International Journal of GEOMATE
(Geotechnique, Construction Materials and Environment)
ISSN: 2186-2982 (P), 2186-2990 (O), Japan
Vol. 31, Issue 145, September 2026, PP. 21-28; DOI: 10.21660/2026.145.5448

EXPERIMENTAL STUDY OF BEARING CAPACITY OF SOIL STABILIZATION WITH MARBLE DUST

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*Corresponding Author, Received: 24 Jan. 2026, Revised: 08 Mar. 2026, Accepted: 01 July 2026

ABSTRACT: Soft soils in road subgrades pose considerable engineering challenges; however, stabilization with marble dust offers an environmentally sustainable alternative. In this study, a 100 × 90 × 90 cm tank was employed to assess soils blended with 0%, 3%, 6%, 9%, and 12% marble dust by dry weight at depths of 10, 20, and 30 cm. Then, the soil mixed with marble dust was cured for 7 days before the testing. The bearing capacity increased proportionally with both the marble dust content and the stabilized layer thickness, reaching its maximum at 12% marble dust across all tested depths. Relative to untreated soil, bearing capacities improved by factors of 3.74, 4.52, and 5.30 for depths of 10, 20, and 30 cm, respectively. At a depth of 30 cm, using either 9% or 12% marble dust resulted in nearly identical bearing capacities, namely 5.30. Therefore, a 9% marble dust mixture is identified as the most efficient for practical applications. The interaction between marble dust percentage and stabilization depth is critical for achieving optimal results. These findings demonstrate that marble dust is a viable and sustainable approach for subgrade and foundation rehabilitation, supporting SDG 9 (infrastructure) and SDG 12 (sustainable construction).

Keywords: Road infrastructures, Waste materials, Soil stabilization, SDGs, Eco-friendly construction

1. INTRODUCTION

Soil needs sufficient bearing capacity for structures. Soft clay soils, with high liquid limits, plasticity, void ratios, and water content, often settle significantly [1]. These characteristics make clay soils difficult to engineer for geotechnical purposes due to their low bearing capacity and water sensitivity [2]. The California Bearing Ratio (CBR) also decreases under heavy rainfall [3], and moisture strongly affects high-plasticity soils such as clay [4].

Clay soil, composed of mineral particles, is plastic when wet and is usually unsuitable for foundations due to its low bearing capacity [2]. Instability arises from limited bearing capacity and reduced shear strength due to shrinkage and expansion. Soil stabilization—adding materials to improve engineering properties—can address this, increasing strength and bearing capacity for better pavement design.

Soil stabilization uses additives to improve soil engineering properties [5]. Materials such as lime, cement, rice husk ash, fly ash, and biogrouting agents are commonly used [6-10]. Fly ash and rice husk ash, alone or with spent catalyst waste, boost clay soil strength and stability while lowering plasticity [8-10]. Adding 0.045% nano-chemical to a 1% cement binder maximizes compressive strength and CBR in soft clay soils [11].

Waste materials are increasingly used for soil stabilization. Bearing capacity, measured by plate bearing tests, improves in cement-stabilized soils [12-13]. Using waste materials aids recycling, reduces pollution, and lowers costs [13]. Foundry waste, like sand, can also stabilize clay soils [14].

Among waste materials, marble dust serves as an effective stabilizing agent. Generated as a byproduct during the cutting of marble blocks and slabs, marble dust is transported by water to settling ponds. The sediment-laden dust is subsequently deposited onto vacant land, contributing to air pollution and posing a significant environmental concern. Marble dust has demonstrated potential to reduce swelling in clay soils and increase their unconfined compressive strength [15-18]. Additionally, marble material has shown favorable performance as a road embankment material, as indicated by improvements in its engineering characteristics [15].

Therefore, employing marble waste as a soil stabilization material promotes sustainable, environmentally responsible practices by utilizing industrial byproducts [15-17]. Laboratory model tests indicate that incorporating 6-9% marble dust yields California Bearing Ratio (CBR) values exceeding 6% [17-18].

Recent studies highlight the use of industrial and construction waste materials as alternative stabilizers for weak soils, thereby supporting sustainable construction practices. Materials containing calcium, silica, and alumina effectively improve soil by strengthening particle bonding and increasing resistance to deformation. Reusing industrial waste materials not only enhances mechanical properties but also mitigates environmental impacts related to waste disposal and raw material consumption [18]. These results align with SDG 9 (infrastructure) and SDG 12 (sustainable construction) [19].

The novelty of this study lies in its use of physical model testing, including slab load tests, to directly assess bearing capacity. Unlike previous research focused on field California Bearing Ratio (CBR) tests, this investigation evaluates slab bearing capacity under layered geometries. It examines the combined effects of mix percentage and subgrade thickness.

Experimental investigations indicate that material composition alone is insufficient to ensure optimal subgrade performance. Structural configuration and improvement layer thickness are also critical factors influencing bearing capacity. Studies on waste-derived construction materials suggest appropriate layer thicknesses enhance load distribution and contribute to structural stability under applied loads, particularly in pavement and foundation applications [6].

While previous studies have assessed marble ash using CBR tests, few have evaluated its performance in controlled layered configurations with direct plate-bearing tests. The interaction between stabilization thickness and additive percentage remains insufficiently explored.

Given these considerations, further research into the use of marble dust to enhance soil bearing capacity is justified. The objectives of this study are to determine the bearing capacity of soil improved with marble dust, identify the optimal mixture, and assess the influence of stabilized soil thickness using laboratory physical model test results.

The remainder of the paper is organized as follows. Section 1 presents the introduction, theoretical background on soil stabilization, research gaps, originality, and contributions relative to previous studies. Section 2 discusses the significance of the research, with emphasis on novelty and originality. Section 3 details the materials and methods, Section 4 presents the results and discussion, and Section 5 concludes the paper.

2. RESEARCH SIGNIFICANCE

This study introduces a novel experimental evaluation of marble dust as a soil stabilizer, using direct plate load testing on layered subgrade models—an approach not previously applied in this context. It uniquely examines the combined effects of additive percentage and stabilization thickness on bearing capacity, quantifying performance gains through controlled physical modeling. By converting industrial marble waste into a geotechnical material, the research offers an innovative, circular-economy solution for ground improvement. The findings provide practical design guidance and present an environmentally responsible, scalable method to enhance weak soils in infrastructure.

3. MATERIALS AND METHODS

3.1 Materials

The materials used in this study were clay soil from Cikarang, as illustrated in Fig. 1.

Fig. 1. Soil sample

Table 1. Test results of untreated soil characteristics

Soil properties	Unit	Value
Undrained shear strength (c_u)	Kg/cm^2	0.066
Moisture content (w)	%	32.47
Liquid Limit (LL)	%	45.02
Plastic Limit (PL)	%	21.11
Plasticity Index (PI)	%	23.91
Specific Gravity (G_s)	-	2.68
Optimum Moisture content (w_{opt})	%	22.5
Max dry density ($g_{d\ max}$)	gr/cm^3	1.35
Fine-Grained	%	68.49

The soil stabilization material was taken from a marble factory in Serang, Banten, as shown in Fig. 2. Before mixing, the materials are sieved through sieve no. 4. The marble dust is mixed at 0%, 3%, 6%, 9%, and 12% by weight of the dry soil, respectively.

Based on previous experimental studies using marble dust mixtures at contents of 3%, 6%, 9%, and 12%, it was found that the CBR value of the soil increased sharply at 6-12% with a subgrade thickness of 10-30 cm [18].

Fig. 2. Marble waste

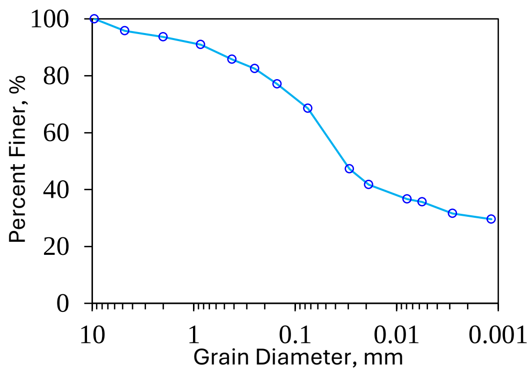

Fig. 3. Grain size distribution of the soil

The grain size distribution of the soil used in this study can be seen in Fig. 3. The characteristics of the soil material used can be seen in several soil property test results, including moisture content (w) = 32.47%, liquid limit (LL) = 45.02%, plastic limit (PL) = 21.11%, plasticity index (PI) = 23.91%, specific gravity (Gs), 2.68, fine-grained = 68.49%, and undrained shear strength = 0,066 kg/cm^2 [17]. The soil properties of the soil used in this study are shown in Table 1. The chemical composition of the marble dust used consists of 68,9% CaO, 14,6% SiO_2, 6% Fe_2O_3, 4,4% MgO, and 3,9% Al_2O_3 [18].

3.2 Preparation of Testing Scheme

A test tank (100 × 90 × 90 cm) was filled with soil and stabilizing materials. A 15 cm-diameter round plate—less than a quarter of the tank's width—was used for loading, thereby minimizing wall effects. The load was gradually increased until significant settlement and soil failure occurred. Clay was added in 10 cm-thick layers (10–50 cm depth), each compacted to match field conditions. For the subgrade, clay was mixed with marble dust and applied in 10–30 cm layers, compacted to the desired moisture and density. Figure 4 illustrates the soil layer arrangement.

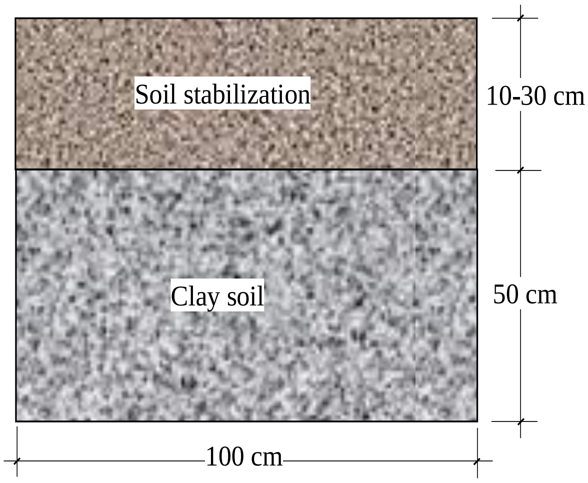

Fig. 4. Soil layer composition

The water content and soil compaction in the test basins remained within standard compaction limits. Soil density and water content were measured for each compaction layer. This quality control maintained values near the optimum water content and maximum dry unit weight. Water content in the soil significantly influences compaction, shear strength, and bearing capacity [16].

After water content and compaction were controlled in the test basins, the soil mixed with marble dust was compacted and cured for at least 7 days. This procedure follows previous research on gypsum-stabilized soil, which demonstrated that the 7-day compressive strength closely approximates the 28-day compressive strength [20]. The curing duration affects the chemical reaction between the stabilization material and the soil, thereby increasing compressive strength over time [18].

In addition to curing, the clay soil was stabilized with 3–12% marble dust, consistent with previous research findings [17]. According to the California Bearing Ratio (CBR) test, a marble dust mixture with a thickness of approximately 20–30 cm satisfied the requirements for base soil [16]. Soil compaction was performed using an optimum water mixture to achieve maximum density.

3.3 Methods

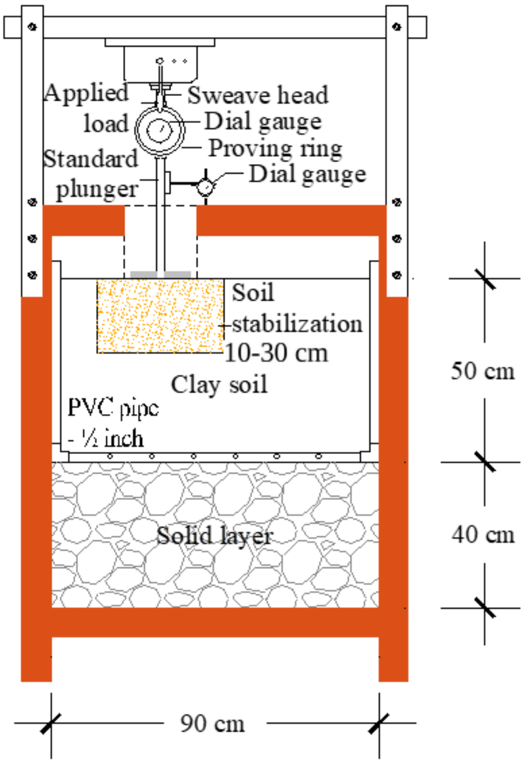

Fig. 5. Physical model test scheme

Plate bearing tests were performed at 10, 20, and 30 cm below the subgrade with varying marble dust contents (0%, 3%, 6%, 9%, 12%). Three tests were done, and the best results were used. The tests followed ASTM D1195 [21]. Pressure was applied using a hydraulic jack, and soil bearing capacity was determined from the pressure-settlement (σ-δ) relationship [17].

Bearing capacity was analyzed for changes in subgrade thickness (H) and marble dust content. The model test scheme (Fig. 5) illustrates how variations in soil thickness and marble dust content affect bearing capacity.

4. RESULTS AND DISCUSSIONS

4.1 Plate Bearing Test Results

The results of the plate-bearing test on a 10 cm-thick subgrade are shown in Fig. 6. Test points were defined by marble dust content. The plate bearing test used the load-settlement relationship [17], with pressure defined as the load divided by the plate area. For a 10 cm subgrade, pressure increased with increasing marble dust content. The pressure-settlement curve was linear up to the peak, which marked the ultimate bearing capacity and the onset of soil failure.

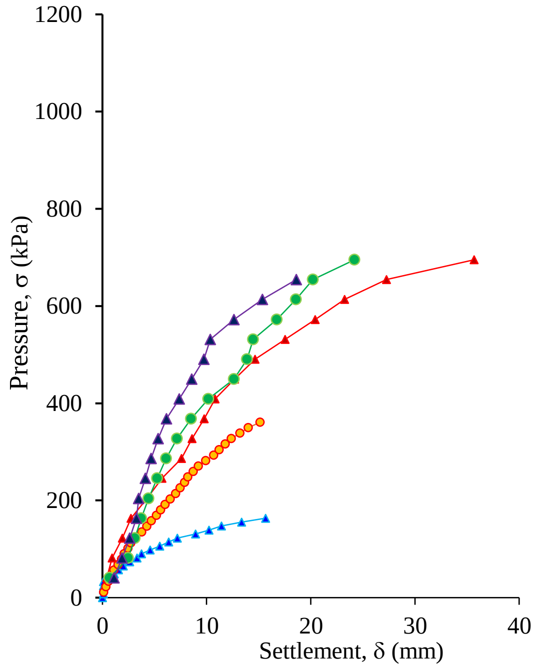

Fig. 6. Relationship between pressure versus settlement for H = 10 cm

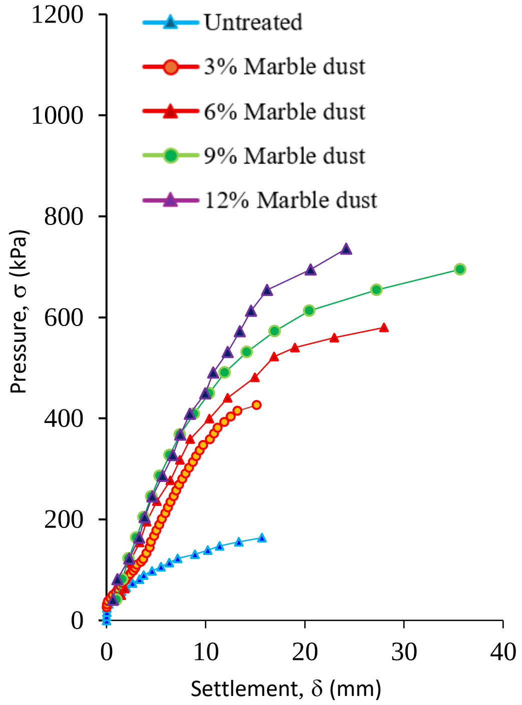

Fig. 7. Relationship between pressure versus settlement for H = 20 cm

Test points were defined by marble dust content. The plate bearing test used the load-settlement relationship [17], with pressure defined as the load divided by the plate area. For a 10 cm subgrade, pressure increased with increasing marble dust content. The pressure-settlement curve was linear up to the peak, which marked the ultimate bearing capacity and the onset of soil failure.

Fig. 7 presents the results of the plate bearing test for the 20 cm subgrade in comparison to the 10 cm subgrade. Soils treated with marble dust exhibited significantly greater strength than untreated soils, and the 20 cm subgrade showed a larger increase in strength than the 10 cm subgrade.

The results of the plate bearing test on a 30 cm subgrade are shown in Fig. 8. The soil strength, when viewed in terms of pressure (σ), shows a significant increase compared to the pressures on the 10 cm and 20 cm subgrades. This can be interpreted to mean that the strength of the stabilized soil still has the potential to increase at the 30 cm subgrade.

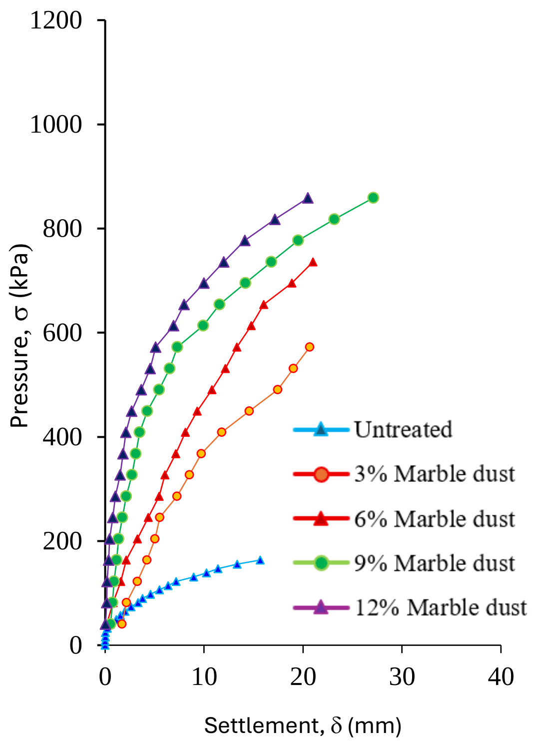

Fig. 8. Relationship between pressure versus settlement for H = 30 cm

When evaluated by marble dust content, soil stabilized with 12% marble dust still has higher strength than other mixtures. However, the overall strength of the soil is not much different from that of soils containing 6% or 9% marble dust.

Strength increased as marble dust content increased in all specimens (Figs. 6–8). Marble dust plays a key role in improving the mechanical properties of clay soil. More fine particles filled the soil matrix voids as marble dust content increased, lowering porosity and creating a denser structure. Lower void ratio improved interparticle contact and enhanced load transfer. As a result, the specimens became more compact and better resisted pressure.

Higher marble dust content also intensified chemical stabilization. Marble dust supplies CaO and SiO_2, which fuel pozzolanic reactions and form calcium silicate hydrate (CSH) gel. More marble dust means more calcium and silica react, increasing the formation of cementitious compounds. CSH binds soil particles, boosting soil cohesion and stiffness. Calcium ions drive flocculation and agglomeration, forming a stable, less compressible structure. Therefore, more marble dust progressively strengthens and reinforces soil.

These results agree with [15], who found that adding calcium- and silica-alumina-rich fly ash to clay soil increased its strength as fly ash content rose, due to better particle bonding and cementitious reactions.

Stabilized soil fails differently from untreated soil. Untreated soil shows a parabolic (curved) failure surface, typical of cohesive soils, with gradual deformation and slow increase in shear resistance. Marble dust-stabilized soil exhibits a linear (straight) failure surface that forms suddenly with little warning, indicating brittle failure once shear resistance is exceeded.

4.2 Generalized Bearing Capacity

Bearing capacity can be determined from the relationship between pressure and settlement, such as in Fig. 9.

The bearing capacity of unstabilized soil is considered low. This is related to the low CBR value of the soil used in this study, which is consistent with previous research that found a CBR value of 1.41% [17]. The CBR value was less than 3%, and the soil was classified as very soft. [22]. This type of soil has low shear strength and high water content [22]. Bearing capacity can be determined using various methods, such as analytical methods based on soil parameter test results and load tests on the soil, as conducted in this study. In addition to these methods, bearing capacity can also be estimated using the finite element method [23].

The results of the analysis of the soil bearing capacity values for both untreated soil and soil stabilized with marble dust, based on the subgrade thickness, can be seen in Fig. 8. The soil's bearing capacity appears to remain capable of increasing at subgrade thicknesses above 30 cm, as evidenced by the linear increase from 10 to 30 cm. This occurs for all types of marble dust mixtures, ranging from 3 to 12%. Previous research has shown that achieving optimal CBR values requires a minimum stabilized soil thickness of 20 cm [18]. The CBR value that met the requirements was obtained at a subgrade thickness of 20-30 cm [18].

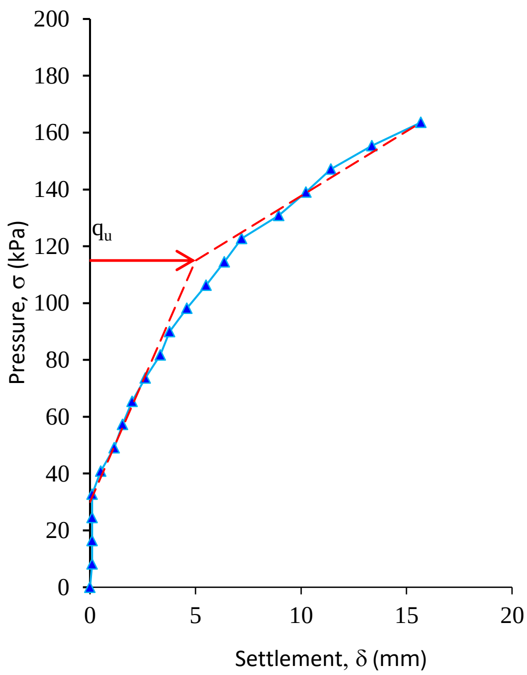

Fig. 9. Generalized bearing capacity

The effect of marble dust content on the soil bearing capacity value can be seen in Fig. 9. The soil bearing capacity for a 10 cm thickness appears to increase linearly for each marble dust mixture. Still, for a 20-30 cm thickness, the increase is linear up to 9%, after which it is not significantly different from 9% marble dust. This increase is due to the structural load-spreading effect of the increasingly thick subgrade layer. This means the optimal mixture is 9%-12% marble dust. Meanwhile, the increase in soil compressive strength is optimal at 7% marble dust [26].

Marble dust is rich in CaO (calcium oxide) and $CaCO_3$ (calcium carbonate). When combined with moist soil, CaO reacts with the silica (SiO_2) and alumina (Al_2O_3) found in clay minerals. The addition of approximately 6 to 9 percent marble ash provides sufficient $Ca(OH)_2$ to react with most of the available silica and alumina. At a 12 percent marble ash content, the increased CaO produces excess $Ca(OH)_2$, but no additional reactive silica or alumina remains. The surplus CaO persists as free lime or unreacted $CaCO_3$ and does not significantly enhance the cementing process [25].

The strength of stabilized soil results from the formation of C-S-H and C-A-H gels, which coat soil particles and bind them at contact points. However, there is a threshold to the extent of bonding achievable. Beyond this point, further addition of binder does not increase the strength of the mixture [26]. The combined effect of chemical saturation and bonding limit produces a diminishing-returns mechanism.

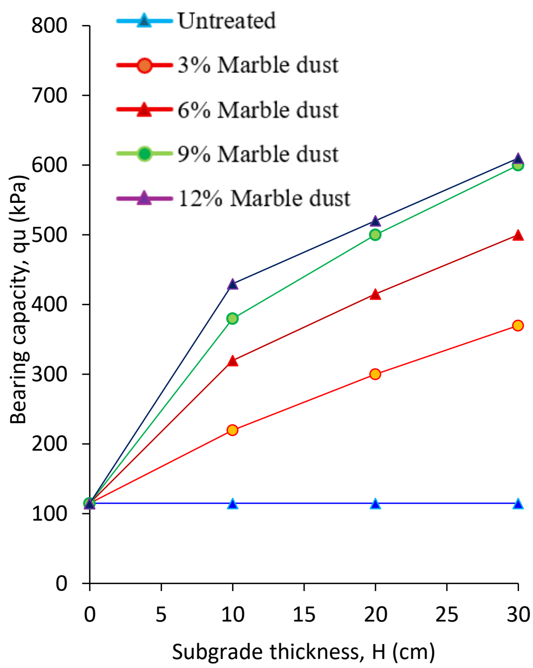

Fig. 10. Relationship between bearing capacity and subgrade thickness

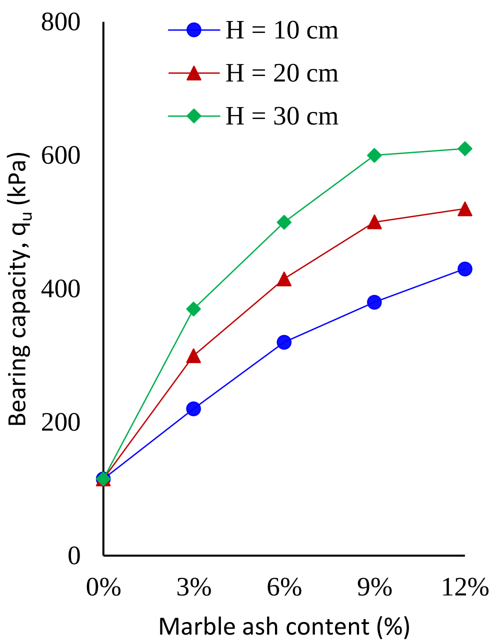

Fig. 11. Relationship between bearing capacity versus marble dust content

The enhancement in bearing capacity of marble dust-stabilized soil is evident in its increased shear strength, particularly the friction angle [16]. The relatively high CaO content in marble dust contributes to improved soil bearing capacity [27]. Marble dust is suitable for use in road surfaces, especially for subgrade repairs.

Beyond its stabilization properties, marble dust also demonstrates potential as an additive in concrete mixes [28]. When combined with fly ash to treat clay soil, marble dust increases strength, improves soil resistance to weathering, and reduces expansion in expansive soils [15]. The combined use of marble dust and fly ash produces a greater improvement than the use of marble dust alone.

Several previous studies have shown that marble dust reduces the swelling properties of clay soil while increasing its strength, is suitable for use in subgrade embankments, and can significantly increase the CBR value of the subgrade. Overall, marble dust offers advantages over other stabilization materials in terms of material utilization, helping reduce the environmental impact of waste from the marble industry and thereby supporting sustainable development. The findings support the use of marble dust for sustainable subgrade and foundation rehabilitation, aligning with SDG 9 (infrastructure) and SDG 12 (sustainable construction) [19].

5. CONCLUSION

Experimental results indicate that marble dust stabilization substantially increases the bearing capacity of soft clay relative to untreated soil. Plate-bearing tests demonstrate that both marble dust content and stabilized-layer thickness influence strength improvements. The addition of marble dust consistently enhanced soil performance. For subgrade thicknesses between 20 and 30 cm, bearing capacity increased linearly up to 9% marble dust, with only marginal gains observed at 12%. Therefore, a 9% marble dust mixture is identified as the most efficient for practical applications.

Subgrade thickness is a critical factor for load-bearing capacity. Bearing capacity increased with greater layer thickness, with significant improvements observed between 20 and 30 cm. Thicker stabilized layers enhanced load distribution and stiffness, thereby increasing resistance to deformation. Stabilized soil exhibited a multiple-fold increase in bearing capacity compared to untreated soil, confirming the effectiveness of marble dust as a soil improvement material.

In summary, this study demonstrates that marble dust stabilization is an efficient and economical technique for improving weak subgrades. The utilization of industrial waste enhances engineering performance while promoting sustainable construction and resource efficiency. Additional field studies are recommended to advance this research further.

6. ACKNOWLEDGMENTS

The authors would like to thank the Directorate of Research and Community Service of Universitas Pelita Harapan for financial support through the internal research grant 180/LPPM UPH/VII/2023.

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