination.

## 4.3. Improvement of CBR in Soaked Condition

The bearing capacity of the subgrade for road pavement design on the CBR parameter is often used in evaluating the subgrade reaction coefficient. Shirur & Hiremath [19] noted that the CBR value of the subgrade is an essential parameter in assessing the serviceability of the subgrade layer. Mir and Baramjeet [37] stated that changes in water content in the subgrade layer would change in the bearing capacity of the subgrade so that in the design of the road pavement layer, the worst conditions will be used, where the soaked CBR value represents the condition of the submerged pavement layer due to soil saturation in the field. According to the Directorate General of Highways [20], the CBR value for the subgrade layer is required to be not less than 6%, and the effective CBR value for subgrade to design road pavement used the smallest value, one of which is the CBR value of the stabilized soil after 4 days of soaking.

Based on the test results of peat soil samples with the soaked condition, untreated soil samples (UT50, UT70, and UT90) without the optimum SCU-CP grout stabilization treatment had low CBR values of 1.17, 2.20, and 2.93%, respectively. Based on these findings, it can be concluded that the worst condition due to saturation is not suitable for use as a subgrade. The grouting treatment using the calcite precipitation method with optimum conditions in increasing the consistency of the peat soil due to the presence of bonds between particles or cohesion by the formed calcite resulted in a significant increase in the CBR soaked value. Comparison results of an increase in the CBR soaked value from the optimum SCU-CP grouting treatment in samples treated for each initial density condition (TE50, TE70, and TE90) to untreated samples are shown in Figure 9.
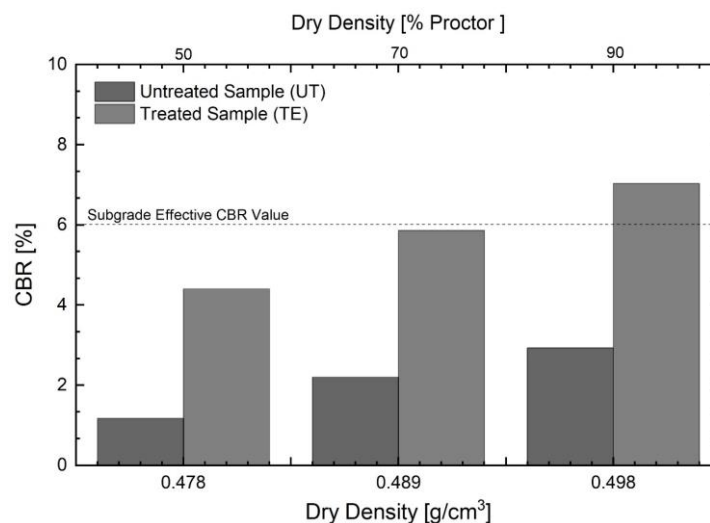


**Figure 9. Results of soaked CBR value improvement of peat soil used in this study**

The soaked CBR values of the treated samples increased compared to those of the untreated samples by 4.40%, 5.86%, and 7.03%. The values of the treated (TE) samples to the untreated (UT) samples of peat soil increased 3.8 times for 50% Proctor density and more than two times for 70% and 90% Proctor densities. Based on the requirements of the subgrade layer, where the effective CBR value of the subgrade is > 6%, the sample treated with a density of 90% Proctor (TE90) resulted in a CBR value of > 6%, while for the 70% (TE70) and 50% (TE50) Proctor densities, it resulted in an increase in grades against untreated samples but did not meet requirements as a subgrade. The increase in the CBR soaked value of treated conditions on peat soil that still does not meet the subgrade layer requirements can be influenced by the physical condition of the peat soil, based on Canakci et al. [28]. The amount of increased carbonate in organic soils is relatively low at 8% compared to sandy soils, which reaches 35%. Putra et al. [38] reported that the growth of calcite crystals could be disrupted due to the organic content and saturation conditions. This result shows that the saturation condition due to the soaked condition, as well as the physical condition of the peat soil, affects the increase in the resulting CBR value. The density parameter also significantly affects calcite crystals produced in wet conditions as an alternative for stabilization. Putra et al. conducted research regarding the improvement of organic soil shear strength using soybean as a biocatalyst, which resulted in an increase in organic soil in the range of 130–148 kPa, but the shear strength increase in organic soil was relatively lower than in sandy soil

due to its organic content. Undissolved soybeans may hamper the process of precipitation, so calcite production is limited. Putra et al. also stated that the high content of organic materials might limit the rhombohedral and spherical shape of the precipitated materials formed. Based on SEM analysis in research conducted by Putra et al., in the treated sample, the promoted precipitated materials were dominated by the amorphous form and may affect the organic content in soil and undissolved soybeans [39].

Mir & Baramjeet [37] also examined the effect of saturation on the bearing capacity of the subgrade using clay soil with an initial density value of 1.84 g/cm$^3$ and an OMC of 16.4%, the results of the modified Proctor test, with soaking treatment variations of 0–5 days. The results showed a drastic decrease in the dry density value of the soil after one day of soaking, the decrease in dry density was minimal the next day, and the CBR value decreased twice lower than that in the unsoaked condition. The drastic decrease in the density value from the initial MDD on the first day occurred due to changes in the water content, which caused the water content in the soil sample to exceed the OMC limit, causing the density to decrease and thus affecting the CBR value. Shirur & Hiremath [19] also analyzed the effect of water content on saturation levels and CBR values. Regarding the relationship between soil CBR value and soil properties, it is found that, based on the results of simple linear regression analysis, the CBR value will decrease with an increase in the values of the plasticity index and water content. The results of these studies correlated with the findings of this study, where the CBR soaked value with a standard soaking period of 96 h is low for each variation in Proctor density without the optimum SCU-CP grouting treatment as a result of an increase in water content that exceeds the OMC limit, thereby changing saturation level and decreasing the density. Based on the results obtained from CBR soaked value, the alternative for stabilizing peat soil that represents the worst conditions in the field due to soil saturation, density of 90% Proctor can be an alternative because it has a CBR value of >6%.

## 4.4. Swelling Potential of Peat Soil Sample

Swelling potential in road pavement construction is analyzed in terms of its effect on the pavement. Yuliet et al. [40] stated that the influence of soil swelling in soil on highway pavement construction causes the phenomenon of heave and cracking in the pavement layer. According to Khursheed et al. [41], it is influenced by three primary characteristics: the CBR value as bearing capacity, water content, and the potential for shrinkage-swelling. Ikeagwuani & Nwonu [42] reported that soil swelling is affected by two essential characteristics, namely the OMC and MDD. Hence, in this study, the swelling potential was conducted in varying densities, i.e., 50%, 70%, and 90% maximum densities resulting from the Standard Proctor density. In addition, the samples were prepared in two treatment conditions: untreated (UT) and treated (TE). Therefore, the correlation between dry density values, CBR values, and the swelling potential in obtaining alternative stabilization of peat soil as a subgrade layer can be analyzed. The measured swelling potential of peat soil is based on the sample height (h1) change to the initial height (h$_o$) from the height change dial reading.

The comparison of the measured swelling potential was also analyzed for its correlation to the decrease in the dry density value compared to the initial density value. The results of comparing the swelling potential of peat soil in untreated (UT) and treated (TE) samples are shown in Figure 10. Referring to Figure 10, the swelling potential measured in the UT sample is greater than that in the TE sample, which is 1.89%, 1.70%, and 0.83% for UT50, UT70, and UT90, respectively, and 1.79%, 0.81%, and 0.70% for TE50, TE70, and TE90, respectively. The decrease in swelling value based on the expansion test results shows that the optimum SCU-CP grouting solution can reduce swelling potential, and the resulting swelling level also depends on the density of the soil. The measurable swelling potential of soil can also measure the level of expansiveness based on the percentage of swelling produced. The classification of the expansivity level proposed by Prakash and Sridharan [43], where the measurement is based on the vertical development of the loaded soil, and the classification of the expansivity level can be seen in Table 4. Referring to Table 4, peat soils belong to the soils with a low level of expansivity and the highest measurable swelling rate produced by soil, which is 1.89% for untreated samples with a density of 50% proctor (UT50) and 1.79% for samples treated with a density of 50% proctor (TE50), but in this case, it should be noted that there is a compaction effect that is carried out so that the level of expansivity decreases. According to Saride et al. [44], although the level of expansivity is low, peat soil is included in soils with high organic content, so the potential for water absorption in saturated conditions needs to be considered from changes in volume.

**Table 4. Degree of the expansiveness of soil classification [43]**

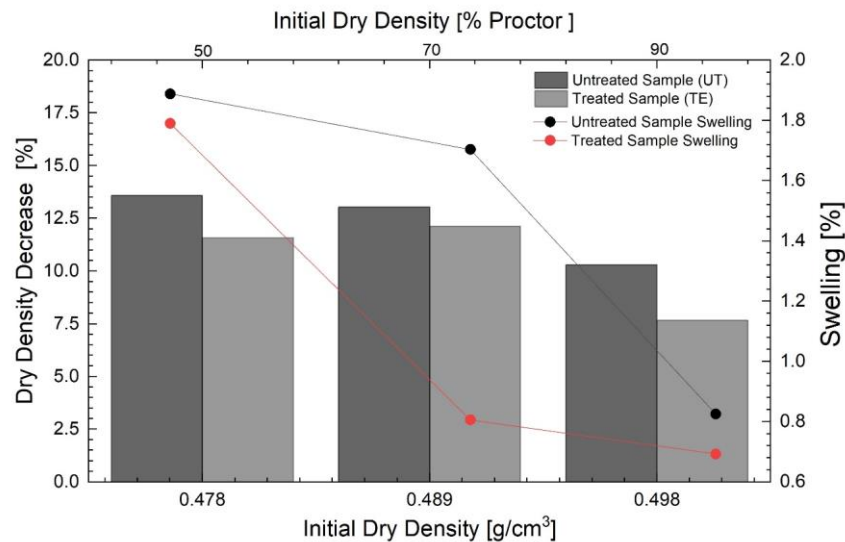| Free Swell Ratio [%] | Clay Type | Soil expansivity |
|---|---|---|
| <1 | Non swelling | Negligible |
| 1–5 | Mixture | Low |
| 5–15 | Swelling | Moderate |
| 15–25 | Swelling | High |
| >25 | Swelling | Very High |

**Figure 10. Swelling potential and MDD decrease of peat soil used in this study**

The measured swelling value in the treated (TE) and untreated (UT) samples decreased, although it was insignificant. This result is related to the effect of the organic content of peat soil. As per Saride et al. [44], organic soil tends to bind water so that it can break the hydration reaction of lime (lime), and with high organic content, the OMC value increases, resulting in a low MDD so that the potential for swelling reduction produced by stabilizing the type of lime has an insignificant decrease. Chen et al. [45] reported that biomass decomposition in organic soils could restrain lime formation between soil grains. Therefore, based on this statement, the stabilization using the calcite precipitation method, which is a type of lime stabilization, can be influenced by the presence of organic content, which can affect the formation of calcite crystals between soil grains. The correlation of dry density value to the resulting swelling potential can be seen in the 90% Proctor density. This Proctor density has a lower swelling value than the 50% and 70% Proctor densities in the untreated and treated samples, 0.85% and 0.70%, respectively. Based on this, the value of swelling soil potential is influenced by dry density, where the higher the dry density level, the lower the swelling value of the soil. This trend follows the research conducted by Ferber et al. [46]; the research resulted in a negative exponential relationship between the dry density and swelling values, where an increase in dry density values will decrease swelling potential values.

In this study, soil samples' initial dry density values decreased after the soaking period. The decrease in dry density values analyzed was carried out on untreated and treated samples. After the soaking period, the dry sensitivity values in untreated samples for each condition, UT50, UT70, and UT90, decreased by 13.58, 13.04, and 10.29%, respectively, to their initial densities. Meanwhile, in the sample with the optimum SCU-CP solution grouting treatment, the percentage decrease was lower than in the untreated sample for the initial density of each condition (TE50, TE70, and TE90), which are 11.58, 12.12, and 7.66%, respectively. The resulting trend based on these results demonstrates the effect of calcite on increasing the bond between soil grains, allowing the potential for expansion and density reduction to be lower than without grouting treatment. This result is in accordance with the statement of Putra et al. [47], where the calcite crystals formed from precipitation can become adhesive between soil grains, reducing the movement between soil grains and increasing stiffness. The swelling potential generated in the treated samples for each density variation indicates that the calcite bond between soil grains can be disrupted. According to [48], stabilization with the type of lime is influenced by organic content; in the presence of a high OMC value, the distance between the soil aggregate grains increases, thereby reducing the level of binding. Felicetti et al. [49] stated that the grain size can affect the adhesion between calcite and soil grains, where the adhesion value will decrease along with the smaller diameter of the soil grains. Following this study, where peat soil is a fine-grained soil, there is an influence between the calcite bonds due to the diameter of the peat soil particles causing swelling, even though the resulting swelling potential is lower than that of the untreated sample. The distribution of calcite formed in soil grains can also affect the level of swelling produced, so SEM testing is required to determine the soil's shape, size, and distribution.

## 5. Conclusion

Stabilization of peat soil using the SCU-CP method increased the CBR value in the treated soil samples (TE50, TE70, and TE90) by 2.91, 2.20, and 2.14 times, respectively, compared to the untreated samples (UT50, UT70, and UT90) in the unsoaked condition. In contrast, the CBR values for the treated samples were increased by 3.8, 2.7, and 2.4 times, respectively, in the soaked condition. The soil density positively correlated with the CBR value; in untreated and treated samples, the highest CBR values were obtained in samples with 90% Proctor density (UT90) under soaked

and unsoaked conditions. The higher the density of the soil, the greater the CBR value. Soil density significantly affects the CBR value because an increase in density can reduce the distance between soil particles due to the reduced pore space, resulting in a change in the level of soil consistency. In this study, the increase in CBR value was also influenced by the treatment of mixing the solution on the soil sample using the premixing method, where the premixing method of the calcite precipitation was not limited by the amount of pore space and density level.

Density variations in soil affect the CBR value when using the optimum SCU-CP solution. In the treated samples, the highest increase in CBR value was found at 50% Proctor density (TE50) compared to samples TE70 and TE90. Although the value of the resulting CBR does not meet the requirements of the subgrade (<6%), it indicates that the effective increase in the CBR value is due to the presence of calcite bonds in soil particles that occur at 50% Proctor density. The high level of density can reduce the effectiveness of calcite binding between soil particles because calcite crystals are formed at short distances. Alternatives that can be recommended based on the test results, namely unsoaked CBR, which represents typical conditions in the field, 70% and 90% Proctor densities with the optimum SCU-CP grouting treatment, can be used as a method of stabilizing peat soil as a subgrade. However, considering the compaction effort, 70% Proctor density under normal conditions is the best alternative. Furthermore, considering the soil saturation level in the field in soaked conditions and swelling in the subgrade, 90% Proctor density with grouting treatment can be recommended as a "non-dewatering stabilization method. It is necessary to evaluate the distribution of calcite so that it can be determined if the mass of calcite in the sample segment is related to the uniform distribution of calcite and swelling potential.

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, H.P. and I.Y.; methodology, H.P.; validation, I.Y. and H.P.; formal analysis, I.Y.; investigation, I.Y.; resources, I.Y.; data curation, I.Y and H.P.; writing—original draft preparation, I.Y.; writing—review and editing, H.P.; visualization, I.Y. and H.P.; supervision, H.P.; project administration, H.P.; funding acquisition, H.P. 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 in the article.

### 6.3. Funding

### 6.4. Conflicts of Interest

The authors declare no conflict of interest.

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