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Performance of Soil Biogrouting as a Subgrade Material of the Road Pavement

Jack Widjajakusuma [1*], Aaazokhi Waruwu [1], Yulia Yunita Kusnadi [1], Jason Lujaya [1], Kevin Aprilio Wibowo [1]

[1] *Department of Civil Engineering, Universitas Pelita Harapan, Tangerang, Indonesia*.

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Abstract

Soft clay subgrade is unsuitable for road pavement because it has low bearing capacity and CBR value. Therefore, the soil needs stabilization, but with a sustainable stabilization method. One of these methods is biogrouting, namely grouting, which uses bacteria. Thus, the main objective of this study was to determine the performance of *Bacillus subtilis* and *Bacillus amyloliquefaciens* bacteria in stabilizing the soil. The performance of these bacteria was quantified by the CBR value and soil-bearing capacity experimentally in a laboratory model test with each soil thickness of 0-30 cm. The CBR value of the soil improved by the biogrouting method by about 4 times the CBR value of untreated soil. The increase in bearing capacity was obtained about 4 times for treated soil with *Bacillus subtilis* and about 5 times for treated soil with *Bacillus amyloliquefaciens*. The layer thickness significantly improves the performance of the subgrade at a layer thickness of 20 cm. The new result of this study is that both bacteria are native Indonesian bacteria, so they are suitable for use in Indonesia. In addition, *Bacillus amyloliquefaciens* has never been used in research to increase soil-bearing capacity.

Keywords: Clay; Physical Model; CBR; Bearing Capacity; Subgrade.

1. Introduction

Road pavement is a series of layers of selected materials placed on top of a natural subgrade to withstand traffic loads. It can be either flexible or rigid. Good pavement performance is influenced by the performance of all components in the pavement, including subgrade performance. The subgrade is the foundation layer that supports the vehicle load directly through the pavement layer above it.

In general, the problems often encountered in pavement subgrade soils are the California Bearing Ratio (CBR) value and the low bearing capacity of the soil. Clay properties such as grain size, consistency limit, liquid limit, plastic limit, and shrinkage limit significantly affect changes in the CBR value of the subgrade [1]. Clay soils exhibit high settlement when subjected to a load because they have a high liquid limit, moisture content, and pore ratio [2]. One way to overcome the settlement and high pore ratio is to use vertical drainage, a mechanical soil improvement [3]. Other methods of mechanical soil improvement are geosynthetics [4] or soil replacement [5]. However, some disadvantages of geosynthetics include long-term durability and handling, storage, and installation, which must be assured by quality assurance and plastic waste [6].

In addition, there is also chemical stabilization, or chemical grouting, which involves adding chemicals to increase the structural integrity and durability of the soil [7]. Examples of stabilization materials include lime, cement, volcanic

* Corresponding author: jack.widjajakusuma@uph.edu

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ash, rice husk ash, palm kernel shell ash, and fly ash [8-12]. Adding lime, volcanic ash, and a combination can increase the CBR value, reduce the development potential, and decrease the soil plasticity index [13]. Soil improvement by the stabilization method with cement and rice husk ash can improve soil characteristics, such as lowering the liquid-plastic limit index and increasing shear strength [8]. Anburuvel [14] stated that cement can stabilize all types of soil with a 5% dosage, while lime is only suitable for high-plasticity soil. However, stabilization methods using chemical additives such as cement, lime, and fly ash are limited because they require considerable production costs, have adverse ecological impact, and increase carbon emissions [15, 16]. Furthermore, soil layers stabilized by sulphate-containing cement or lime can result in heaving and early pavement failure [12].

In recent years, there has been environmentally friendly and cost-effective grouting, which is called bacteria-assisted grouting or biogrouting. Biogrouting is the process of calcium carbonate generation through microbially induced calcium carbonate precipitation (MICP). In this process, bacteria guide the formation of calcium carbonate through a series of biochemical reactions, such as their metabolic functions and the absorption and transformation of nutrients in the environment. The resulting calcium carbonate is usually granular or crystalline, forming a calcium carbonate skeleton [17]. These bio-cement skeletons are deposited between soil particles or on the surface of soil particles, increasing cohesion and friction between soil particles [18-20], thus improving the macroscopic properties of soil [21]. In addition, calcium carbonate fills the voids between particles and can be a binding material between soil grains, resulting in a decrease in soil porosity [22], creating sandy soil non-collapse strain softening shear behavior [23], thereby reducing liquefaction potential [24-26]. Thus, the biogrouting method has a greater impact on improving soil properties than conventional methods [27, 28].

One of the bacteria that can produce calcite crystallization is *Bacillus subtilis*, a gram-positive, nonpathogenic, endospore-forming, and rod-shaped bacterium [29]. Endospores help *Bacillus* survive in extreme conditions such as high temperatures and drought. *B. subtilis* cells are about 4–10 micrometers long and about 0.25–1.0 micrometers in diameter. *B. subtilis* can grow at 30–35°C and pH 6–9 [30]. *B. subtilis* has shown promising results in soil improvement, namely increasing soil cohesion, bearing capacity, and shear strength [19, 20] as well as reducing soil erosion [31]. *B. subtilis* can increase the CBR value and bearing capacity of the soil. Using B. subtilis at 6% showed the most optimal increase with a curing time of 28 days [32]. There was an increase of 4 times after 150 days of treatment, and the unconfined compressive strength value increased tenfold after 35 days of treatment compared to the original soil [33]. Other studies have shown that *B. subtilis* can increase the shear strength of organic soil [20], the unconfined compressive strength, and the cohesion of expansive soil [19]. Both studies showed increased shear strength, compressive strength, and cohesion values with increasing curing time [19, 20].

Like *B. subtilis*, *Bacillus amyloliquefaciens* is a gram-positive, nonpathogenic, endospore-forming, rod-shaped bacterium commonly found in soil environments. *B. amyloliquefaciens* can grow at 20-35°C and pH 5-7. *B. amyloliquefaciens* has a length of about 1.8-3 micrometers and a diameter of about 0.7-0.9 micrometers [34]. Lee [35] showed that *B. amyloliquefaciens* could produce high levels of calcite. Several researchers have used *B. amyloliquefaciens* to reduce soil erosion with satisfactory results. [36, 37].

The main objective of this study was to determine the effectiveness of *B. subtilis* and *B. amyloliquefaciens* in stabilizing subgrade soil in terms of CBR value and soil-bearing capacity in a small-scale laboratory model. The results of this study are expected to provide an environmentally friendly alternative for soil improvement that increases CBR value and soil-bearing capacity for road construction work. The reason for choosing *B. subtilis* and *B. amyloliquefaciens* is that these bacteria are native species in Indonesia, which will reduce the cost of the bacteria procurement and facilitate smooth adaptation to Indonesian weather conditions. *B. subtilis* and *B. amyloliquefaciens* were isolated from Cikarang soil and a bee's digestive tract, respectively. This performance comparison is compelling, as no previous research has used *B. amyloliquefaciens* in enhancing soil-bearing capacity.

The paper is organized as follows: Section 2 presents the sample, the CBR test, and the plate bearing test. Section 3 presents the results, comparing original soil with soil treated with *B. subtilis* and *B. amyloliquefaciens*. Section 4 concludes this study.

2. Research Methods

This research was conducted experimentally in the Soil Mechanics laboratory of the Civil Engineering Study Program at Pelita Harapan University. The primary research material was soft clay obtained from Cikarang. The bacteria used for biogrouting consisted of *B. subtilis* and *B. amyloliquefaciens*.

The sieve analysis result of the specimen is shown in Figure 1. Clay soil is prepared by sieving using a No. 4 sieve before being compacted in a test tank. The condition of the original soil was compacted according to the density of the soil in the field based on a density test, while the soil treated using the biogrouting method was prepared in dry conditions and then mixed with water based on the results of standard compaction tests in the laboratory. The soil was cured for 1 year. This soil was used as a subgrade, the lowest part of the road pavement layer, as shown in Figure 2.

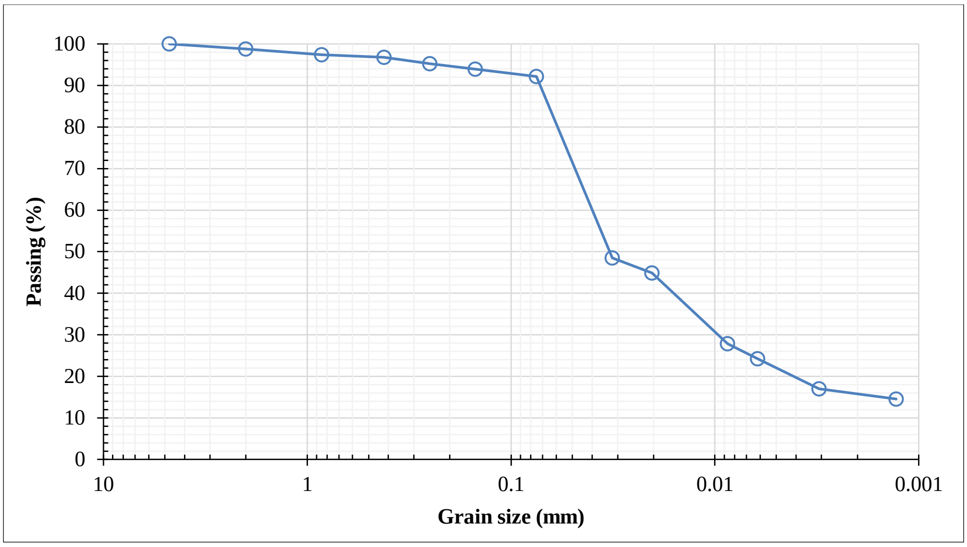

Figure 1. Sieve analysis result of specimen

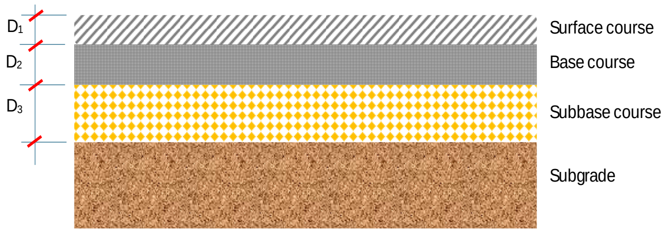

Figure 2. Typical layer of road pavement

Clay soil was compacted layer by layer in a test tank and prepared as a subgrade treated using the biogrouting method from the bacteria *B. subtilis* and *B. amyloliquefaciens*. The test scheme in the laboratory can be seen in Figure 3.

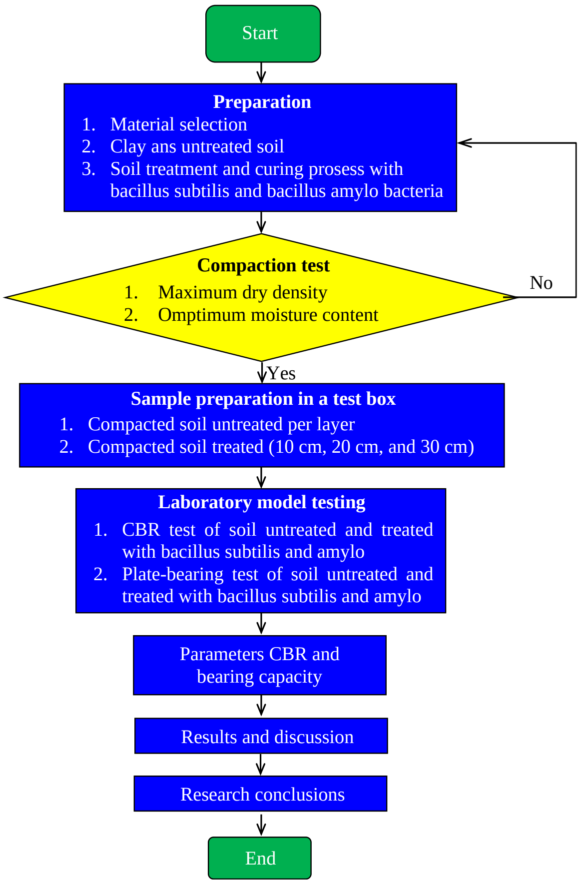

Figure 3. Flowchart of the research methodology

These bacteria utilized calcium sourced from shells to produce CaO as a source of $CaCO_3$ in clay soil particles. The culture medium, which acted as a nutrient medium for both bacteria, consisted of 0.4% yeast extract, 0.5% dextrose, and 0.25% calcium oxide and was then sterilized using an autoclave at 121°C for 15 minutes. The bacterial inoculation process was conducted under sterile conditions in vials containing 10 ml of 0.8% Nutrient Broth (NB). The bacteria were sprinkled onto the original soil and allowed to settle in the test tank.

The subgrade treated using the biogrouting method was varied based on layer thicknesses of 10 cm, 20 cm, and 30 cm, respectively, for both *B. subtilis* and *B. amyloliquefaciens* bacteria. At each point, tests are differentiated by the CBR and plate-bearing tests (Figure 4). The CBR tool was set in a test tank above the biogrouting soil. The CBR test was performed by applying pressure through the crank to measure the penetration reading from the dial gauge and the load read from the proving ring. Similarly, plate bearing testing was carried out on plates placed on biogrouting soil. Bearing capacity was determined from the relationship between pressure and settlement [38].

Figure 4. CBR and plate bearing test of the subgrade layer model in the laboratory

Based on the CBR test results on the relationship between penetration and load, the CBR value indicated subgrade performance. In contrast, from the plate bearing test, the bearing capacity of the soil was obtained from the relationship between settlement and working pressure. These two parameters served as a reference in assessing the subgrade performance of a road pavement component. The results of both tests could be used as conclusions demonstrating performance improvement of biogrouted soil, both in terms of the effectiveness of using the biogrouting method of the two types of bacteria used and the impact of the layer thickness on soil stabilization.

3. Results and Discussion

The soil used as subgrade for road pavement through model tests in the laboratory was clay soil, either without improvement or with improvement using the biogrouting method. The density in the test tank was designed using standard compaction. The density parameter was determined from the dry unit weight value of the soil, as shown in Figure 5. The compaction test results showed that the dry unit weight value of the soil repaired with biogrouting was higher than the soil without improvement.

The soil density with biogrouting using *B. amyloliquefaciens* was significantly higher in dry bulk density than soil without treatment. In contrast, soil with biogrouting using *Bacillus subtilis* is similar to soil without treatment. The performance of both types of biogrouting showed significant improvement over the original soil. The performance of *B. amyloliquefaciens* was superior to that of *B. subtilis*. The thickness of the biogrouting soil layer had a significant effect at a thickness of 20 cm, whereas at 30 cm, it showed an inconsequential effect.

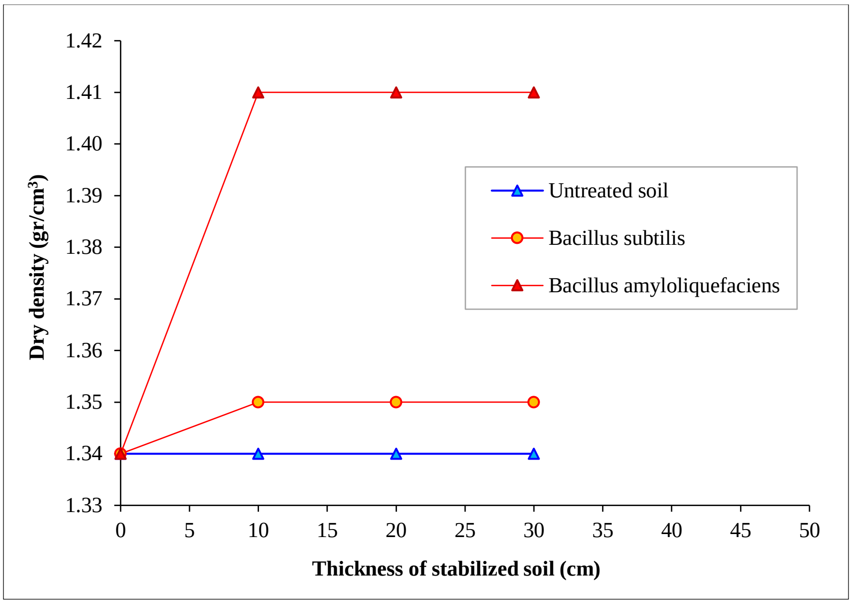

Figure 5. Soil density test results

3.1. Result of California Bearing Ratio (CBR) Test

The performance of biogrouting soil as a subgrade material can be seen through the results of the CBR (California Bearing Ratio) test and plate load test. A typical CBR test is shown in the load-penetration relationship for the original soil (Figure 6). The CBR value obtained by the highest CBR analysis is between 0.1 inch and 0.2 inch of penetration. The CBR value of the soil without treatment was 0.73% and can be classified as very soft clay soil. Soil CBR values are influenced by the water content applied in the soil mixture [39]. Soft soil has a high water content, so the CBR value is low.

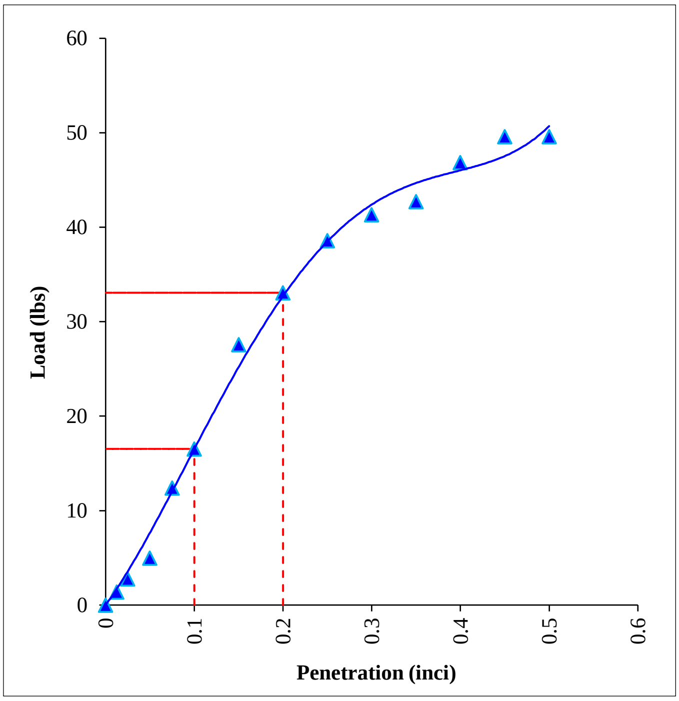

Figure 6. CBR test results of the original soil

Improvement of soil CBR is needed to enhance subgrade performance on road pavement. The subgrade model was carried out in a test tank in the laboratory with biogrouting soil thicknesses of 10 cm, 20 cm, and 30 cm, respectively. The performance of the biogrouting soil from the CBR test results in the test tank is shown in Figure 7. The performance of the subgrade based on the CBR value is more clearly seen in the relationship between layer thickness and the CBR value of each type of repair carried out (Figure 8). The two types of bacteria used had nearly identical effects on increasing CBR performance at a layer thickness of 20-30 cm.

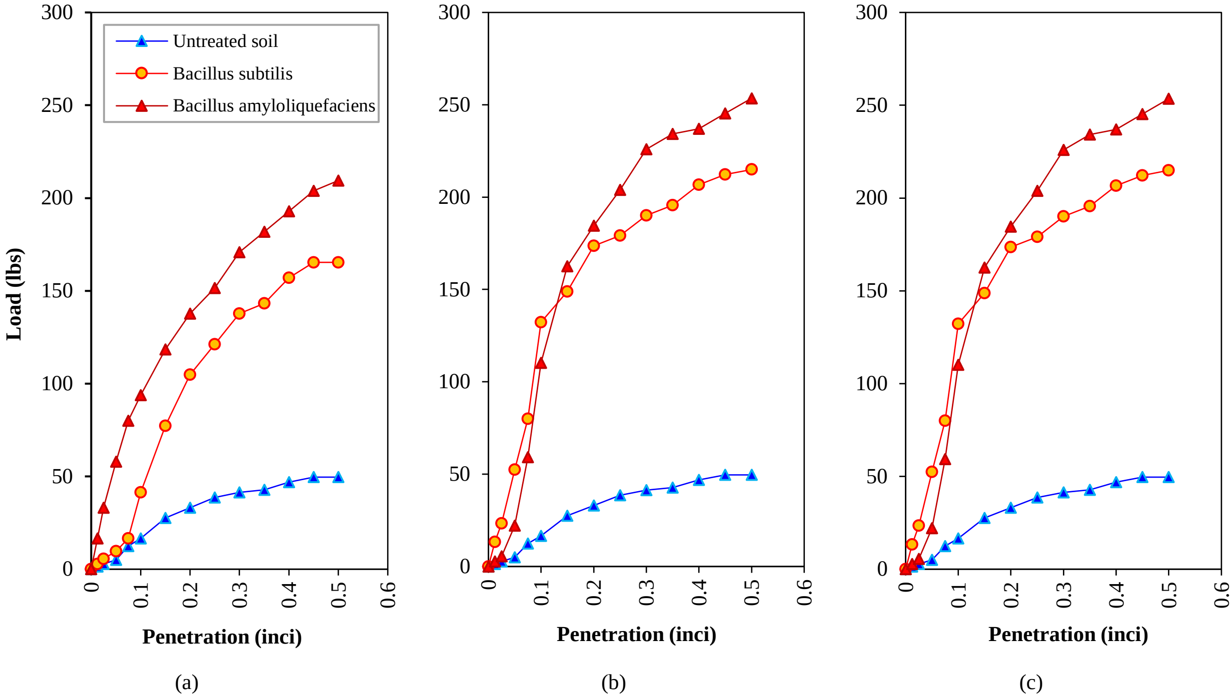

Figure 7. CBR test results on biogrouting soil: (a). t = 10 cm; (b). t = 20 cm; (c). t = 30 cm

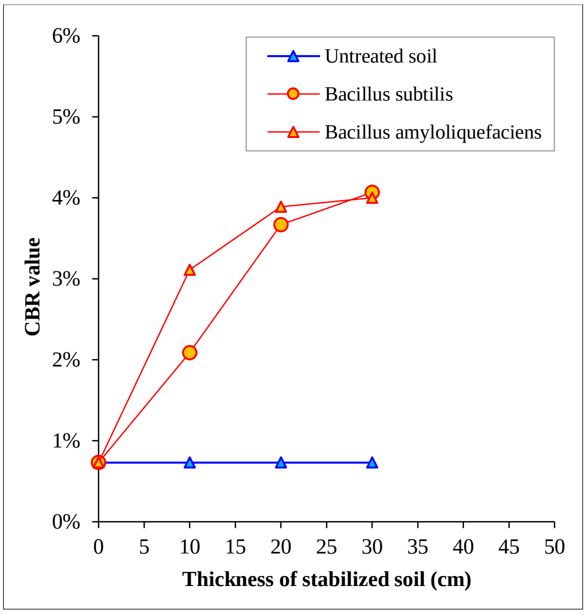

Figure 8. CBR performance of subgrades of biogrouted soils

An increase in the thickness of the stabilized soil was accompanied by an increase in the CBR value for the biogrouted soil mixture. The CBR value of the biogrouted soil increased by approximately 4 times the CBR value of the original soil. Thus, the performance of the road pavement subgrade is expected to improve by 4 times. Increasing the CBR value of the base soil also contributes to reducing the thickness of the road pavement layer.

The CBR value of the soil increases as the stabilized soil thickens. Apart from the thickness of the stabilized soil layer, water content can also affect the CBR value of the soil. According to Varela et al. [40], high water content can lower the CBR value of the soil. However, under specific water content conditions, it can yield maximum CBR values [41]. This correlates with soil compaction tests' maximum density and optimum water content.

3.2. Result of Plate Bearing Test

The performance of other biogrouted soils as a subgrade for road pavement can be observed from the bearing capacity through plate-bearing tests conducted in the laboratory. Typical plate-bearing test results can be seen in the test results for soil without improvement (Figure 9). The plate-bearing test results illustrate the bearing capacity value determination based on the relationship between pressure and settlement. Bearing capacity was obtained from the intersection of two linear lines. The same method was applied to other test results to determine the soil-bearing capacity value. Thus, the subgrade bearing capacity performance of the biogrouted soil can be evaluated.

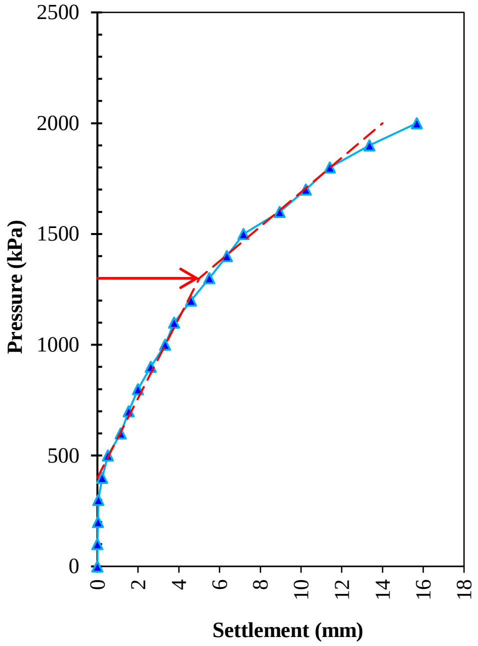

Figure 9. Plate bearing test results on untreated soil

The test results of the biogrouted soil bearing plate and its comparison with the original soil without treatment are shown in Figure 10. The pressure behavior of soil with biogrouting was significantly higher than that of soil without biogrouting. Soil treated with biogrouting exhibited an increase in calcium carbonate ($CaCO_3$) precipitation. The degree of improvement is influenced by the $CaCO_3$ content used in stabilization. The critical threshold for $CaCO_3$ content that significantly affects the stabilization effectiveness is 23%, as at this level, deformation and pore pressure are at their highest values, while stress and cyclic resistance are at their lowest values [42]. Soil improvement using the biogrouting method substantially enhances the loads that the road pavement subgrade can support.

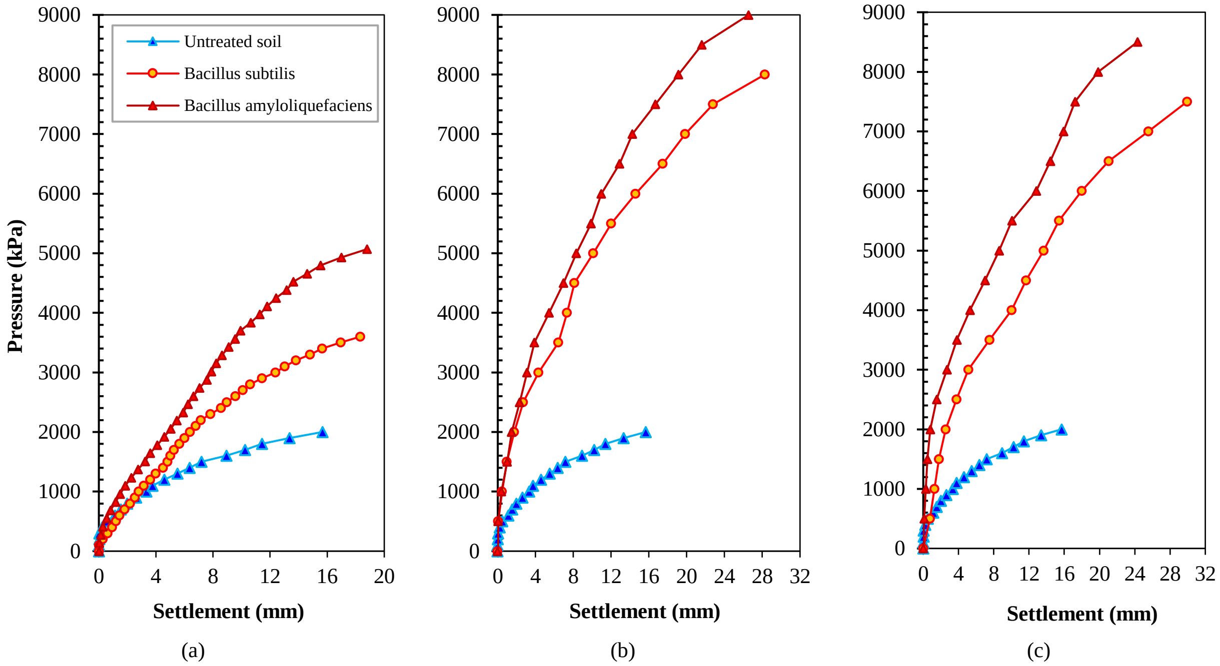

Figure 10. Plate bearing test results on biogrouting soil: (a). t = 10 cm; (b). t = 20 cm; (c). t = 30 cm

An increase in the thickness of the biogrouted soil layer resulted in higher pressure, both for soil treated with *B. amyloliquefaciens* and *B. subtilis*. However, the performance of biogrouted soil using *B. amyloliquefaciens* yielded superior results compared to using *B. subtilis*. This aligns with the increase in soil density and higher CBR values in the biogrouting method using *B. amyloliquefaciens*. When analyzing the effect of layer thickness, the maximum soil-bearing capacity value was achieved at 20 cm, as shown in Figure 11. The soil bearing capacity increased linearly at layer thicknesses of 10 cm and 20 cm, then decreased slightly at 30 cm. On average, the bearing capacity was approximately four times greater than that of soil without treatment.

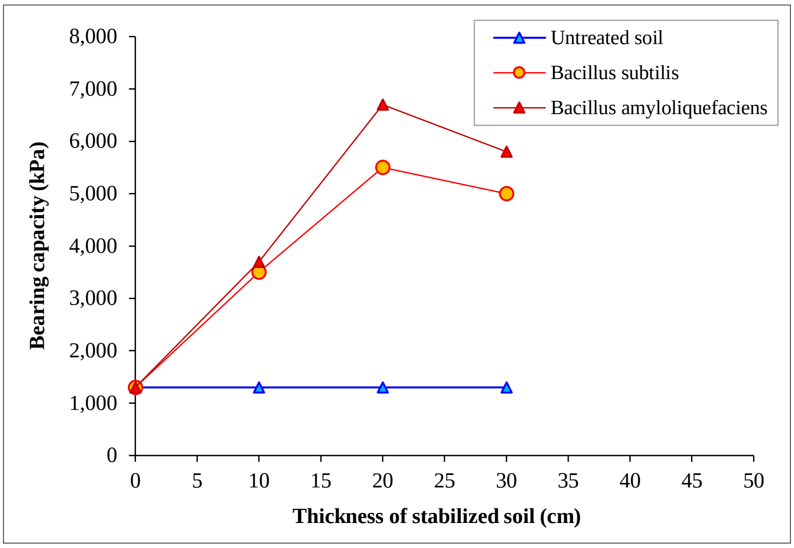

Figure 11. The relationship between ratio S/σ and number of dynamic loads

4. Conclusion

Several conclusions were obtained based on the results and discussions in this study. The conclusions were obtained from soil compaction, CBR test results, and plate-bearing test results from each untreated soil sample, and soil treated with *B. subtilis* and *B. amyloliquefaciens*. Soil density was measured in dry density values of 1.34 gr/cm^3 for untreated soil, 1.35 gr/cm^3 for treated soil with *B. subtilis*, and 1.41 gr/cm^3 for treated soil with *B. amyloliquefaciens*. The density of treated soil with *B. subtilis* was not significantly different from untreated soil, but soil treated with *B. amyloliquefaciens* exhibited an increase of 5.2% in density. This was influenced by the unification of soil grains due to the bacterial grouting.

In general, it was found that soil improvement using the biogrouting method could enhance the performance of the base soil, as seen from the increase in CBR and bearing capacity values. Based on the CBR test on 30 cm soil layer thickness, the CBR value was 1.12% for untreated soil, 4.07% for soil treated with *B. subtilis*, and 4% for soil treated with *B. amyloliquefaciens*. The CBR value of soil treated using the biogrouting method increased by approximately 4 times that of untreated soil. The increase in soil CBR value correlated with an increase in bearing capacity value. This was observed from the highest bearing capacity of 1300 kPa for untreated soil, 5500 kPa for soil treated with *B. subtilis*, and 6700 kPa for soil treated with *B. amyloliquefaciens*. The obtained increase in bearing capacity was about 4 times on soil treated with *B. subtilis* and about 5 times for soil treated with *B. amyloliquefaciens*. The layer thickness of base soil had the most significant improvement at 20 cm. Soil improvement with biogrouting using *B. amyloliquefaciens* was more effective than using *B. subtilis* in increasing CBR values and soil-bearing capacity. Thus, if this method is applied on subgrade, road pavement performance on biogrouting soil is also expected to improve.

5. Declarations

5.1. Author Contributions

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

5.2. Data Availability Statement

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

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Pule, B. B., & Yendaw, J. A. (2024). The effect of geotechnical soil properties on CBR value: review. AI in Civil Engineering, 3(1), 19. doi:10.1007/s43503-024-00039-1.

[2] Waruwu, A., Telaumbanua, D. P. T., & Waruwu, T. O. (2023). Estimating Consolidation Settlement Using the Physical Properties of Clay Soil Under Embankment. International Review of Civil Engineering, 14(6), 570–579. doi:10.15866/irece.v14i6.23311.

[3] El Kamash, W., Hafez, K., Zakaria, M., & Moubarak, A. (2021). Improvement of Soft Organic Clay Soil Using Vertical Drains. KSCE Journal of Civil Engineering, 25(2), 429–441. doi:10.1007/s12205-020-0561-9.

[4] Markiewicz, A., Koda, E., & Kawalec, J. (2022). Geosynthetics for Filtration and Stabilisation: A Review. Polymers, 14(24), 5492. doi:10.3390/polym14245492.

[5] Afrin, H. (2017). A Review on Different Types Soil Stabilization Techniques. International Journal of Transportation Engineering and Technology, 3(2), 19. doi:10.11648/j.ijtet.20170302.12.

[6] Hoyme, H., Vollmert, L., & Ehrenberg, H. (2022). Plastic in the ocean and global warming: New challenges for geosynthetics. IOP Conference Series: Materials Science and Engineering, 1260(1), 012022. doi:10.1088/1757-899x/1260/1/012022.

[7] Karol, R. H. (2003). Chemical Grouting and Soil Stabilization. CRC Press. Boca Raton, United States. doi:10.4324/9780429213830.

[8] Widjajakusuma, J., & Winata, H. (2017). Influence of Rice Husk Ash and Clay in Stabilization of Silty Soils Using Cement. MATEC Web of Conferences, 138. doi:10.1051/matecconf/201713804004.

[9] Endriani, D., Bawadi, N. F., & Ritonga, A. H. (2025). The effect of adding palm shell ash on soil shear strength. IOP Conference Series: Earth and Environmental Science, 1467(1), 12014. doi:10.1088/1755-1315/1467/1/012014.

[10] Marques, A., Syahril, S., & Tita, E. E. (2024). The effect of lime and phosphoric acid on the CBR value of soft soil based on curing time. E3S Web of Conferences, 479, 6001. doi:10.1051/e3sconf/202447906001.

[11] Hendrawan, A. J., Harianto, T., Djamaluddin, A. R., & Muhiddin, A. B. (2024). Study on Pull-Up Behavior of Double Fold Anchor with Field Full Scale Test. Civil Engineering Journal, 10(12), 3998–4007. doi:10.28991/CEJ-2024-010-12-012.

[12] Mohammed, A. A., Nahazanan, H., Nasir, N. A. M., Huseien, G. F., & Saad, A. H. (2023). Calcium-Based Binders in Concrete or Soil Stabilization: Challenges, Problems, and Calcined Clay as Partial Replacement to Produce Low-Carbon Cement. Materials, 16(5), 2020. doi:10.3390/ma16052020.

[13] Yin, Z., Lekalpure, R. L., & Ndiema, K. M. (2022). Experimental Study of Black Cotton Soil Stabilization with Natural Lime and Pozzolans in Pavement Subgrade Construction. Coatings, 12(1), 103. doi:10.3390/coatings12010103.

[14] Anburuvel, A. (2024). The Engineering Behind Soil Stabilization with Additives: A State-of-the-Art Review. Geotechnical and Geological Engineering, 42(1), 1–42. doi:10.1007/s10706-023-02554-x.

[15] Behnood, A. (2018). Soil and clay stabilization with calcium- and non-calcium-based additives: A state-of-the-art review of challenges, approaches and techniques. Transportation Geotechnics, 17, 14–32. doi:10.1016/j.trgeo.2018.08.002.

[16] Mehta, K. P. (2001). Reducing the environmental impact of concrete. Concrete International, 23(10), 61-66.

[17] Zhang, X., Wang, H., Wang, Y., Wang, J., Cao, J., & Zhang, G. (2025). Improved methods, properties, applications and prospects of microbial induced carbonate precipitation (MICP) treated soil: A review. Biogeotechnics, 3(1), 100123. doi:10.1016/j.bgtech.2024.100123.

[18] DeJong, J. T., Mortensen, B. M., Martinez, B. C., & Nelson, D. C. (2010). Bio-mediated soil improvement. Ecological Engineering, 36(2), 197–210. doi:10.1016/j.ecoleng.2008.12.029.

[19] Sugata, M., Widjajakusuma, J., Augestasia, A., Zacharia, A., & Tan, T. J. (2020). The use of eggshell powder as calcium source in stabilizing expansive soil using Bacillus subtilis. Journal of Physics: Conference Series, 1567(3), 32058. doi:10.1088/1742-6596/1567/3/032058.

[20] Widjajakusuma, J., Sugata, M., Changgrawinata, A., Jap, L., Zacharia, A., & Tan, T. J. (2019). Study on tropical organic soil stabilization based on biogrouting. IOP Conference Series: Materials Science and Engineering, 620(1), 12032. doi:10.1088/1757-899X/620/1/012032.

[21] Fu, T., Saracho, A. C., & Haigh, S. K. (2023). Microbially induced carbonate precipitation (MICP) for soil strengthening: A comprehensive review. Biogeotechnics, 1(1), 100002. doi:10.1016/j.bgtech.2023.100002.

[22] Whiffin, V. S., van Paassen, L. A., & Harkes, M. P. (2007). Microbial carbonate precipitation as a soil improvement technique. Geomicrobiology Journal, 24(5), 417–423. doi:10.1080/01490450701436505.

[23] DeJong, J. T., Fritzges, M. B., & Nüsslein, K. (2006). Microbially Induced Cementation to Control Sand Response to Undrained Shear. Journal of Geotechnical and Geoenvironmental Engineering, 132(11), 1381–1392. doi:10.1061/(asce)1090-0241(2006)132:11(1381).

[24] Montoya, B. M., DeJong, J. T., Boulanger, R. W., Wilson, D. W., Gerhard, R., Ganchenko, A., & Chou, J.-C. (2012). Liquefaction Mitigation Using Microbial Induced Calcite Precipitation. GeoCongress, 1918–1927. doi:10.1061/9780784412121.197.

[25] Cheng, L., Cord-Ruwisch, R., & Shahin, M. A. (2013). Cementation of sand soil by microbially induced calcite precipitation at various degrees of saturation. Canadian Geotechnical Journal, 50(1), 81–90. doi:10.1139/cgj-2012-0023.

[26] Diana, N. A., Soemitro, R. A. A., Ekaputri, J. J., Satrya, T. R., & Warnana, D. D. (2025). Biogrouting with microbial-induced carbonate precipitation (MICP) for improving the physical and mechanical properties of granular soils potential liquefaction. MethodsX, 14. doi:10.1016/j.mex.2025.103246.

[27] Maston, O., Ouahbi, T., Taibi, S., Hajjar, A. El, Sapin, L., Esnault-Filet, A., Duchemin, B., & Fleureau, J. M. (2025). Effect of MICP treatment on the mechanical properties of clay soils. Transportation Geotechnics, 50, 101483. doi:10.1016/j.trgeo.2025.101483.

[28] Payan, M., Sangdeh, M. K., Salimi, M., Ranjbar, P. Z., Arabani, M., & Hosseinpour, I. (2024). A comprehensive review on the application of microbially induced calcite precipitation (MICP) technique in soil erosion mitigation as a sustainable and environmentally friendly approach. Results in Engineering, 24, 103235. doi:10.1016/j.rineng.2024.103235.

[29] Feng, J., Chen, B., Sun, W., & Wang, Y. (2021). Microbial induced calcium carbonate precipitation study using Bacillus subtilis with application to self-healing concrete preparation and characterization. Construction and Building Materials, 280, 122460. doi:10.1016/j.conbuildmat.2021.122460.

[30] Harwood, C. R., Pohl, S., Smith, W., & Wipat, A. (2013). Bacillus subtilis. Model Gram-Positive Synthetic Biology Chassis. Methods in Microbiology, 40, 87–117. doi:10.1016/B978-0-12-417029-2.00004-2.

[31] Zakavi, M., Askari, H., & Shahrooei, M. (2024). Isolation and characterization of a resistance Bacillus subtilis for soil stabilization and dust alleviation purposes. Scientific Reports, 14(1), 25490. doi:10.1038/s41598-024-77613-1.

[32] Hasriana, H. (2018). A Study on Clay Soil Improvement with Bacillus Subtilis Bacteria as the Road Subbase Layer. International Journal of GEOMATE, 16(52). doi:10.21660/2018.52.97143.

[33] Alkadri, Djamaluddin, A. R., Harianto, T., & Arsyad, A. (2024). Soil Mechanical Characteristics Improvement With Bacterial Biocementation Technology. International Journal of GEOMATE, 26(115), 27–33. doi:10.21660/2024.115.4160.

[34] Ngalimat, M. S., Yahaya, R. S. R., Baharudin, M. M. A. A., Yaminudin, S. M., Karim, M., Ahmad, S. A., & Sabri, S. (2021). A review on the biotechnological applications of the operational group bacillus amyloliquefaciens. Microorganisms, 9(3), 1–18. doi:10.3390/microorganisms9030614.

[35] Lee, Y. N. (2003). Calcite Production by Bacillus amyloliquefaciens CMB01. Journal of Microbiology, 41(4), 345–348.

[36] Hemayati, M., Nikooee, E., Habibagahi, G., Niazi, A., & Afzali, S. F. (2023). New non-ureolytic heterotrophic microbial induced carbonate precipitation for suppression of sand dune wind erosion. Scientific Reports, 13(1), 5845. doi:10.1038/s41598-023-33070-w.

[37] Mohebbi, M. M., Habibagahi, G., Niazi, A., & Ghahramani, A. (2019). A laboratory investigation of suppression of dust from wind erosion using biocementation with Bacillus amyloliquefaciens. Scientia Iranica, 26(5), 2665–2677. doi:10.24200/sci.2018.20220.

[38] Waruwu, A., Widjajakusuma, J., Denzel, B., & Calvin, F. (2024). the Bearing Capacity of Peat Soil With Bamboo Reinforcement. International Journal of GEOMATE, 26(113), 19–25. doi:10.21660/2024.113.4090.

[39] Purwana, Y. M., Nikraz, H., & Jitsangiam, P. (2012). Experimental study of suction-monitored CBR test on sand-kaolin clay mixture. International Journal of GEOMATE, 3(2), 419–422. doi:10.21660/2012.6.39.

[40] Varela, F., Cerro-Prada, E., & Escolano, F. (2018). Preparation, characterization and modeling of unbound granular materials for road foundations. Applied Sciences (Switzerland), 8(9), 1548. doi:10.3390/app8091548.

[41] Li, T., Kong, L., & Liu, B. (2020). The California bearing ratio and pore structure characteristics of weakly expansive soil in frozen areas. Applied Sciences (Switzerland), 10(21), 1–22. doi:10.3390/app10217576.

[42] Lasheb, M., & Melbouci, B. (2025). Experimental Study of the Dynamic Behavior of Stabilised Marl with Lime. Civil Engineering Journal (Iran), 11(1), 131–160. doi:10.28991/CEJ-2025-011-01-09.