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Improvement of the Shear Strength and Reduction of the Permeability of Sandy Soil using *Soybean Crude Urease Calcite Precipitation* (SCU-CP)

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Abstract: Calcite precipitation is a sustainable soil improvement method because it can increase soil strength and is environmentally friendly. This study aimed to evaluate the use of an innovative soil improvement method, namely soybean crude urease calcite precipitation (SCU-CP), in modifying the strength and permeability of sandy soil. Two types of reagents based on their purity, namely pro analysis (PA) and technical (technical grade), combined with two types of soybeans, namely seeds (conventional) measuring 0.1–0.5 mm and manufactured soybean powder measuring <0.1 mm, were used in this study as the main ingredients in the preparation of calcite. This research was conducted using various tests, including test-tube testing, soil characterization, compressive strength testing (UCS), and permeability testing. The results showed that the variation in reagent purity had no significant effect on the sand soil parameters. Technical and pro-analytical reagents can produce significant soil strength in soils with UCS values >50 kPa and reduce permeability by 50%. Meanwhile, soybean type is an important parameter affecting soil strength in the SCU-CP method. The smaller size of the soybean can lead to a large amount of soybean content in the SCU-CP solution, which affects the disruption of the calcination and bonding process in the soil. This study also showed that the variation in curing time had no significant effect on the soil properties. This study concluded that the particle size of soybean powder is an important factor in the SCU-CP method.

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1. Introduction

As the population grows, so does the need for land for infrastructure development in the region. However, this increase is not followed by an increase in the amount of land available; therefore, currently, infrastructure development must be carried out on various land conditions, including soils with low bearing capacity, such as loose sand. Therefore, a soil improvement method is required to increase the shear strength of sand for its use as a construction site. Efforts to improve the strength of sandy soils have been carried out using a variety of methods, such as polypropylene fiber synthesis materials [1,2], eggshell waste and mine dust [3], and chemical grouting material injection methods, such as biopolymer and calcite precipitation methods [4–7].

The results of research conducted by Yasuhara et al. [8] show that the strength of sandy soil after improvement by the calcite precipitation method with pure urease can produce strength values of up to 400 kPa. Research was also conducted on the permeability of sandy soil, and it was found that the hydraulic conductivity of sandy soil was significantly reduced, and a permeability of $1x10^{-2}$ cm/s was produced. The use of pure urease as a catalyst is considered less economical because of its high cost, which accounts for 90% of the total material cost [9].

This method of utilizing soybeans is known as the soybean crude urease calcite precipitation (SCU-CP) method [10]. Based on the results of research conducted by Pratama et al. (2021), the use of soybean as a biocatalyst can replace pure urease with an increase in soil strength of up to 623.18 kPa [11]. Another study reported that the use of soybeans in the calcite precipitation method can increase the strength of sandy soil by up to 168 kPa [12].

The soybean crude urease calcite precipitation (SCU-CP) method uses a solution with a combination of calcium chloride ($CaCl_2$) and urea as a reagent that acts as a reaction-forming compound, and the addition of soybean biocatalysts to form calcium carbonate ($CaCO_3$) crystal precipitates. The application of the SCU-CP method on a large scale requires attention to economic value, in addition to the effectiveness of the improvements that can be achieved in the improved soil; therefore, the quality and purity of the materials used are very important. The use of high-purity reagent materials (purity level >90%) has been reported to be highly effective [13,14]. However, the application of this method on a large scale is limited by high material costs; therefore, it is necessary to evaluate the effectiveness of using reagents with lower purity as an alternative replacement to reduce material costs in the calcite precipitation method. Technical-grade reagents are an alternative to pro-analysis reagents because, in addition to being relatively cheaper, these grade reagents also have a purity level of more than 50% [15]. In addition to strength, the soil permeability parameter is also important for evaluating the effectiveness of the calcite method for soil improvement. Reduced soil permeability values indicate the presence of calcite deposits that fill soil pores [8,16]. In this study, variations in reagent purity and soybean type were evaluated to determine their effect on the ability of the SCU-CP method to increase the strength and decrease the permeability of sandy soils. In addition, the curing time of the samples after reinforcement with the SCU-CP solution was evaluated for its effect on soil strength and permeability parameters.

2. Materials and Methods

2.1. Materials

The materials used in this study included Bangka sand, soybean seeds crushed to a size of 0.1–0.5 mm (conventional soybeans), Gasol brand soybean powder with a size <0.1 mm, Emsure ACS brand pro-analysis grade urea with a purity of >95%, urea with technical grade specifications, Emsure ACS brand pro-analysis grade calcium chloride ($CaCl_2$) dihydrate with a purity of >95%, calcium chloride ($CaCl_2$) dihydrate with technical grade specifications, and distilled water.

2.2. Research Procedures

Tests were carried out starting with calcite precipitation testing, properties, compressive strength testing, and soil permeability. Tests were conducted with four combinations of sample variations: pro-analysis reagent + Gasol soybean (GL); pro-analysis reagent + soybean powder (SL); technical reagent + Gasol soybean (GT); and technical reagent + soybean seed powder (ST), as presented in Table 1. Calcite precipitation tests were conducted to determine the mass of calcite precipitation and the calcite precipitation ratio. The concentrations of the reagents and soybeans used in all variations were based on the optimum composition reported by Pratama et al. [11], namely, the reagent solution used was 1 mol/L for both urea and $CaCl_2$, and the composition of soybeans used as a biocatalyst was 20 g/L. Soil property tests were conducted to determine the characteristics and classification of the soil used, including grain size, specific gravity, and porosity.

The strength of the soil was evaluated using unconfined compression strength (UCS) testing to determine the strength of the sandy soil at various repair variations. In this test, the soil samples were improved with four variations of reagent soybean and three variations of curing period, namely 7, 14, and 21 days. The soil compressive strength test was conducted according to SNI 3638:2012 [17] regarding the free-compressive strength test method for cohesive soils. The strength value (UCS) is indicated by the ratio of the maximum load factor to the cross-sectional area of the test specimen. Soil permeability testing was conducted to determine the ability of sandy soil to pass water before and after the SCU-CP method. This test was conducted according to JIS A1218 [18] regarding the method for permeability of saturated soil, with four sample variations based on the reagent and soybean composition.

Table 1. Experimental condition

Sample	Reagent grade	Soybean
GL	Pro Analysis	Gasol <0.1 mm
SL	Pro Analysis	Conventional 0.1 - 0.5 mm
GT	Technical	Gasol <0.1 mm
ST	Technical	Conventional 0.1 - 0.5 mm

3. Result and Discussion

3.1. Calcite Precipitation

Calcite precipitation tests were conducted to evaluate the amount and ratio of precipitation produced for each reagent and soybean composition. The results of the precipitation tests are shown in **Figure 1**. Figure 1 shows that all four reagents and soybean variations produced high calcite masses and precipitation ratios of approximately 100%. Gasol soybean produced the highest amount of precipitate and precipitation ratio in both pro-analysis reagent (GL) and technical reagent (GT), with the amount of precipitate reaching 3.44 g with a precipitation ratio of 114.78%. Meanwhile, the use of soybean seed powder produced a slightly lower amount of 2.95–3.31 with a ratio of 110.44%. This may be due to differences in the quality of the two types of soybeans used. Soybean selection and pretreatment before milling could be the cause of this quality difference.

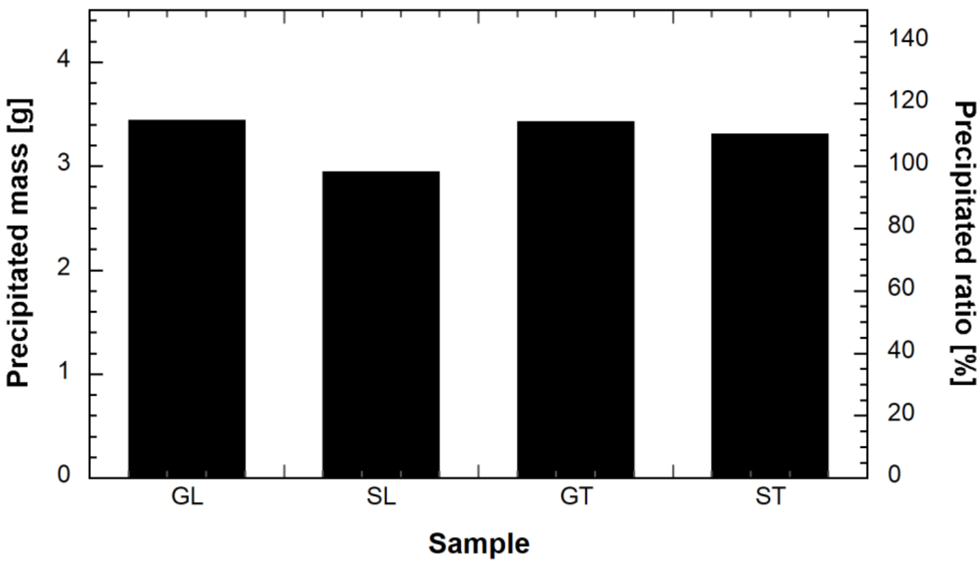

Figure 1. Calcite precipitation test results

Further research on the pre-treatment of soybeans from seeds to powder is needed in future studies. The precipitation ratio is the ratio between the mass of calcite precipitation formed in the SCU-CP solution and the theoretical mass of calcite formed according to the hydrolysis reaction, which is 3 g. The mass of calcite precipitation is the amount of precipitate formed in the SCU-CP solution. The resulting precipitation ratio value was more than 100% in each variation, except for the SL variation, which produced a value close to 100%. A precipitation ratio exceeding 100% indicates that the material remained in the SCU-CP solution [14]. The material was delivered as soybean paste sediment, which had a high consistency but did not contain calcite [19].

3.2. Soil Properties

Soil property tests were conducted to determine the physical properties and classification of the soil used. The testing parameters related to soil properties included specific gravity, pore number, and grain size gradation. Based on the specific gravity test results, the specific gravity of the sample soil particles was 2.60, with pore number values during maximum (e_{maks}) and minimum (e_{min}) conditions of 0.91 and 0.69, respectively. The actual pore number value (e) used for the soil sample was 0.81. The results of the grain size gradation test obtained the D10, D30, and D60 values of the sand samples tested were 0.21 mm, 0.32 mm, and 0.49 mm, respectively, resulting in a uniformity coefficient (Cu) of 2.39 and a gradation coefficient (Cc) of 1.02. Hence, according to the Unified Soil Classification System (USCS), the sand sample tested was classified as poorly graded sand (SP) [20]. The results of the grain size gradation analysis are presented in **Figure 2**.

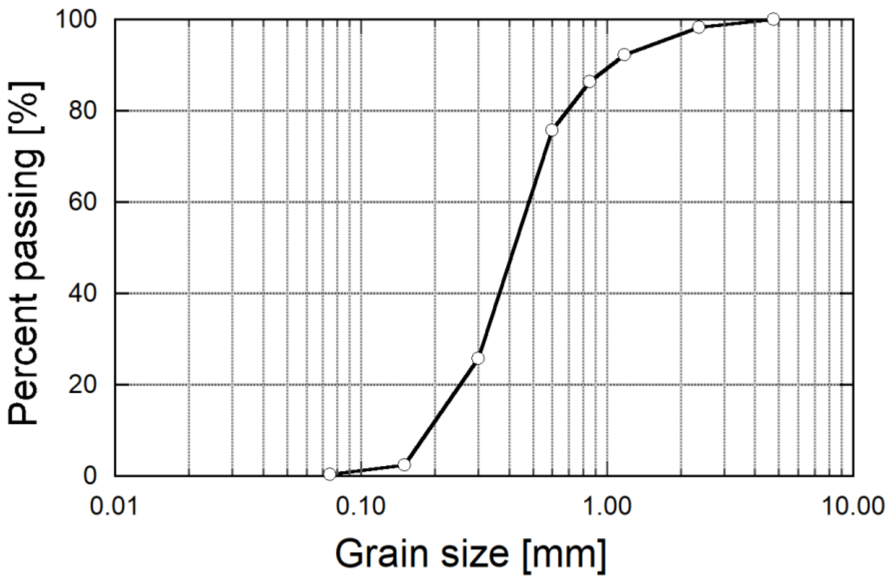

Figure 2. Grain size gradation of sand soil samples

3.3. Soil Strength

UCS testing was conducted to determine the free compressive strength (qu) of the soil samples. In this study, UCS testing was conducted to determine the strength of soil after improvement using the SCU-CP solution at various combinations of reagents and soybeans. In this study, soil samples were treated with soil improvement using the SCU-CP method with four variations of reagents and soybean materials (GL, SL, GT, and ST), as well as 7, 14, and 21 days of curing time. The UCS values of sand soil after the application of SCU-CP are shown in **Figure 3**. Figure 3 shows that the resulting soil strength values varied with each combination of reagent and soybean, with a maximum strength value of 66.18 kPa achieved in the pro-analysis reagent + technical reagent variation at 14 d curing time. These results also indicate that the purity of the reagents used did not significantly change the UCS values. In contrast to the use of soybeans, soybean powder derived from soybean seeds produced better UCS values for both types of reagents used. This may have occurred because of the difference in the size of the two types of soybeans used. Gasol soybeans have a smaller size (<0.1 mm) than the powder from ground soybean seeds (0.1–0.5 mm).

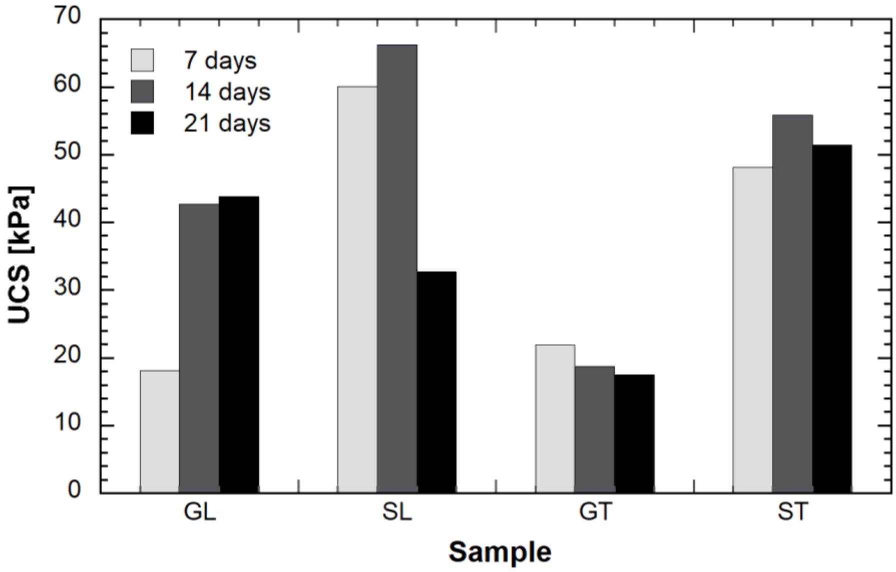

Figure 3. UCS Test Results

The effect of soybean powder size can affect the organic content that is not dissolved in the SCU-CP mixture, which can interfere with the calcination process, thus affecting the strength of the resulting soil [21]. A larger soybean size increases the mass of soybeans that are not dissolved in the solution and do not pass through the sieve during SCU-CP solution preparation [12]. The difference in the UCS values can also occur due to the formation of calcite bonds in the soil that are disturbed by the organic content produced by soybeans [22]. This can be identified from the amount of precipitate formed, which exceeded the 100% ratio. In addition, variations in curing time generally did not have a significant effect on soil strength, indicating that the calcination process was completed after a sample age of 7 d; therefore, the additional curing time had no effect on soil strength [23,24]. The results of this study also indicate that the use of technical reagents can achieve a relatively high soil strength of 66.18 kPa.

3.3. Soil Permeability

The permeability value is important for determining the effect of calcite formed in the process of soil improvement by the SCU-CP method on the ability of sand soil to pass water, expressed by the permeability coefficient value. Sand permeability testing in this study was conducted on four variations of samples that had been treated with SCU-CP, as in the free compressive strength test, and control samples without treatment. The results of the soil permeability testing are shown in **Figure 4**. The permeability test results show that the permeability value in the control sample (without improvement) and after improvement with the SCU-CP method in four variations of reagents and soybean powder, namely GL, SL, GT, and ST, are 0.22, 0.11, 0.15, 0.16, and 0.19 cm/s, respectively.

The soil permeability in the control sample showed the highest value of 0.22 cm/sec. The addition of the SCU-CP solution in all variations significantly decreased the permeability value. Soil samples reinforced with pro-analysis reagent and Gasol soybean (GL) exhibited the lowest permeability values. This was followed by samples with pro-analysis reagent and conventional soybean (SL), technical reagent and Gasol soybean, and finally technical reagent and conventional soybean. These results also indicate that the quality of the reagents and soybeans greatly affects the resulting soil permeability values. In addition, the resulting permeability value also shows that the improved subsoil can still pass water, even though its strength has increased. This is an advantage of this method, as it does not make the improved soil impermeable [8,25].

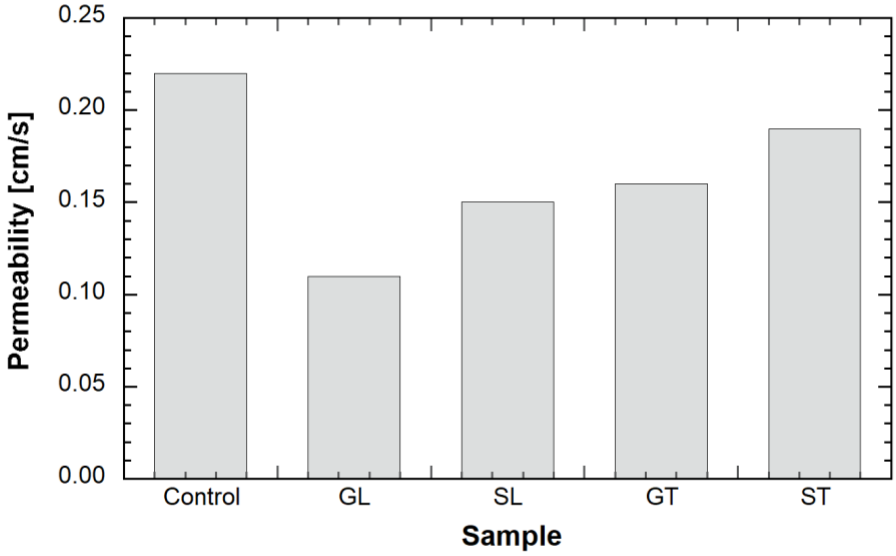

Figure 4. Soil permeability test results

4. Conclusion

The SCU-CP method is a soil improvement method that utilizes soybean as a biocatalyst to form calcite. Based on the results, it is known that variations in the reagent purity and the size of the soybeans used as samples affect the strength of the sand soil. The purity of the reagent did not significantly affect the resulting soil strength. Meanwhile, the use of soybean powder pulverized to a larger size of 0.1–0.5 mm showed better results than Gasol soybeans <0.1 mm. The sample achieved the highest sand soil strength in the combination of technical reagents and soybean powder, with a UCS value of 66.18 kPa. The curing time variation in the samples showed that the curing time did not affect the resulting soil strength values. The effect of using the SCU-CP method also influenced the soil permeability value, which reached a maximum decrease of 50% from the control sample. This shows that the increase in soil strength after soil reinforcement using the SCU-CP method does not cause the soil pores to be completely closed and still allows water to pass through. This result is certainly very good from an environmental perspective. The results of this study indicate that the SCU-CP method with technical reagents and pulverized soybean powder can be used as an effective and environmentally friendly alternative soil improvement method.

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