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Comparison of Shear Strength between Peat Soil Grouting and Biogrouting

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Abstract: Peat soil presents major challenges for civil engineering applications due to its high acidity, low bearing capacity, low shear strength, and high water content. This study investigates the improvement of peat soil shear strength through a combined stabilization approach: grouting using industrial and agricultural waste materials, followed by biogrouting employing indigenous Bacillus cereus. Calcium carbide residue (CCR) and rice husk ash (RHA) were used as grouting agents to supply calcium and silica for the formation of calcium silicate hydrate (C–S–H) compounds. Subsequently, biogrouting was carried out on selected specimens using B. cereus isolated from peat soil in Cikarang, Indonesia, to induce $CaCO_3$ precipitation. Bacterial treatment was applied 30 days after grouting. For the grouting-only specimens, cohesion increased by 124.62% with an internal friction angle gain of 5° after 30 days; after 60 days, cohesion increased by 137.58% and friction angle by 7°; and after 90 days, cohesion reached a 148.13% increase relative to untreated peat. The incorporation of B. cereus via biogrouting further enhanced shear strength. After 30 days of biogrouting, cohesion increased by 115.73% relative to the 60-day grouting-only condition, with a 2° friction angle. After 60 days of biogrouting, cohesion improved by 151.03% compared with the 30-day biogrouting condition, with a 3° friction angle; after 112 days, cohesion rose by an additional 32.83%, with a 4° friction angle. The study provides three main contributions: the combined use of CCR and RHA as sustainable waste-based grouting materials, the application of indigenous B. cereus as a biogrouting agent, and a two-stage stabilization strategy that first reduces peat acidity through grouting and then applies biogrouting to further enhance shear strength.

Keywords: peat soil; Bacillus cereus; calcium carbide residue; rice husk ash; biogrouting; soil stabilization.

泥炭土注浆与生物注浆抗剪强度的对比研究

摘要：泥炭土因其低 pH 值（高酸性）、低承载力、低抗剪强度及高含水量等特性，给工程建设带来诸多挑战。本研究旨在通过利用废弃材料进行注浆改良，并结合蜡状芽孢杆菌（*Bacillus cereus*）进行生物注浆，以改善泥炭土的工程性质。注浆材料采用电石渣（Calcium Carbide Residue, CCR）与稻壳灰（Rice Husk Ash, RHA），分别提供钙源与硅源，以形成硅酸钙水化物（C-S-H）。除常规注浆稳定外，部分样品进一步进行了生物注浆处理。生物注浆通过利用从印度尼西亚芝加朗（Cikarang）土壤中分离得到的蜡状芽孢杆菌诱导碳酸钙（$CaCO_3$）沉淀来实现。菌液在注浆稳定处理 30 天后加入。经注浆稳定 30 天后，土壤黏聚力提高了 124.62%，内摩擦角增加到 5°；60 天后，黏聚力提高至 137.58%，内摩擦角为 7°；90 天后，黏聚力提高至 148.13%。与传统注浆相比，采用蜡状芽孢杆菌（*Bacillus cereus*）进行生物注浆的土样在黏聚力增强方面表现出显著优势。30 天生物注浆后，黏聚力较 60 天传统注浆样品提高 115.73%，内摩擦角为 2°；60 天生物注浆样品的黏聚力较 30 天提高 151.03%，内摩擦角为 3°；112 天后，黏聚力较 60 天进一步提高 32.83%，内摩擦角为 4°。本研究的创新点包括：（1）将电石渣与稻壳灰联合用作废弃物注浆材料；（2）采用本地分离的蜡状芽孢杆菌作为生物注浆菌种；（3）提出“先注浆降低酸度，再生物注浆强化”的复合稳定化方法。

关键词：泥炭土；蜡状芽孢杆菌；电石渣；稻壳灰；土壤稳定化.

1. Introduction

Indonesia contains one of the largest peatland areas worldwide, with an estimated 14.9 million ha, accounting for approximately 7.8% of the country’s total land area [1]. Peat is widely recognized as a problematic geomaterial, characterized by low bearing capacity, high compressibility, high moisture content, and large settlements under structural loads [2,3]. Since bearing capacity is closely linked to shear strength, the inherently low shear strength and high water content of peat necessitate improvement before it can safely function as a subgrade. Soil improvement may be achieved by adding stabilizing agents or by employing reinforcement techniques. Horizontal reinforcement has been extensively applied; bamboo grid reinforcement, for example, has been shown to increase the bearing capacity of peat soils [4–6]. Vertical reinforcement can be implemented using bamboo piles, concrete piles, or nailed slab systems. Bamboo piles have been reported to reduce settlement under embankment loads [7,8], while nailed slab systems and concrete piles can stiffen the reinforcement system, increase bearing capacity, and reduce settlement [9–11]. These reinforcement systems are generally more suitable for relatively thick peat deposits. By contrast, improvement of a shallow peat layer (on the order of 1 m) can be more effectively achieved through stabilization treatments. In this study, peat improvement was carried out using grouting and biogrouting.

Grouting is a soil stabilization technique in which chemical agents are mixed with the soil to enhance its strength [12]. In this work, calcium carbide residue and rice husk ash were used as grouting agents, each at 3.5% of the dry soil weight. Calcium carbide residue was selected as a calcium source because it is a waste product from acetylene gas production processes, such as welding and space heating [13]. Rice husk ash was selected as a silica source because rice production in Indonesia reached 55.16 million tons in 2020 [14], with rice husks constituting approximately 20–30% of the grain weight and typically remaining underutilized.

Thus, the combined use of these two materials offers a potential waste valorization pathway. Previous studies have shown that mixing calcium carbide residue and rice husk ash can increase soil strength [15].

In addition to grouting, soil improvement was also carried out using biogrouting. Biogrouting is a stabilization technique that employs microorganisms to induce calcium carbonate ($CaCO_3$) precipitation. The $CaCO_3$ crystals produced during this process can fill pores and act as a cementing agent between soil particles, thereby improving soil strength and stiffness [16]. In the present study, biogrouting was applied 30 days after the grouting process, once the chemical stabilization had taken effect. Bacillus species are known to produce $CaCO_3$ crystals depending on the growth medium [17].

Soil stabilization can be achieved through various stabilizing materials, including lime, cement, volcanic ash, rice husk ash, and other pozzolanic additives. The addition of lime, volcanic ash, or their combination has been shown to increase the California Bearing Ratio (CBR), reduce swelling potential, and decrease the plasticity index [18]. Similarly, improvement using cement and rice husk ash has been reported to enhance soil properties, such as lowering the liquid limit and plasticity index, and increasing shear strength [19].

Environmentally friendly soil improvement can be realized by injecting bacteria into the soil matrix. Bacterially treated soils have demonstrated increased shear and compressive strength, particularly with longer curing periods. For organic soils treated with Bacillus subtilis, extended curing times led to progressive gains in shear strength [20]. Comparable trends have been observed in expansive soils, where free compressive strength and cohesion increased with curing time [21].

The bacterium used in this study was Bacillus cereus. Bacillus cereus is a Gram-positive species, typically 3–5 μm in length and 1–1.2 μm in diameter. It grows primarily under aerobic conditions, although some vegetative cells can survive in anaerobic environments. Bacillus cereus can grow over a broad temperature range of 4–55 °C and at pH values between 4.9 and 10. It can ferment glucose, fructose, and trehalose, but not pentoses or many other sugar alcohols [22]. Bacillus cereus is commonly found in soil, and in this study, the strain was isolated from the Cikarang area. Although B. cereus is an opportunistic pathogen often associated with foodborne illness, several strains are commercially used as human probiotics, and in natural environments B. cereus can suppress plant diseases caused by pathogens [23]. A B. cereus strain isolated from dolomite surfaces in karst environments has been reported to precipitate $CaCO_3$ [24], and urease activity in B. cereus has been shown to induce biomineralization [25].

Previous research has consistently indicated that peat soil requires improvement before it can be used as a reliable subgrade material. To be suitable for subgrade applications, peat must satisfy minimum requirements for bearing capacity and shear strength. Biogrouting has emerged as a promising technique for enhancing subgrade performance, but systematic comparisons between biogrouting and conventional grouting in peat soils remain limited. Therefore, this study aims to compare the effectiveness of grouting and biogrouting in improving the shear strength and overall engineering performance of peat soil.

2. Methods

2.1. Materials and Equipment

In this study, laboratory tests were carried out to determine the physical and mechanical properties of peat soil and its improvement after grouting and biogrouting. The main materials and equipment used were as follows:

1. Disturbed peat soil sampled from Kubu Raya, West Kalimantan, Indonesia.
2. Culture medium composed of 0.6 g/120 mL yeast extract, 0.6 g/120 mL dextrose, and 0.3 g/120 mL calcium carbide residue.
3. Bacillus cereus bacteria used as the biogrouting agent.
4. Triaxial shear test apparatus for determining shear strength parameters.
5. Additional standard geotechnical laboratory equipment required for sample preparation, curing, mixing, and testing (e.g., mixers, moulds, balances, moisture cans, and curing containers).

2.2. Preparation of Specimens

The peat soil used in this research was obtained in a disturbed state. Tests on soil characteristics were first conducted on the untreated (pure) peat soil. Subsequently, mechanical testing was performed on three groups of specimens: untreated peat soil, peat soil stabilized by grouting, and peat soil stabilized by grouting followed by biogrouting.

For the grouting-stabilized specimens, peat soil was thoroughly mixed with the designated proportions of calcium carbide residue and rice husk ash to obtain a homogeneous mixture before placement into the moulds. The overall preparation procedure for grouting stabilization is illustrated in Figure 1.

Biogrouting-treated specimens were prepared by first applying the grouting treatment and allowing it to cure, followed by the introduction of the bacterial suspension according to the biogrouting protocol described in the subsequent sections.

(a)　　　　　　　　　　　　(b)　　　　　　　　　　　　(c)

Figure 1. Grouting research materials: (a) Peat; (b) Calcium Carbide Waste; (c) Rice Husk Ash (Photo by the authors)

Before testing the shear strength of the soil, the peat soil is first compacted by pounding it 25 blows [26]. After compaction, the peat soil is moulded to the desired size. For the grouting and biogrouting stabilisation specimens, the soil was mixed with calcium carbide waste and rice husk ash, each as much as 3.5% of the total weight of the soil, before compaction. For biogrouting stabilisation specimens, bacteria were added 30 days after the soil was stabilised by the grouting method.

2.3. Bacterial Preparation

The bacterial preparation process consisted of making culture medium and liquid culture of bacteria, the process of inoculation bacteria, the process of incubation bacteria, and readings of bacterial growth (Figure 2). Culture medium is a growth medium that provides nutrients and energy for bacteria. Bacterial liquid culture is a culture medium to which bacteria have been added after the bacterial inoculation process.

Inoculation is the process of transferring bacteria from one medium to another. This process is carried out aseptically so that bacteria are not contaminated. The bacterial liquid culture was incubated in an incubator shaker machine for 24 hours at a speed of 100 rpm and a temperature of 37°C. After incubation, bacterial growth was measured using a spectrophotometer, which provided Optical Density (OD) readings. The OD value is the turbidity value of the medium. The OD reading aims to determine the density of bacteria growing in the medium. The higher the OD value, the more bacteria are assumed to be in the medium.

After all the bacterial preparation processes were completed, a liquid bacterial culture medium was added to the previously prepared specimens to test the soil's mechanical properties. Each test object was added with 10 mL of bacterial liquid culture.

(a)　　　　　　　　　　　　(b)　　　　　　　　　　　　(c)

Figure 2. Biogrouting research materials: (a) Bacterial liquid cultures; (b) Liquid culture of bacteria after incubation; (c) Samples with bacterial liquid cultures (Photo by the authors)

2.4. Soil Characteristic Test

The process of testing soil characteristics is conducted on peat soil. The tests carried out include testing the specific gravity, the density, the moisture content, and the ash content. The device provides a measurement accuracy of precision and complies with standard ASTM requirements. Testing of soil-specific gravity, soil density, and soil moisture content is carried out based on the Soil Mechanics Laboratory Manual [26]. Soil ash content testing was carried out according to ASTM D-4427. It involved burning dry peat soil at 440 ± 40°C for one hour.

2.5. Soil Properties Testing

The soil properties were tested to determine the shear strength of the peat soil. The soil properties were tested on pure peat soil with stabilised grouting, with treatment periods of 30, 60, and 90 days, and on peat soil with added Bacillus cereus bacteria, with curing periods of 30, 60, and 112 days. The test carried out is triaxial, as shown in Figure 3.

Figure 3. Triaxial test (Photo by the authors)

Triaxial testing will determine the value of the angle of internal friction (ϕ) and the cohesion (c). The test is conducted based on the Soil Mechanics Laboratory Manual [26]. All experiments were performed under controlled laboratory conditions at a temperature of 20-25 °C and relative humidity of 40-60%.

3. Results and Discussion

3.1. Soil Characteristic Test Results

The test results discussed include the results of testing for soil-specific gravity, soil density, moisture content, and ash content. From the test results above, itcan also be calculated the value of the void ratio, porosity, and degree of saturation.

The following are the results obtained from the tests carried out, as shown in Table 1. The physical properties of the soil were determined prior to testing for peat soils as these values applicable.

3.2. Comparison of Soil-Grouting and Biogrouting on Stress-Strain Relationship

The soil properties test is triaxial. The test was conducted to determine the values of cohesion and angle of internal friction, as shown on the Mohr circle graph. To investigate the effect of grouting stabilising agents and bacteria on the cohesion and angle of internal friction, tests were conducted on pure peat soil, peat soil mixed with a grouting stabilising agent, and soil supplemented with a liquid culture of Bacillus cereus bacteria. For soils combined with stabilising agents, tests were conducted after 30, 60, and 90 days. In contrast, tests for soils supplemented with bacterial liquid culture were performed after 30, 60, and 112 days. Each test was carried out with three soil samples.

Table 1. The results of testing soil characteristics

No.	Parameter	Unit	Value
1.	Specific Gravity	-	1,721
2.	Wet Density	gr/cm^3	1,11
3.	Moisture Content	%	238,56
4.	Dry Density	gr/cm^3	0,33
5.	Void Ratio	-	4,15
6.	Porosity	-	0,806
7.	Degree of Saturation	%	96,46
8.	pH	-	6,4

The results of the triaxial test show the relationship between stress and strain in soil grouting and bio-grouting, as shown in Figure 4 and Figure 5. Soil improvement with stability grouting and biogrouting is quite effective in increasing the ability of peat soil to carry loads. The results showed that bio-grouting improved peat soil was still better than peat-grouting in supporting the load. The curing period is also seen to have a good impact on increasing the ability of peat soil to carry loads.

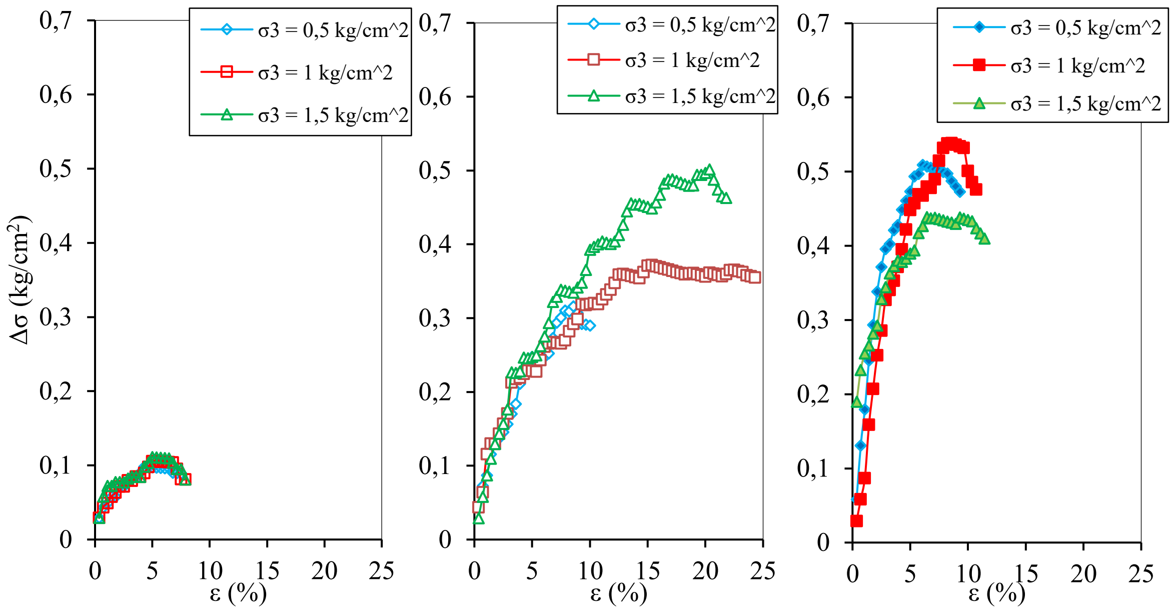

Figure 4. Relationship between strain and soil deviatoric stress: (a) Pure peat; (b) 30-day grouting; (c) 30-day biogrouting (Developed by the authors)

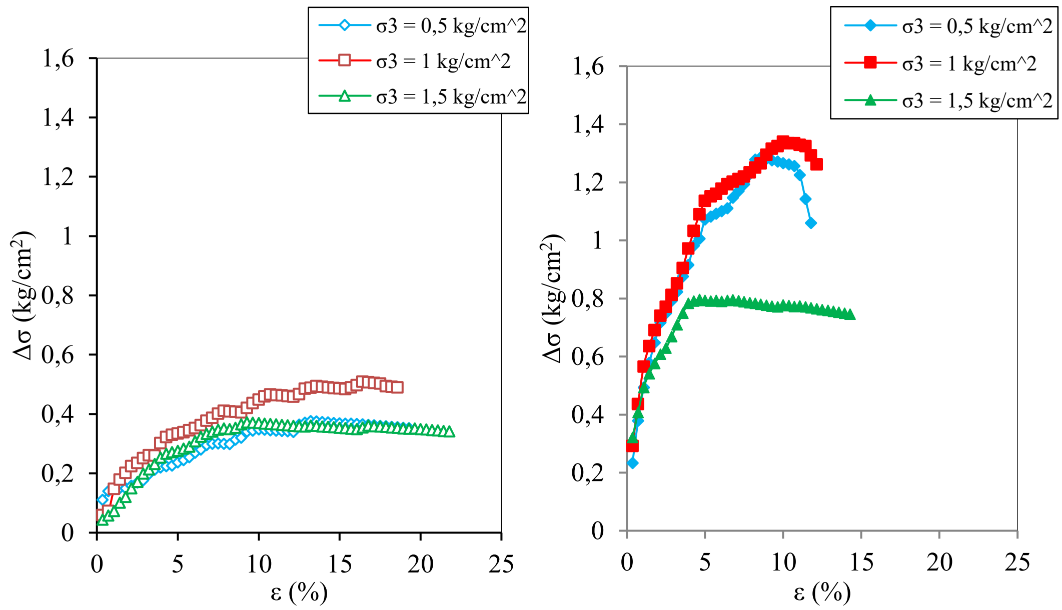

Figure 5. Relationship between strain and soil deviatoric stress: (a) 60-day grouting; (b) Biogrouting 60 days (Developed by the authors).

3.3. Comparison of Soil-Grouting and Biogrouting on Parameters of Shear Strength

Table **2** presents the parameters of shear strength, including cohesion and the angle of internal friction. There is an increase in the cohesion value in peat soil due to soil improvement by stabilising grouting and biogrouting. The cohesion value of peat soil with stabilised grouting, with a treatment period of 30 days, increased by 124.62% compared to pure peat soil, from 0.0455 kg/cm^2 to 0.1022 kg/cm^2.

Table 2. Triaxial test results (Developed by the authors)

Soil Sample	Curing Period (days)	Cohesion (kg/cm^2)	The Angle of Internal Friction (°)
Peat Soil	-	0.0455	0
Soil Grouting	30	0.1022	5
	60	0.1081	7
	90	0.1129	7
Biogrouting Soil (+30 days of grouting)	30	0.2332	2
	60	0.5854	3
	112	0.7776	4

The comparison of the cohesion values of peat-grouting and bio-grouting soils can be seen in Figure 6. These results indicate that adding a grouting stabilising agent can increase soil cohesion. The increase in cohesion value for peat soil with stabilised grouting, after a treatment period of 60 days, was only 5.77% of that for the soil with a treatment period of 30 days, from 0.1022 kg/cm^2 to 0.1081 kg/cm^2. The cohesion value in soil with a treatment period of 90 days also increased by 4.44% from soil with a treatment period of 60 days, from 0.1081 kg/cm^2 to 0.1129 kg/cm^2. These results indicate that the treatment period can increase the value of soil cohesion, but not significantly.

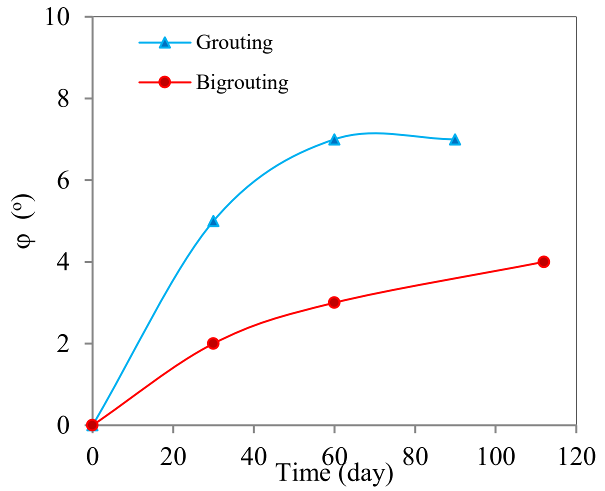

Figure 6. Comparison of peat soil cohesion values (Developed by the authors)

Stabilisation of biogrouting with Bacillus cereus bacteria was carried out on the soil after 30 days of grout stabilisation. The results of the cohesion values of the soil with 30 days of biogrouting stabilisation were 115.73% greater than those of 60 days of grouting stabilisation, from 0.1081 kg/cm^2 to 0.2332 kg/cm^2. These results indicate that the precipitation of CaCO3 by Bacillus cereus bacteria can increase the value of soil cohesion. In the soil with 60 days of biogrouting stabilisation, the cohesion value increased by 151.03% from that of the soil with a 30-day curing period, from 0.2332 kg/cm^2 to 0.5854 kg/cm^2. Then, on the soil with biogrouting stabilisation for 112 days, the cohesion value increased by 32.83% from the soil with a curing period of 60 days, from 0.5854 kg/cm^2 to 0.7776 kg/cm^2. These results indicate that the curing period of bacteria can increase the value of soil cohesion. In contrast to grouting, the increase in biogrouting-stabilised soil is quite large. This is because, as long as nutrients and calcium are in the soil, bacteria can continue to grow and precipitate CaCO3.

The increase in the shear angle in the soil can be seen in Figure 7. Soil with grouting stabilisation for 30 days experienced an increase in the angle of internal friction by 5°, compared to pure peat soil without an internal friction angle. These results prove that the addition of a grouting stabilising agent is beneficial in increasing the angle of internal friction. The increased angle of internal friction is also influenced by the soil treatment period, as seen from the results of the angle of internal friction with grouting stabilisation for 60 days, increasing by 2° from the soil with grouting stabilisation for 30 days, i.e., from 5° to 7°. Then the angle of internal friction with grouting stabilisation for 90 days did not increase.

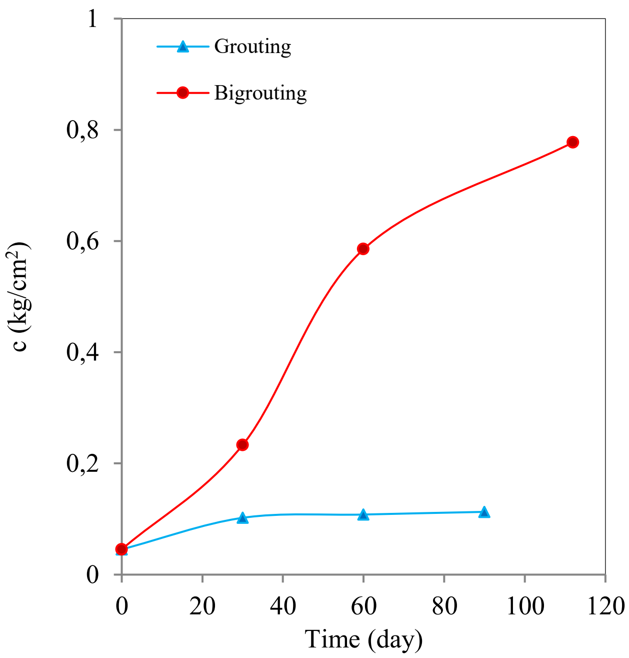

Figure 7. Comparison of the angle of internal friction in peat soil (Developed by the authors)

For soils with biogrouting stabilisation for 30 days, in contrast to the cohesion value, the angle of internal friction is 2°. Then, the angle of internal friction with biogrouting stabilisation for 60 days increased from the soil with biogrouting stabilisation for 30 days, which was 3°. Then, the angle of internal friction with biogrouting stabilisation for 112 days also increased from the soil with biogrouting stabilisation for 60 days, which was 4°. In general, the angle of internal friction with stabilised biogrouting is smaller than that in the soil with stabilised grouting. In this case, further research is needed.

4. Conclusion

Some of the conclusions obtained in this study included:

1. The addition of grouting material can increase peat soil shear strength. This can be seen from the increase in the cohesion value of the peat soil by 124.62% and the angle of internal friction by 5° after a 30-day curing period. The curing period of the grouting material affects the value of the shear strength of the peat soil, but it is not significant. It examines the increase in cohesion and internal friction angle from

30 to 60 days and from 60 to 90 days, which rose by 5.77% and 4.44%, respectively. The angle of internal friction is increased by 2°.

2. Treating two soil improvement methods can increase the shear strength of soil peat compared to only the grouting stabilisation method. This can be seen from the increase in the cohesion value of the peat soil from 115.73% on the 30th day of biogrouting soil compared to the 60th day of stabilised grouting soil. Then, the cohesion value of the 60th day biogrouting stabilisation soil is also 418.51% greater. However, the angle of internal friction was lower, namely 2° on the 30th day of biogrouting and 3° on the 60th day of biogrouting. The curing period of Bacillus cereus bacteria affected the value of the shear strength of peat soil. This can be seen from the increase in the cohesion value and the angle of internal friction from the 30-day curing period to 60 days, namely, the cohesion value increased by 151.03% and the angle of internal friction increased to 3°. Then, from the curing period of 60 days to 112 days, the cohesion value increased by 32.83% and the angle of internal friction increased to 4°.
3. Practical implications for the use of biogrouting methods for soil improvement, applied on a field scale for road construction work. The existing soil is grouted with a specific number of bacteria and then cured for a long period before being used as a subgrade.
4. The method of soil improvement with biogrouting should require further research for the curing of test specimens for more than 90 days using a curing system with different temperatures to see the potential for increasing cohesion and the angle of internal.

Declarations

Author Contributions

The following statements should be used:

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

Data Availability Statement

No new data were created or analysed in this study. Data sharing does not apply to this article.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors have fully addressed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies.

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