International Journal of GEOMATE, Dec., 2024 Vol.27, Issue 124, pp.49-56
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.124.4647
Geotechnique, Construction Materials and Environment

THE PERFORMANCE OF SOIL STABILIZATION WITH MARBLE ASH IN PHYSICAL MODEL TESTS IN THE LABORATORY

*Aazokhi Waruwu[1], Sadvent Martondang Purba[1], Nehemia Yulius Wijaya[1], Nicholas Anthony Sumantri[1], Indah Laura Pangemanan[1]

[1]Civil Engineering Department, University of Pelita Harapan, Indonesia

*Corresponding Author, Received: 23 July 2024, Revised: 19 Oct. 2024, Accepted: 25 Oct. 2024

ABSTRACT: Clay is one type of soil frequently used as a subgrade. Clay soils as subgrade soils with poor performance are found in expansive, soft, and very soft clays. The clay soils have low CBR value and low bearing capacity. Problematic soil characteristics can interfere with the performance of the road construction above it. Inadequate subgrade soils require improvement with soil stabilization to improve characteristic properties. Therefore, an experiment was conducted by adding marble ash to clay soil to improve soil characteristics and increase the CBR value. The research method was conducted through field testing, laboratory testing, and physical model testing in a test box. This research utilized the addition of marble ash content of 3%, 6%, 9%, and 12%, which were mixed with clay soil in thicknesses of 10 cm, 20 cm, and 30 cm. The results showed that the increase in CBR value for 6-12% marble ash is not much different. The average increase in CBR for 6% marble ash is 5.11 times, for 9% marble ash is 5.28 times, and for 12% marble ash is 5.70 times, while for 3% marble ash, it is only around 2.99 times. The minimum CBR value of 5% for subgrade soil was obtained at 6% marble ash content with a soil thickness of about 20-30 cm. CBR values above 5% can be used as a subgrade for road construction.

Keywords: CBR, Clay soil, Marble ash, Stabilization, Subgrade

1. INTRODUCTION

Soil is the most fundamental element in construction. In road construction, subgrade is the material under the subbase, base, and surface course for flexible pavement [1]. Each region has soil types with different characteristics [2]. Problematic soil characteristics can interfere with the performance of the road construction above it [3].

Clay soils as subgrade soils with poor performance are found in expansive, soft, and very soft clays [2-4]. Clay soils have small grains that expand or even soften when the moisture content in the soil is high, resulting in low bearing capacity. The nature of clay is shown in its high moisture content, liquid limit, and void ratio [6]. The particle size of pavement materials may affect the properties of road base and subbase materials [7].

Expansive clay is a type of soil that can undergo drastic volume changes when exposed to water, so that the soil expands or shrinks depending on the moisture content in the soil. Roadways that are frequently flooded may have an impact on their subgrade performance. It was indicated from the California Bearing Ratio (CBR) samples that those that were soaked longer had smaller CBR values [8].

The strength of the subgrade can be determined from the CBR value. The performance of the subgrade can be evaluated by the CBR value; the higher the CBR value of the subgrade, the better its performance in supporting the construction. Soils with low CBR values also show low density, as indicated by the small dry density value of the soil, which results in a low CBR value [9]. In general, soils made from expansive and soft clays have low grades [10]. Inadequate subgrade soils require improvement with soil stabilization to improve characteristic properties by adding additives to support the construction [11].

Stabilization methods that can improve the characteristics of clay soil with low bearing capacity are mechanical, chemical, and biogrouting. The most widely used method is chemical, as it significantly improves the properties of the soil [12]. The chemical method is a method that combines soil with specified additives such as fly ash, marble ash, cement, and other materials. The additives used may consist of one type of additive or a combination of several materials. The unconfined compressive strength performance of fly ash-stabilized soil is better than fine aggregates in construction waste [13].

Several soil stabilization materials have the potential to improve soil properties. Geopolymer materials are used as soft clay stabilization to increase stiffness and strength [14]. Waste oyster shell material added to the soil may increase its strength and other characteristics [15]. The addition of expanded polystyrene shows an increase in compressive strength [16]. A combination of several additives may include cement, lime, volcanic ash, and fly ash. The addition of 3% lime and 20% volcanic ash increases the CBR value of natural soil by about ten times, reduces about 29% of plasticity, and minimize about 88% of swelling soils The addition of 3% lime and 20% volcanic ash increases the CBR value of natural soil by about ten times, reduces about 29% of plasticity, and minimizes about 88% of swelling soils [17]. The combination of sand and cement optimizes soil stabilization, as seen from the unconfined compression strength value [18]. The use of fly ash to improve the clay soil reduces plasticity, increases density, and facilitates unconfined compression strength with an optimal mixture of 15-20% [19].

Chemical stabilization methods may also use environmentally friendly materials from waste materials. For example, waste material of about 1% plastic bottle with a 9% cement mixture increases the unconfined compressive strength of clay soil [20]. Marble ash is a waste material derived from marble stone processing. Marble ash is obtained from cutting and polishing marble stone. Recycling marble ash as waste is important to reduce environmental pollution [21].

Waste marble powder reduces plasticity and swelling soils, increasing the unconfined compression strength to 3.5 times [22]. Industrial waste materials may pollute the surrounding environment. Industrial waste can be implemented as an environmentally friendly soil stabilization material rather than being dumped and becoming a landfill [23].

The utilization of marble ash for improving high plasticity clay soil obtained maximum results with the addition of 45% marble ash; this was found to increase 2.76 times the CBR value and 1.5 times the unconfined compressive strength value [24]. When marble ash is mixed with fly ash, the CBR and the unconfined compressive strength values increase at a mixture of 5% marble ash and 10% fly ash [25].

Marble stone waste in the form of ash has the potential to be used as a soil stabilization material. The impacts on improving soil characteristics and increasing soil strength are shown in the increase in CBR and unconfined compressive strength values [26]. However, previous research results required a large amount of marble ash or a mixture of other materials. Therefore, it is necessary to conduct research to prove the performance of marble ash in stabilizing clay soil as a subgrade through laboratory-scale physical model tests [27].

Experimental studies are expected to determine the effect of marble ash stabilization on clay soil samples in the test basin as a base soil model in the field. The effect of marble ash stabilization was identified by the increase in CBR value and other soil characteristics. This study aimed to determine the percentage of marble ash addition to clay soil that is effective in producing CBR values for subgrade road construction.

2. RESEARCH SIGNIFICANCE

The use of marble ash from industrial waste as a soil stabilization material has a positive impact in reducing environmental pollution. These wastes can be accommodated as materials that can improve soil characteristics as subgrades in road construction work. The addition of marble ash to clay soil is expected to have a significant effect on increasing the CBR value of the soil. Physical model tests were conducted to obtain the effect of marble ash content and the thickness of the stabilized soil layer that significantly increased the CBR value.

3. MATERIALS AND METHODS

3.1 Materials

The materials used for this research were clay soil and marble ash that passed the No. 40 sieve (Fig. 1a). The soil used was clay soil from an apartment project located in Meikarta, Orange Road Boulevard, Bekasi Regency, West Java. Meanwhile, the marble ash used came from the remaining marble production of PT Jaya Abadi Granita factory located at Raya Serang Road, KM 69 Banten (Fig. 1b).

(a) (b)

Fig. 1. Research materials: (a) Clay soil (b) Marble ash

3.2 Preparation of Samples

In addition to sampling, the soil at the site was tested using field CBR with a Dynamic Cone Penetrometer (DCP) to determine the CBR value directly at the site. The soil characteristics taken were identified through sieve analysis, Atterberg limits, moisture content, specific gravity, and compaction tests. Compaction tests on soil with the addition of marble ash material at 0%, 3%, 6%, 9%, and 12% were intended to obtain the maximum dry weight and optimum moisture content. The optimum moisture content was used to determine the amount of water used in soil mixtures with marble ash. The CBR test samples were prepared by compacting them in 3 (three) layers with 25 blows.

3.3 Methods

The CBR performances of subgrade soils were known through field CBR tests in laboratory physical models. The physical model test can be conducted in a laboratory test bed by modeling the soil density as in the field [28].

Physical model tests were conducted through a test box filled with untreated clay soil. The test box measures 120 cm x 90 cm x 90 cm, consisting of a thickness of 40 cm filled with coarse and fine aggregates and a thickness of 50 cm filled with untreated clay soil, as used in the study [23-26]. The density of the untreated soil was adjusted to the density of the soil in the field. In contrast, the density of the marble ash stabilized subgrade was determined based on the density test results from the compaction test.

The surface subgrade was differentiated by marble ash mix and stabilized soil thicknesses of 10 cm, 20 cm, and 30 cm, respectively. Core cutter tests were conducted on compacted soil every 10 cm to control soil density, and this was conducted for the next layer until it reached a total thickness of 50 cm.

For each change in marble ash content and layer thickness, field CBR testing was conducted to obtain the subgrade CBR value. The CBR testing process in the test box is shown in Fig. 2. The field CBR testing procedure followed the ASTM D4429-09a. CBR of stabilized soil was tested on the ground surface with load penetration.

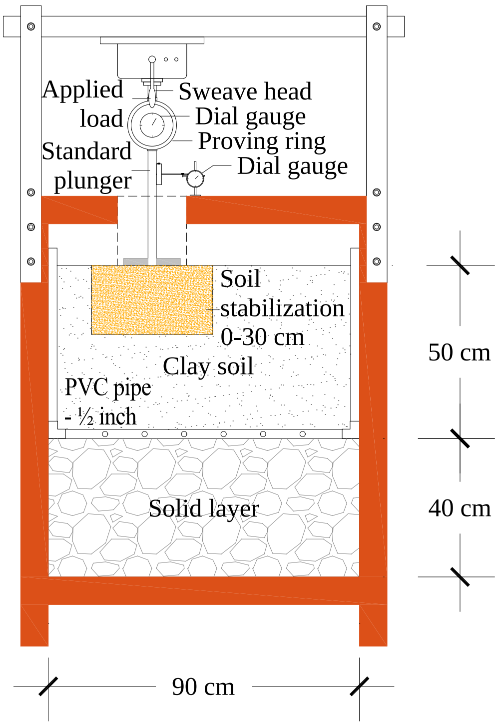

Fig. 2. The physical model test in the laboratory

The test point was in the middle of the stabilized soil layer and was held by a block installed on top of the test box. The position of the tool was adjusted so that the penetration piston was above the ground surface, and the proving ring was connected to the end of the jack. The pressure was applied by turning the crank until penetration occurred into the soil layer. The load reading was done through the proving ring, and the penetration reading was done through the deformation dial. CBR testing was conducted to determine the performance of the subgrade soil based on the CBR value obtained from the test results.

4. RESULTS AND DISCUSSIONS

4.1 Dynamic Cone Penetrometer Test

Dynamic cone penetrometer (DCP) testing was conducted to identify CBR values obtained directly in the field, and the results can be seen in Fig. 3. The DCP test results are a collection of 6 test points at the sampling location. Through the correlation between the number of blows and the penetration value, the field CBR value is obtained with an average of 1.41%. This CBR value is still quite low, which indicates improvement efforts are needed by using the marble ash in the hypothesis that the soil CBR value will increase. Marble ash waste has the potential to improve weak subgrade and be a solution to reduce the impact of environmental damage [26].

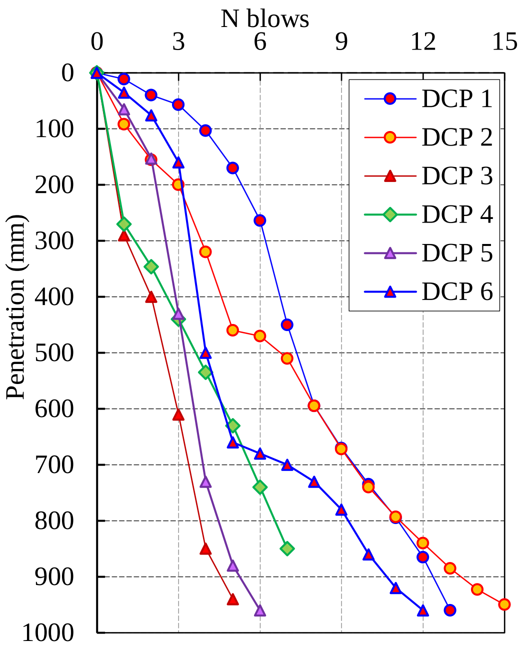

Fig. 3. DCP test results

4.2 Soil Characteristics Test Results

The results of the untreated soil characteristics test can be seen in Table 1. The moisture content testing was conducted using undisturbed soil samples. The average moisture content of the original soil from the test results was 32.97%. This soil exhibits a high moisture content. The specific gravity value obtained was 2.68. This value indicates that the soil belongs to gravel, sand, silt, and inorganic clay soil types. In the sieve and hydrometer tests, the soil grains that passed sieve number 200 were found to be 84.34%.

Table 1. Test results of untreated soil characteristics

Soil properties	Unit	Value
Field CBR	%	1.41
Moisture content (*w*)	%	32.97
Liquid Limit (*LL*)	%	45.02
Plastic Limit (*PL*)	%	21.11
Plasticity Index (*PI*)	%	23.91
Specific Gravity (G_s)	-	2.68
Fine-Grained	%	84.34

The results of the Atterberg limits test showed that the liquid limit was 45.02%, the plastic limit was 21.11%, the plasticity index was 23.91%, and more than 50% of the particles passed the No. 200 sieve. Based on the USCS classification, the soil type can be classified as CL (Clay Low), which includes soil with moderate to low plasticity. Meanwhile, based on the AASHTO classification, the soil type is classified as A-6, clay soil.

As seen in Table 2, marble ash may affect the Atterberg limits. With each addition of marble ash, the soil's plasticity index decreased, indicating a lower plasticity. The *PI* value obtained was lower, indicating that the marble ash could change the plasticity of the clay soil.

Compaction testing was conducted for each mixture differentiated by 0%, 3%, 6%, 9%, and 12% marble ash content. The optimum moisture content and maximum dry density parameters were obtained through this compaction, as shown in Fig. 4. Soil stabilization materials have an impact on increasing soil density, which is indicated by the increase in maximum dry density value [11].

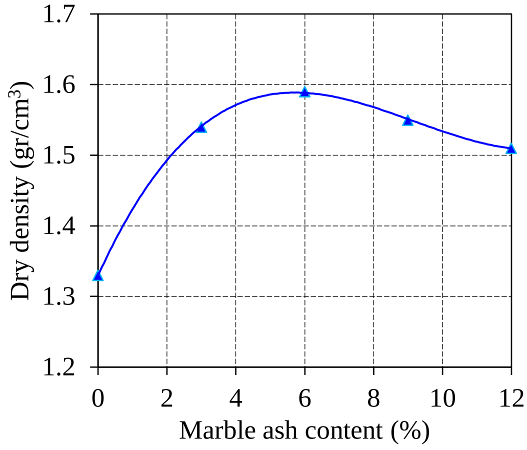

Fig. 4. Relationship between marble ash content and dry density

The 3% marble ash compaction test obtained an optimum moisture content of 23.3% and a dry density value of 1.54 gr/cm^3. The compaction of 6% marble ash obtained an optimum moisture content of 23.7% and a dry density value of 1.59 gr/cm^3. Compaction of 9% marble ash obtained an optimum moisture content of 25.5% and a dry density value of 1.55 gr/cm^3. Meanwhile, at 12% marble ash compaction, the optimum moisture content was 27.5%, and the dry density value was 1.51 gr/cm^3. Soil density relatively increased as the marble ash content increased, but the addition of 6% marble ash performed better than the others. Soils with high density tend to produce high CBR values [9].

4.3 CBR Test Results

CBR tests were conducted at each point for both untreated soil and marble ash-mixed soil of different thicknesses through physical modeling in laboratory tests. The unmixed soil in the box test was modeled according to the nature conditions in the field, while the marble ash mixed soil was modeled according to the compaction test results. The test results of marble ash-stabilized soil for stabilization thicknesses of 10 cm, 20 cm, and 30 cm can be seen in Fig. 5 to Fig. 7.

Table 2. Characteristic results after the addition of marble ash

Marble ash (%)	G_s	Fine-Grained	*LL* (%)	*PL* (%)	*PI* (%)
0	2.68	84.34	45.02	21.11	23.91
3	2.68	82.32	43.70	24.18	19.53
6	2.70	79.67	42.29	28.45	13.83
9	2.70	76.63	40.97	31.33	9.64
12	2.68	73.40	40.54	32.85	7.69

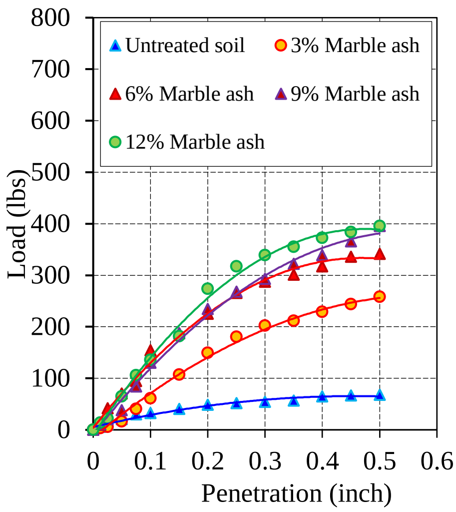

Fig. 5. The CBR test results for t = 10 cm

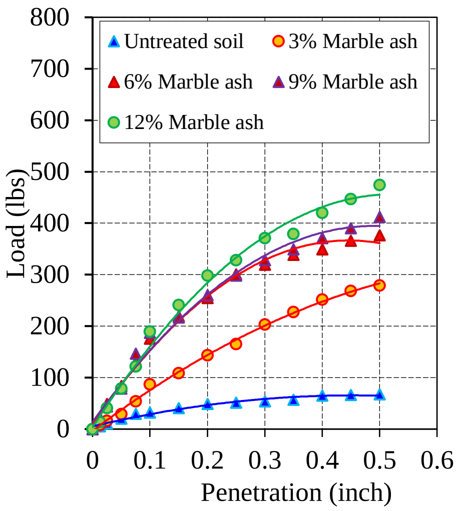

Fig. 6. The CBR test results for t = 20 cm

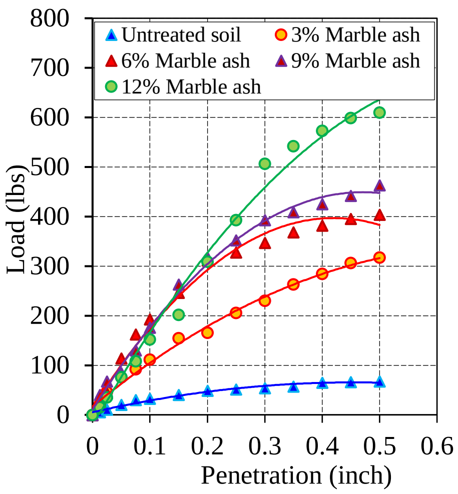

Fig. 7. The CBR test results for t = 30 cm

The CBR test results showed that the addition of marble ash already showed an effect at the addition of 3% marble ash and continued significantly up to 6% marble ash. The performance of marble ash was visible with the addition of 9% and 12% marble ash but increased in lower and insignificant values compared to the 6% marble ash. Improvement of soil characteristics such as increasing density, decreasing plasticity index, and increasing compressive strength was better obtained by using 6% marble ash [31].

4.4 The Effect of Marble Ash on CBR Value

The effect of marble ash on marble ash was shown in different stabilization soil thicknesses and marble ash contents. The relationship between stabilization soil thickness and CBR value was shown in Fig. 8, while the correlation between marble ash content and CBR value was shown in Fig. 9. The increase in CBR value due to the addition of thickness showed a dominant influence on 6% marble ash, while 3% marble ash had less impact on the addition of layer thickness. The increase in CBR values for soils with mixtures above 6% marble ash did not appear to significantly increase values. Thus, adding 6% marble ash with a thickness of about 20 cm showed good results due to the increased CBR value of subgrade soil.

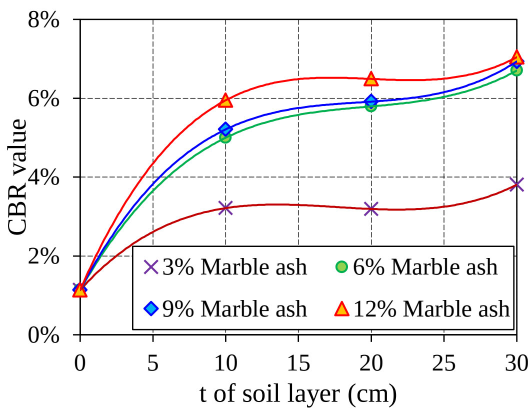

Fig. 8. Relationship between soil layer thickness and CBR value

Fig. 8 shows the correlation between ash content and the CBR value. The highest CBR value was obtained in a mixture of 12% marble ash compared to 3%, 6%, and 9% marble ash content. Meanwhile, for each stabilization thickness, the highest CBR value was obtained at a stabilization thickness of 30 cm. A significant increase in CBR value occurs when 6% marble ash content is added to the soil. Soil volume decreased, and macropores increased, so the CBR value of the soil increased [32]. The soil CBR value was directly proportional to the density and inversely proportional to the void ratio of the soil [33]. The results showed that the minimum CBR value of 5% for subgrade soil was obtained at 6% marble ash content with a soil thickness of about 20-30 cm.

The increase in CBR value is seen significantly in soil stabilized with marble ash above 6% (Fig. 9). The increase in CBR value continues at 9% and 12%, although not as high as from 3% to 6%. The average increase in CBR for 6% marble ash is 5.11 times, for 9% marble ash is 5.28 times, and for 12% marble ash is 5.70 times, while for 3% marble ash, it is only around 2.99 times. The increase in CBR value for 6-12% marble ash is not much different from each other. Based on the results of this study, the increase in CBR value for 12% marble ash content is not too high, the same thing for 9%. So it is considered that 12% is the maximum amount. Thus, the use of marble ash in this study is recommended at least 6% of the dry weight of the soil. This is the same as the results of previous research, where the addition of 6% marble ash can be optimal in increasing the soil's compressive strength and bearing capacity [31].

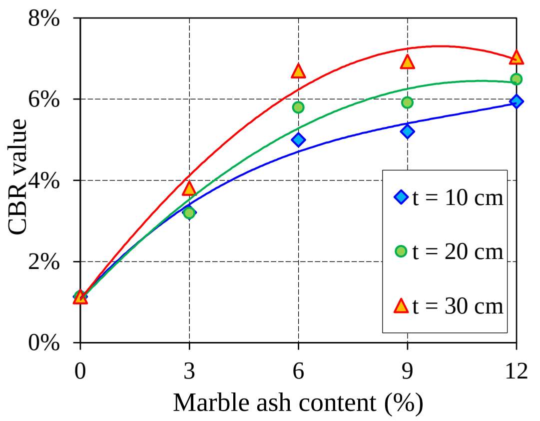

Fig. 9. Relationship between marble ash percentage and CBR value

5. CONCLUSIONS

Based on the research results and discussions, several conclusions were obtained regarding the characteristics of the soil studied and the performance of the CBR of the subgrade due to improvements using marble ash. Based on the results of the soil characteristics test, it was found that the soil used in the study was classified as clay with low plasticity, as indicated by the number of soil grains smaller than 0.075 mm, the liquid limit value, and the soil plasticity index. This soil shows low bearing capacity, as seen from the CBR value of the soil in the field, so improvement efforts are needed when used as a road subgrade. The stabilization chosen in this research was the addition of marble ash as waste from the marble factory. The marble ash that occurs in the plasticity of the clay may interfere with the decreased plasticity of the clay and the increased density of the soil. The improvement in these characteristics was followed by an increase in the CBR value of the subgrade. Good performance for the subgrade was obtained at 6% marble ash with a layer thickness of about 20–30 cm. The CBR value in this mixture can fulfill the minimum requirement of subgrade soil with a CBR above 5%. Further research is needed to see the long-term effects of soil stabilization and the effect of stabilized soil thickness above 30 cm.

6. ACKNOWLEDGMENTS

The author expresses gratitude to the Universitas Pelita Harapan for funding this research. This research was funded by internal research funding with grant number 180/LPPM-UPH/VII/2023, P-01-FaST-VII/2023. The author also thanks all parties involved in this research.

7. REFERENCES

[1] Donato M., Gouveia B. G., A. S. de Medeiros, M. A. V. da Silva, and Oda S., Mechanical Analysis of Subgrades of Road Pavements in Life Cycle Assessment. Civil Engineering Journal (Iran), Vol. 8, Issue 7, 2022, pp. 1492–1506.

[2] Al-Bared M. A. M. and Marto A., A Review on The Geotechnical and Engineering Characteristics of Marine Clay and The Modern Methods of Improvements. Malaysian Journal of Fundamental and Applied Sciences, Vol. 13, Issue 4, 2017, pp. 825–831.

[3] Mwaipungu R. R. and Ahmed S., The Challenges Posed by Problem Soils on The Performance of Road Pavements: Review of a Tanzanian Manual for Pavement Design and Materials. WIT Transactions on Ecology and the Environment, Vol. 226, Issue 1, 2017, pp. 593–603.

[4] Liu Y. and Vanapalli S. K., Mechanical Behavior of a Floating Model Pile in Unsaturated Expansive Soil Associated with Water Infiltration: Laboratory Investigations and Numerical Simulations. Soils and Foundations, Vol. 61, Issue 4, 2021, pp. 929–943.

[5] Jannuzzi G. M. F., Danziger F. A. B., Martins I. S. M., and Lunne T., Penetration and Retrieval Forces During Sampling in a Very Soft Clay. Soils and Foundations, Vol. 61, Issue 2, 2021, pp. 303–317.

[6] Waruwu A., Telaumbanua D. P. T., and Waruwu T. O., Estimating Consolidation

Settlement Using the Physical Properties of Clay Soil Under Embankment. International Review of Civil Engineering, Vol. 14, Issue 6, 2023, pp. 570–579.

[7] Thai, H. N., Kato, A., Nguyen, H. G., Nguyen, T. D., Tong, T. K., Nguyen, V. T., Uchimura, T., Maki, T., and Kawamoto, K., Effects of Particle Size and Type of Aggregate on Mechanical Properties and Environmental Safety of Unbound Road Base and Subbase Materials: A Literature Review. International Journal of GEOMATE, Vol. 20, No. 78, 2021, pp. 148–157.

[8] Abdul Ghani A. N., Roslan N. I., and Abdul Hamid A. H., Road Submergence During Flooding and Its Effect on Subgrade Strength. International Journal of GEOMATE, Vol. 10, Issue 3, 2016, pp. 1848–1853.

[9] Tatsuoka F., Hashimoto T., and Tateyama K., Soil stiffness as a Function of Dry Density and The Degree of Saturation for Compaction Control. Soils and Foundations, Vol. 61, Issue 4, 2021, pp. 989–1002.

[10] Sudjianto A. T., Susilo S. H., Tolan P. M., Agung P. A. M., and Hasan M. F. R., Increasing the Stability of Expansive Soil Using Lapindo Sediments Materials. International Journal of GEOMATE, Vol. 25, Issue 108, 2023, pp. 154–162.

[11] Muntaha M., Fitrie R. H. A., Wahyuni F., and Tajunnisa Y., The Use of Alkaline Activators With High Calcium Fly Ash As Soft Clay Stabilization Materials. International Journal of GEOMATE, Vol. 25, Issue 109, 2023, pp. 9–17.

[12] Al-Bared M. A. M., Harahap I. S. H., and Marto A., Sustainable Strength Improvement of Soft Clay Stabilized with Two Sizes of Recycled Additive. International Journal of GEOMATE, Vol. 15, Issue 51, 2018, pp. 39–46, 2018.

[13] Jili Q., Junfeng W., Andrian B., and Hao Z., Characterization and Comparison Research on Composite of Alluvial Clayey Soil Modified with Fine Aggregates of Construction Waste and Fly Ash. Science and Engineering of Composite Materials, Vol. 28, Issue 1, 2021, pp. 83–95.

[14] Wu J., Min Y., Li B., and Zheng X., Stiffness and Strength Development of The Soft Clay Stabilized by The One-part Geopolymer under One-Dimensional Compressive Loading. Soils and Foundations, Vol. 61, Issue 4, 2021, pp. 974–988.

[15] Wurie N. N., Zheng J., and Traore A. F., Mechanical, Leaching, and Microstructure Properties of Mine Waste Rock Reinforced and Stabilised with Waste Oyster Shell for Road Subgrade Use. Materials (Basel), Vol. 15, Issue 8, 2022, pp. 1–21.

[16] Jili, Q., Junfeng, W., Andrian, B., and Hao, Z., Modification of Mechanical Properties of Shanghai Clayey Soil with Expanded Polystyrene. Science and Engineering of Composite Materials, Vol. 29, Issue 1, 2022, pp. 37–49.

[17] Yin Z., Lekalpure R. L., and Ndiema K. M., Experimental Study of Black Cotton Soil Stabilization with Natural Lime and Pozzolans in Pavement Subgrade Construction. Coatings, Vol. 12, Issue 1, 2022, p. 103.

[18] Xu M., Liu L., Deng Y., Zhou A., Gu S., and Ding J., Influence of Sand Incorporation on Unconfined Compression Strength of Cement-based Stabilized Soft Clay. Soils and Foundations, Vol. 61, Issue 4, 2021, pp. 1132–1141.

[19] Seyrek E., Engineering Behavior of Clay Soils Stabilized with Class C and Class F Fly Ashes. IEEE Journal of Selected Topics in Quantum Electronics, Vol. 25, Issue 2, 2018, pp. 273–287.

[20] Bozyigit I., Bulbul F., Alp C., and Altun S., Effect of Randomly Distributed Pet Bottle Strips on Mechanical Properties of Cement Stabilized Kaolin Clay. Engineering Science and Technology, an International Journal, Vol. 24, Issue 5, 2021, pp. 1090–1101.

[21] Zorluer I. and Gucek S., The Effects of Marble Dust and Fly Ash on Clay Soil. Science and Engineering of Composite Materials, Vol. 21, Issue 1, 2014, pp. 59–67.

[22] Zumrawi M. M. E. and Abdalla E. A. E., Stabilization of Expansive Soil Using Marble Waste Powder. in Second Conference of Civil Engineering in Sudan, Vol. 2, Issue December, 2018 pp. 266–271.

[23] Ahmad A., Sutanto M. H., Ahmad N. R. B., Bujang M., and Mohamad M. E., The Implementation of Industrial byproduct in Malaysian Peat Improvement: A Sustainable Soil Stabilization Approach. Materials (Basel)., Vol. 14, Issue 23, 2021, pp. 1–22.

[24] Choksi R., Mishra C. B., and Patel N., Pursuance of Waste Marble Powder to Improve Soil Stabilization. International Research Journal of Engineering and Technology, Vol. 5, Issue 5, 2018, pp. 1695–1698.

[25] Zorluer I. and Demirbas A., Use of Marble Dust and Fly Ash in Stabilization of Base Material. Science and Engineering of Composite Materials, Vol. 20, Issue 1, 2013, pp. 47–55.

[26] Pateriya A. S., Robert D. J., Dharavath K., and Soni S. K., Stabilization of Marble Wastes Using Cement and Nano Materials for Subgrade Applications. Construction and

Building Materials, Vol. 326, 2022, p. 126865.
[27] Waruwu A., Yanto D. P. E. S., Susanti R. D., and Harefa S., Study Bearing Capacity of Subgrade Using Combination Bamboo Grid and Stabilized Soil. Journal of Infrastructure Planning and Engineering (JIPE), Vol. 1, Issue 2, 2022, pp. 87–92.
[28] Waruwu A., Widjajakusuma J., Denzel B., and Calvin F., The Bearing Capacity of Peat Soil with Bamboo Reinforcement. International Journal of GEOMATE, Vol. 26, Issue 113, 2024, pp. 19–25.
[29] Waruwu A., Hardiyatmo H. C., and Rifa'i A., Deflection Behavior of The Nailed Slab System-Supported Embankment on Peat Soil. Journal of Applied Engineering Science, Vol. 15, Issue 4, 2017, pp. 556–563.
[30] Waruwu A., Susanti R. D., Napitupulu N., and Sihombing J. O., The Combination of Bamboo Grid and Concrete Pile as Soil Reinforcement under The Embankment. Magazine of Civil Engineering, Vol. 106, Issue 6, 2021, p. 10610.
[31] Celline F., Sinaga R., Gandawijaya D. G., and Waruwu A., Study of the Bearing Capacity of Stabilized Clay with Marble Ash. Jurnal Saintis, Vol. 24, Issue 1, 2024, pp. 11–20, 2024.
[32] Li T., Kong L., and Liu B., The California Bearing Ratio and Pore Structure Characteristics of Weakly Expansive Soil in Frozen Areas. Applied Sciences (Switzerland), Vol. 10, Issue 21, 2020, pp. 1–22.
[33] Montes-Arvizu M. E., Chavez-Alegria O., Rojas-Gonzalez E., Gaxiola-Camacho J. R., and Millan-Almaraz J. R., CBR Predictive Models for Granular Bases Using Physical and Structural Properties. Applied Sciences (Switzerland), Vol. 10, Issue 4, 2020, pp. 1–13.

8. ABBREVIATIONS

AASHTO	: American Association of State Highway and Transportation
CBR	: California Bearing Ratio
CL	: Low plasticity Clay
DCP	: Dynamic Cone Penetrometer
Gs	: Specific Gravity
LL	: Liquid Limit
PI	: Plasticity Index
PL	: Plastic Limit
t	: Thickness
USCS	: Unified Soil Classification System
w	: Moisture content