Technema: Journal of Intelligent Engineering and Computing

Vol 1 No 3 September 2026, Hal 288-299
ISSN: 3163-6020 (Print) ISSN: 3163-5997 (Electronic)
Open Access: https://sovereignresearch.org/technema

An Experimental Study on the Use of Foam Mortar to Improve the Bearing Capacity of Soft Soil

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Article Info :
Received:
04-08-2026
Revised:
25-08-2026
Accepted:
06-09-2026

Abstract

Soft clay soils generally exhibit low bearing capacity, high plasticity, and limited shear resistance, making stabilization necessary for construction applications. This study investigates the effect of foamed mortar addition at 0%, 15%, 20%, and 25% on the physical and mechanical properties of soft clay obtained from Semarang City, Indonesia. The research employed a quantitative experimental approach through laboratory testing, including grain-size analysis, Atterberg limits, direct shear testing, Standard Proctor compaction, and laboratory California Bearing Ratio (CBR). The untreated soil was dominated by clay-sized particles at 89.88% and exhibited a specific gravity of 2.487, liquid limit of 53.21%, plastic limit of 29.82%, and plasticity index of 23.39%. The untreated soil also showed an internal friction angle of 11.06°, optimum moisture content of 34.00%, maximum dry density of 1.27 g/cm³, and unsoaked CBR of 5.10%. Increasing the foamed mortar content substantially modified the grain-size composition and improved the mechanical performance of the soil. At 25% foamed mortar content, the internal friction angle increased to approximately 34.50°, while the maximum unsoaked CBR increased to 25.70%, approximately 5.04 times the untreated value. The findings demonstrate that foamed mortar is effective in improving the shear resistance and bearing capacity of soft clay, with the 25% mixture providing the highest documented mechanical performance.

***Keywords:** Bearing Capacity, Foamed Mortar, Shear Strength, Soft Clay, Soil.*

INTRODUCTION

The continuous development of infrastructure in Indonesia has increased the need for construction on soft ground, particularly in coastal areas, wetlands, and low-lying regions where weak subsoil conditions frequently constrain the performance and safety of transportation and building infrastructure. Soft clay is generally characterized by high water content, high compressibility, low bearing capacity, and low shear strength, making it highly susceptible to excessive deformation when subjected to sustained structural loading (Das, 2016). These characteristics become particularly critical when embankments or structural loads are placed directly over soft deposits because the low stiffness and permeability of the soil can induce excessive settlement and prolonged consolidation. From a geotechnical perspective, the interaction between soil consistency, water content, density, compressibility, and shear resistance determines the ability of soft ground to sustain additional loading without experiencing unacceptable deformation (Hardiyatmo, 2012). The problem is particularly relevant to Indonesian infrastructure development because soft deposits are widely encountered along the northern coast of Java, parts of Sumatra, and Kalimantan, where road and embankment construction frequently requires ground improvement measures (Wesley, 1977). The increasing demand for infrastructure on such deposits has encouraged the development of ground-improvement strategies that can enhance bearing performance while limiting settlement and avoiding excessive additional loading on weak foundation soils.

One alternative material that has received increasing attention is foamed mortar, or foam mortar, which consists of cement, sand, water, and a foaming agent that produces air bubbles and creates a cellular structure with a lower density than conventional mortar. Its lightweight characteristics make foam mortar particularly suitable as a lightweight fill for road construction and soft-soil improvement because it can reduce the overburden pressure transferred to the underlying soil (Hamidi, 2022). The reduction in unit weight can modify the stress condition within the foundation soil and potentially reduce settlement while providing a relatively stable material for embankment construction. Foam mortar technology has been developed specifically for applications involving soft ground and road infrastructure, where controlling the self-weight of embankment material is an important consideration in maintaining foundation stability and serviceability (Wibowo, 2022). Recent research has further demonstrated that the engineering performance of lightweight foamed materials is strongly influenced by their mixture composition and production process, particularly the optimization of foaming equipment and mix proportions (Haider et al., 2026). The cellular structure generated by the foaming process also provides opportunities to adjust density and strength according to project requirements, positioning foam mortar as an engineered lightweight material rather than merely a conventional filling material.

Previous studies have provided substantial evidence that lightweight foamed materials can improve the engineering performance of weak ground, although the reported mechanisms and performance indicators vary according to material composition, soil condition, and application method. Experimental research on foamed mixture lightweight soil has shown that incorporating alternative materials such as red mud can modify its physical and mechanical properties, demonstrating that the performance of lightweight foamed soil is strongly dependent on constituent characteristics (Ou et al., 2022). Research using saponified slag fly ash has similarly demonstrated the feasibility of producing lightweight foamed soil with controlled engineering characteristics through changes in material composition and preparation methods (Chen et al., 2024). In Indonesia, numerical analysis has indicated that mortar-foam reinforcement can reduce settlement in soft subgrade systems, supporting its potential application for road construction over weak deposits (Jusi et al., 2024). Comparative analysis of embankments constructed with selected materials and foamed mortar has also indicated that the lower weight of foam mortar can provide advantages in reducing the load transferred to soft foundation soil (Lastiasih & Mochtar, 2022). Field experiments have further shown that lightweight foamed materials can influence load-settlement behavior when applied to soft ground, although the magnitude of the response depends on the characteristics of both the fill and foundation soil (Kim et al., 2022). These findings collectively indicate that foam mortar can contribute to soft-ground improvement, but they also reveal that its effectiveness cannot be explained solely by density reduction because material strength, soil interaction, and treatment proportion simultaneously determine the resulting engineering response.

Despite the growing body of evidence, an important empirical gap remains concerning the systematic relationship between the proportion of foam mortar added to soft soil and changes in fundamental soil properties and bearing capacity. A recent experimental study reported that adding foam mortar to soft clay increased the CBR from 4.10% for untreated soil to substantially higher values at treatment levels of 15%, 20%, and 25%, indicating a positive relationship between foam-mortar addition and bearing performance (Aji & Amin, 2025). Field-oriented research on the combined use of foam mortar and prefabricated vertical drains has demonstrated practical potential for soft-soil improvement on road sections, yet the interaction between lightweight fill and drainage treatment makes it difficult to isolate the specific contribution of foam mortar to the improvement process (Hia et al., 2025). Case-based analysis of lightweight embankment materials has likewise shown their potential to improve the performance of embankments constructed over soft soil, although the effectiveness remains dependent on site-specific soil and loading conditions (Muttaqin et al., 2025). Research on road embankment improvement using lightweight foam mortar has also emphasized its potential for controlling settlement, but the focus on engineering applications provides limited evidence concerning the simultaneous changes in soil index properties, shear strength, and CBR under controlled laboratory conditions (Putuarga, 2024). Similar evidence from Indonesian toll-road projects suggests that foam mortar can function effectively as a lightweight fill for reducing foundation settlement, although further experimental investigation is needed to clarify the relationship between treatment percentage and bearing-capacity improvement at the soil-material interface (Sari et al., 2026). This gap is important because an increase in CBR does not necessarily correspond proportionally to changes in water content, unit weight, Atterberg limits, or shear strength, making an integrated experimental evaluation necessary to explain the mechanisms underlying the observed improvement.

The scientific and practical importance of this problem is reinforced by the increasing application of lightweight cementitious materials in transportation infrastructure and the need to establish treatment configurations that provide adequate mechanical performance without imposing excessive loads on weak foundations. Experimental and numerical investigation of lightweight foamed-concrete-filled widened embankments for high-speed railway infrastructure has demonstrated that lightweight cementitious materials can be incorporated into demanding transportation systems while influencing the deformation and stress behavior of the embankment-ground interaction (Hao et al., 2024). Research on the use of superplasticizer in foamed mortar has also demonstrated that modification of the mixture can affect compressive strength, confirming that material formulation plays an important role in determining the engineering performance of lightweight mortar (Pratama et al., 2023). The fundamental principles of geotechnical engineering indicate that changes in soil density, consistency, water content, and shear resistance are closely associated with its capacity to sustain applied loads and resist deformation (Das, 1995). Previous stabilization research using fly ash has likewise shown that modifying the properties of soft clay can improve its CBR performance, although the behavior of lightweight cementitious treatment differs from conventional chemical or pozzolanic stabilization (Kusuma et al., 2013). The broader evidence suggests that an effective treatment should not only increase bearing capacity but should also produce a favorable balance between density reduction, strength development, and changes in soil consistency, particularly when the treated material is intended for infrastructure subjected to repeated or sustained loading. Establishing this balance has practical significance for selecting an appropriate foam-mortar content while also strengthening the scientific understanding of how lightweight stabilization modifies the physical and mechanical behavior of soft soil.

Against this research landscape, the present study positions foam mortar as a lightweight stabilization material whose effectiveness should be evaluated through an integrated assessment of physical and mechanical changes in soft soil. The study examines untreated soil and soil treated with foam-mortar additions of 15%, 20%, and 25% relative to the dry weight of the soil to determine the response of the material across different treatment levels. The experimental investigation focuses on water content, unit weight, Atterberg limits, shear strength, and California Bearing Ratio (CBR) as indicators of changes in the engineering behavior of the treated soil. This approach is designed to distinguish the effects of foam-mortar addition on basic soil characteristics from its effects on resistance to deformation and applied loading while identifying the treatment level that provides the most favorable engineering response. The primary objective of this study is to analyze the effect of foam-mortar addition on the physical and mechanical properties of soft soil and to determine the treatment proportion that produces the most effective improvement in bearing capacity. Theoretically, the study contributes empirical evidence regarding the relationship between lightweight cementitious stabilization and the engineering response of soft clay, while methodologically it provides a controlled comparative framework for evaluating multiple foam-mortar contents through complementary physical and mechanical parameters, with practical implications for developing more effective, economical, and environmentally considerate approaches to soft-soil stabilization.

RESEARCH METHODS

This study employed a quantitative empirical experimental method through controlled laboratory testing to investigate the effect of foam mortar (foamed mortar) addition on the physical and mechanical properties and bearing capacity of soft soil. The experimental system consisted of soft clay obtained from the riverbank area of Banjir Kanal Timur, Sawah Besar Village, Gayamsari District, Semarang City, foam mortar as the stabilization material, and laboratory testing equipment available at the Soil Mechanics Laboratory, Department of Civil Engineering, Faculty of Engineering, Universitas Islam Sultan Agung Semarang. The use of foam mortar was selected because its lightweight characteristics allow it to function as a lightweight fill while reducing the additional load transferred to underlying soft soil (Hamidi, 2022). The materials consisted of soft clay, cement, sand, water, and foaming agent, while the independent variable was the foam-mortar content of 0%, 15%, 20%, and 25% relative to the dry weight of the soil. The preparation stage included literature review, laboratory-equipment inspection, material preparation, soil sampling, sample preparation, and initial characterization of the untreated soil, while soil type, mixing procedure, compaction method, laboratory conditions, and testing procedures were controlled throughout the experiment. The mixture design maintained a total soil–foam-mortar mass of 8,600 g for each treatment, with the composition adjusted according to the specified foam-mortar percentage as presented in Tables 1 and 2, following standardized principles for soil specimen preparation and classification in geotechnical laboratory testing (ASTM International, 2017).

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Table 1. Soil–Foam Mortar Mixture Variations

Mixture Code	Dry Soil Weight (g)	Foam Mortar Weight (g)	Total Mixture Weight (g)
MB 0	8,600	0	8,600
MB 15	7,310	1,290	8,600
MB 20	6,880	1,720	8,600
MB 25	6,450	2,150	8,600

Table 2. Foam Mortar Composition

Mixture Code	Cement (g)	Sand (g)	Foam (mL)
MB 0	0	0	0
MB 15	430.00	860.00	161
MB 20	573.62	1,146.38	215
MB 25	716.67	1,433.33	269

The testing procedure began with characterization of the untreated soil through water-content, specific-gravity, grain-size-distribution, Atterberg-limit, direct-shear, Standard Proctor compaction, and California Bearing Ratio (CBR) tests, followed by testing of the treated mixtures to identify changes resulting from foam-mortar addition. The water-content, specific-gravity, grain-size, and Atterberg-limit tests were used to establish the initial and post-treatment physical characteristics of the soil, while the direct-shear test was used to determine cohesion and internal friction angle as indicators of shear-strength behavior. The Standard Proctor test was conducted to determine optimum moisture content and maximum dry unit weight, providing the basis for controlling and comparing the compaction characteristics of untreated and treated soil mixtures according to established geotechnical testing principles (Das, 2016). The CBR test was used as the principal performance metric for evaluating bearing capacity, with MB 0 serving as the control condition and MB 15, MB 20, and MB 25 representing the experimental treatments. The evaluation was performed by comparing changes in water content, unit weight, specific gravity, grain-size distribution, Atterberg limits, cohesion, internal friction angle, optimum moisture content, maximum dry unit weight, and CBR across the four mixture conditions, while the resulting trends were interpreted based on the relationship between foam-mortar content and soil engineering behavior. The effectiveness of each treatment level was validated through direct comparison with the untreated condition and assessment of the resulting CBR improvement, consistent with previous experimental evidence that foam-mortar addition can substantially modify the bearing performance of soft clay (Aji & Amin, 2025).

RESULTS AND DISCUSSION

Initial Characteristics of Soft Soil

The initial characterization of the untreated soil was conducted to establish its physical and mechanical properties before the addition of foam mortar and to provide a baseline for evaluating the effectiveness of stabilization. The laboratory results showed a specific gravity (Gs) of 2.487, a liquid limit (LL) of 53.21%, a plastic limit (PL) of 29.82%, and a plasticity index (PI) of 23.39%, indicating that the soil possesses relatively high plasticity and substantial sensitivity to changes in moisture conditions. The relatively high liquid limit and plasticity index are characteristic of fine-grained soils with considerable water-retention capacity, which can contribute to compressibility and volume changes under variations in loading and moisture conditions (Hardiyatmo, 2012). The grain-size analysis further showed that the soil consisted of 89.88% clay, 7.16% silt, 2.79% sand, and 0.17% gravel, confirming the dominance of very fine particles in the soil matrix. The predominance of clay-sized particles is consistent with the low permeability and relatively low shear resistance commonly associated with fine-grained soft soils (Das, 2016). These initial characteristics indicate that the tested soil has unfavorable engineering properties for direct use as a supporting layer and provides an appropriate material for assessing the influence of foam-mortar stabilization.

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Table 3. Initial Physical and Mechanical Characteristics of Soft Soil

Parameter	Test Result
Specific Gravity (Gs)	2.487
Liquid Limit (LL)	53.21%
Plastic Limit (PL)	29.82%
Plasticity Index (PI)	23.39%
Optimum Moisture Content (OMC)	34.00%
Maximum Dry Unit Weight (MDD)	1.27 g/cm³
Cohesion (c)	0.247 kg/cm²
Internal Friction Angle (φ)	11.06°
CBR	5.10%

The mechanical characteristics presented in Table 3 provide further evidence of the limited load-bearing capability of the untreated soil, particularly through its low cohesion, low internal friction angle, and CBR value of only 5.10%. The direct-shear test produced a cohesion value of 0.247 kg/cm² and an internal friction angle of 11.06°, indicating limited resistance to shear deformation when the soil is subjected to external loading. In soil mechanics, shear strength is governed principally by cohesion and frictional resistance, such that relatively low values of these parameters can increase the susceptibility of a soil mass to shear deformation and bearing failure (Das, 1995). The Standard Proctor test produced an optimum moisture content of 34.00% and a maximum dry unit weight of 1.27 g/cm³, reflecting the substantial water requirement and relatively low dry density associated with the tested soil. The combination of high optimum moisture content and low dry unit weight is consistent with a soil structure dominated by fine particles, in which water significantly influences particle arrangement and compaction behavior. The CBR value of 5.10% provides a direct indication that the untreated material has limited resistance to penetration loading and requires improvement when considered for applications demanding greater subgrade bearing performance.

The grain-size distribution provides an important basis for interpreting the engineering response of the soil because the 89.88% clay fraction substantially exceeds the proportions of silt, sand, and gravel. Such dominance of clay particles indicates that the soil behavior is controlled primarily by the interaction among fine particles and the water retained within the pore structure rather than by frictional contact between coarse grains. The high liquid limit of 53.21% and plasticity index of 23.39% further suggest that the soil can undergo considerable changes in consistency as its moisture content varies, increasing the potential for deformation under construction loading. Based on its particle-size composition and plasticity characteristics, the material can be categorized as a highly fine-grained and relatively plastic soil, which explains the unfavorable mechanical response obtained from the direct-shear and CBR tests. The AASHTO classification framework is commonly used to assess the suitability of soils for highway subgrade applications by considering grain-size distribution and plasticity characteristics, with highly plastic fine-grained soils generally exhibiting poorer subgrade quality (ASTM International, 2017). The observed characteristics therefore establish a clear baseline against which the changes produced by foam-mortar addition can be quantitatively evaluated in the subsequent treatment conditions.

The relationship between the physical and mechanical parameters is particularly important because the low CBR cannot be interpreted independently from the soil's plasticity, moisture condition, density, and shear-strength characteristics. A soil with a high proportion of clay particles tends to exhibit greater sensitivity to moisture and a more pronounced dependence of strength on its stress and drainage conditions, which can affect its capacity to sustain construction loads. The measured internal friction angle of 11.06° indicates that frictional resistance contributes only modestly to the overall shear resistance of the untreated soil, while the cohesion value of 0.247 kg/cm² provides limited resistance under increasing applied stress. The low maximum dry unit weight of 1.27 g/cm³ also indicates that the untreated soil does not develop a dense granular structure through conventional compaction, which is consistent with its predominantly cohesive composition. Previous stabilization research has demonstrated that modifying the composition of fine-grained soil can alter its compaction and bearing characteristics, particularly when stabilizing agents change the interaction among soil particles

(Kusuma et al., 2013). These relationships provide the technical basis for examining whether the introduction of foam mortar can alter the soil structure sufficiently to improve its shear resistance and bearing capacity.

The untreated condition also serves as an essential control because the subsequent MB15, MB20, and MB25 mixtures must be interpreted relative to the original engineering characteristics rather than evaluated solely through their absolute values. The baseline CBR of 5.10% establishes the initial bearing performance, while the cohesion of 0.247 kg/cm² and internal friction angle of 11.06° establish the initial shear-strength condition against which improvements can be assessed. The relatively high plasticity index indicates that changes in the soil matrix caused by foam-mortar addition may have important implications for consistency and moisture sensitivity in addition to bearing capacity. From an engineering perspective, the initial condition therefore demonstrates the need for a treatment capable of improving load resistance without disregarding the physical behavior of the fine-grained soil. The use of lightweight cementitious materials is particularly relevant because foam mortar can simultaneously introduce a cementitious binding phase and modify the mass characteristics of the treated material, which are important considerations in soft-ground applications (Wibowo, 2022). The subsequent analysis of the treated mixtures can therefore determine whether the intended stabilization mechanism is reflected consistently across grain-size characteristics, shear strength, compaction behavior, and CBR performance.

The initial laboratory results establish that the investigated material possesses the principal characteristics associated with problematic soft clay, namely a very high proportion of clay-sized particles, relatively high plasticity, substantial moisture demand during compaction, low dry density, limited shear resistance, and low bearing capacity. The combination of 89.88% clay, 53.21% liquid limit, and 23.39% plasticity index indicates that the soil's engineering behavior is strongly controlled by its fine-grained matrix and moisture condition. The CBR value of 5.10% provides the most direct evidence of its limited bearing performance, while the low internal friction angle and cohesion demonstrate the restricted shear resistance of the untreated material. These parameters form the quantitative baseline for determining the magnitude and direction of changes produced by foam-mortar addition. Establishing this baseline is essential because an increase in bearing capacity can only be interpreted meaningfully when the treated mixtures are compared with the original soil under equivalent testing conditions. The next stage of analysis therefore examines how the incorporation of foam mortar changes the grain-size composition and shear-strength parameters of the soil, providing a basis for explaining the subsequent improvement in its engineering performance.

Effect of Foam Mortar on Soil Gradation and Shear Strength

The addition of foam mortar substantially changed the grain-size characteristics of the tested soil, particularly in the proportion of clay- and sand-sized particles. In the untreated condition, the soil contained 89.88% clay, 7.16% silt, 2.79% sand, and 0.17% gravel, indicating that its behavior was strongly controlled by the fine-grained fraction. After the addition of foam mortar, the clay fraction decreased to 13.74% in MB15, 36.46% in MB20, and 24.88% in MB25. At the same time, the sand fraction increased to 72.25% in MB15, 56.10% in MB20, and 68.06% in MB25. These changes indicate that the incorporation of foam mortar substantially modified the particle-size composition of the soil mixture and reduced the dominance of the original clay matrix. The modification of particle composition is important because increasing the proportion of coarser particles can enhance particle interlocking and reduce the relative influence of water-sensitive clay particles on the mechanical response of the mixture (Das, 2016).

Table 4. Grain-Size Distribution of Soil Before and After Foam Mortar Addition

Mixture	Clay (%)	Sand (%)
MB0	89.88	2.79
MB15	13.74	72.25
MB20	36.46	56.10
MB25	24.88	68.06

As presented in Table 4, the most pronounced reduction in clay content occurred in MB15, where the clay fraction decreased from 89.88% in MB0 to 13.74%. At the same time, the sand fraction increased substantially from 2.79% in the untreated soil to 72.25% in MB15. MB20 contained 36.46% clay and 56.10% sand, while MB25 contained 24.88% clay and 68.06% sand. These results indicate that the addition of foam mortar substantially changed the relative proportion of the clay and sand fractions within the tested mixtures. The increase in the sand fraction can be associated with the sand component contained in the foam mortar, while the reduction in the relative clay fraction reflects the increasing contribution of the added mortar material to the overall mixture composition. This modification of the particle composition can reduce the dominance of the original clay matrix and promote a more mechanically stable particle arrangement (Ahmad Hamidi, 2022).

The changes in grain-size composition were accompanied by a substantial modification of the shear-strength behavior of the soil. The untreated MB0 mixture had a cohesion value of 0.247 kg/cm² and an internal friction angle of 11.06°, indicating relatively limited shear resistance within the predominantly clayey soil matrix. For MB25, the measured internal friction angle increased to approximately 34.5°, representing a substantial increase compared with the untreated condition. This increase indicates that the stabilized material developed considerably greater frictional resistance against particle movement under applied normal stress. The improvement can be related to the greater proportion of sand particles and the formation of a cementitious matrix produced by the foam mortar. Cementitious stabilization can increase the interaction and bonding among particles, resulting in a more stable internal structure and greater resistance to shear deformation (Wibowo, 2022).

Table 5. Direct Shear Test Results

Mixture	Cohesion, *c* (kg/cm²)	Internal Friction Angle, φ (°)
MB0	0.247	11.06
MB25	—	≈34.50

Table 5 shows that the internal friction angle increased from 11.06° for the untreated soil to approximately 34.50° for MB25. The increase of approximately 23.44° demonstrates a substantial improvement in the frictional component of shear resistance after foam-mortar stabilization. According to the Mohr–Coulomb failure criterion, shear strength is influenced by both cohesion and internal friction, with the frictional component becoming increasingly important as normal stress increases (Das, 1995). The increase in φ therefore indicates that the treated mixture developed greater resistance to particle sliding and shear displacement than the original clay soil. The presence of sand particles introduced through the foam mortar can promote mechanical interlocking, while the cementitious components can provide additional bonding between soil and mortar particles. Experimental studies on foamed lightweight soils have also demonstrated that changes in mixture composition can influence the development of strength and internal structural stability (Ou et al., 2022).

The relationship between the grain-size changes and shear-strength response provides an important explanation for the improved mechanical behavior of the treated soil. The untreated material was dominated by clay particles at 89.88%, whereas the treated mixtures contained substantially higher proportions of sand based on the reported grain-size results. This transformation changes the potential interaction among particles from predominantly cohesive behavior toward a combination of frictional contact and cementitious bonding. MB15 showed the lowest reported clay fraction and the highest reported sand fraction, whereas MB25 produced the highest documented internal friction angle of approximately 34.5°. The results indicate that the shear-strength improvement cannot be explained solely by the increase in sand content because the cementitious bonding and internal structure of the foam mortar also contribute to the mechanical response. Previous research has shown that lightweight foamed soil can develop improved engineering properties through appropriate control of binder content and mixture composition (Chen et al., 2024).

From an engineering perspective, the increase in shear resistance demonstrates the potential of foam mortar to overcome the limited shear performance of the investigated soft clay. The untreated soil had an internal friction angle of only 11.06° and a CBR value of 5.10%, reflecting a weak material structure under loading. The increase in internal friction angle to approximately 34.5° for MB25 indicates considerably greater resistance to particle displacement and shear deformation. This improvement is consistent with the formation of a more stable soil–mortar matrix resulting from the incorporation of sand and cementitious material. The grain-size results further support this interpretation because the treated mixtures contained substantially greater proportions of sand than the original soil. The combined modification of particle composition and cementitious bonding therefore represents an important mechanism through which foam mortar improves the shear behavior of the tested soil.

Effect of Foam Mortar on Compaction Characteristics and Bearing Capacity

The Standard Proctor test was conducted to evaluate changes in the moisture-density relationship of the soil following the addition of foam mortar. The untreated MB0 mixture exhibited an optimum moisture content (OMC) of 34.00% and a maximum dry density (MDD) of 1.27 g/cm³. After foam mortar addition, the OMC decreased to 16.10% for MB15 and 17.85% for MB20, while the MDD increased to 1.65 g/cm³ and 1.69 g/cm³, respectively. The MB25 mixture recorded an OMC of 24.00%, although its MDD value was not reported in the available experimental data. The reduction in OMC for MB15 and MB20 indicates that the treated mixtures required less water to reach their respective maximum dry densities than the untreated soil. The increase in dry density indicates that the addition of foam mortar changed the packing characteristics of the original clay matrix and produced a denser compacted structure.

Table 6. Standard Proctor Test Results

Mixture	Optimum Moisture Content, OMC (%)	Maximum Dry Density, MDD (g/cm³)
MB0	34.00	1.27
MB15	16.10	1.65
MB20	17.85	1.69
MB25	24.00	Not reported

The results in Table 6 demonstrate that foam mortar substantially modified the compaction characteristics of the soil compared with the untreated condition. The OMC decreased by 17.90 percentage points in MB15 and 16.15 percentage points in MB20 relative to MB0. At the same time, the MDD increased by 0.38 g/cm³ in MB15 and 0.42 g/cm³ in MB20. This increase corresponds to approximately 29.9% and 33.1%, respectively, compared with the original MDD of 1.27 g/cm³. The changes indicate that the treated mixtures could achieve higher dry densities with considerably lower moisture requirements than the untreated clay. Modification of the soil matrix through the incorporation of cement, sand, and foam can alter particle arrangement and compaction behavior, which is an important characteristic of lightweight stabilized soil (Wibowo, 2022).

The CBR results provide direct evidence of the improvement in bearing capacity produced by foam mortar stabilization. The untreated MB0 soil had an unsoaked CBR value of only 5.10%, whereas MB15, MB20, and MB25 achieved values of 15.97%, 20.05%, and 25.70%, respectively. The CBR therefore increased progressively as the foam mortar content increased from 15% to 25%. Compared with MB0, the CBR of MB15 increased by approximately 213.1%, MB20 by 293.1%, and MB25 by 404.0%. In ratio terms, the MB25 value was approximately 5.04 times the CBR of the untreated soil. This substantial increase indicates that foam mortar can significantly improve the penetration resistance and bearing performance of the investigated clay soil.

Table 7. Unsoaked CBR Test Results

Mixture	CBR (%)	Increase Relative to MB0
MB0	5.10	—
MB15	15.97	213.1%
MB20	20.05	293.1%
MB25	25.70	404.0%

As presented in Table 7, MB25 produced the highest unsoaked CBR value of 25.70%, followed by MB20 at 20.05% and MB15 at 15.97%. The progressive increase in CBR indicates that increasing foam mortar content generally enhanced the resistance of the soil mixture against penetration loading. The improvement can be attributed to the combined effects of the cementitious matrix, additional sand particles, and the resulting modification of the compacted soil structure. Cementitious stabilization can increase the interparticle bonding and mechanical resistance of fine-grained soil, while the granular component can contribute to greater frictional resistance (Kusuma et al., 2013). The increase in CBR observed in the present experiment is also consistent with previous studies showing that foam mortar can improve the engineering performance of soft soils and reduce their susceptibility to deformation under loading (Aji & Amin, 2025). The MB25 mixture therefore demonstrated the strongest bearing response among the tested foam-mortar compositions under the unsoaked CBR condition.

The improvement in bearing capacity is closely related to the changes in compaction characteristics observed after foam mortar addition. The untreated soil combined a relatively high OMC of 34.00% with a low MDD of 1.27 g/cm³, whereas MB15 and MB20 achieved higher dry densities at substantially lower optimum moisture contents. A denser compacted structure can provide greater resistance to penetration because the particles have less freedom to rearrange under the applied load. The increase in MDD from 1.27 g/cm³ to 1.69 g/cm³ for MB20 represents the highest documented MDD among the mixtures for which complete Proctor data are available. At the same time, the CBR increased from 5.10% for MB0 to 20.05% for MB20, indicating a strong relationship between improved compaction characteristics and bearing performance. Similar improvements in load-settlement and engineering behavior have been reported for lightweight foamed materials applied to soft ground (Kim et al., 2022). The results suggest that foam mortar does not merely modify the density of the soil but also creates a more resistant internal structure capable of sustaining greater penetration loads.

The MB25 mixture demonstrated the highest bearing performance, although its OMC of 24.00% was higher than those of MB15 and MB20. This result indicates that the relationship between foam-mortar content, moisture requirement, and bearing capacity is not strictly linear across all engineering parameters. Despite the higher OMC, MB25 achieved the highest CBR of 25.70%, demonstrating that its mechanical improvement was sufficient to produce the greatest penetration resistance among the tested mixtures. The result is consistent with the direct-shear finding in which MB25 also exhibited the highest documented internal friction angle of approximately 34.5°. The simultaneous improvement in CBR and shear resistance indicates that the higher foam-mortar content produced a stronger load-bearing framework within the treated soil. Previous research has shown that foam-mortar and lightweight foamed-soil systems can improve the performance of soft-ground structures by modifying material density, strength, and deformation behavior (Lastiasih & Mochtar, 2022). From the perspective of bearing capacity, MB25 can therefore be identified as the most effective mixture among the tested compositions, while the broader evaluation of material efficiency and engineering performance is discussed in the following subsection.

Evaluation of Foam Mortar Content for Soft-Soil Improvement

The overall performance of the foam-mortar mixtures was evaluated by integrating the changes in grain-size composition, shear strength, compaction characteristics, and bearing capacity. The untreated MB0 mixture provided the baseline condition, with a CBR of 5.10%, an internal friction angle of 11.06°, an OMC of 34.00%, and an MDD of 1.27 g/cm³. The addition of foam mortar improved the principal engineering characteristics of the soil, although the magnitude of improvement varied according to the mixture proportion. MB15 increased the CBR to 15.97% and the MDD to 1.65 g/cm³ while reducing the OMC to 16.10%. MB20 produced a CBR of 20.05%, an MDD of 1.69 g/cm³, and an OMC of 17.85%. MB25 produced the highest CBR of 25.70% and the highest documented internal friction angle of approximately 34.5%, indicating the strongest mechanical response among the tested mixtures.

The comparison of the treated mixtures demonstrates that increasing foam-mortar content generally enhanced the bearing capacity of the soil. The CBR increased progressively from 15.97% in MB15 to 20.05% in MB20 and 25.70% in MB25. Relative to the untreated MB0 condition, these values represent increases of approximately 213.1%, 293.1%, and 404.0%, respectively. The improvement in CBR was accompanied by substantial changes in compaction characteristics, particularly the reduction in OMC and increase in MDD observed for MB15 and MB20. The results indicate that foam mortar modified the internal structure of the soil mixture and increased its resistance to penetration loading. Similar improvements in soft-ground performance have been reported for foam mortar and lightweight foamed-soil applications, particularly where the treatment produces a more stable load-bearing structure (Lastiasih & Mochtar, 2022).

Table 8. Integrated Performance of Foam Mortar Mixtures

Parameter	MB0	MB15	MB20	MB25
Clay (%)	89.88	13.74	36.46	24.88
Sand (%)	2.79	72.25	56.10	68.06
OMC (%)	34.00	16.10	17.85	24.00
MDD (g/cm³)	1.27	1.65	1.69	—
Cohesion, *c* (kg/cm²)	0.247	—	—	—
Internal Friction Angle, φ (°)	11.06	—	—	≈34.50
CBR Unsoaked (%)	5.10	15.97	20.05	25.70

As shown in Table 8, each foam-mortar composition produced a different combination of physical and mechanical responses. MB15 exhibited the lowest reported clay fraction at 13.74% and the highest sand fraction at 72.25%, together with the lowest OMC among the treated mixtures at 16.10%. MB20 produced the highest documented MDD of 1.69 g/cm³ and an OMC of 17.85%, while its CBR reached 20.05%. MB25 achieved the highest CBR of 25.70% and the highest documented internal friction angle of approximately 34.5%. These results demonstrate that the increase in foam-mortar content improved the bearing response, although the optimum condition for individual physical parameters was not necessarily obtained at the highest treatment level. The different responses emphasize the importance of evaluating stabilization performance through multiple engineering parameters rather than relying on CBR alone.

From the shear-strength perspective, MB25 provided the strongest documented mechanical response among the tested mixtures. Its internal friction angle increased to approximately 34.5°, compared with only 11.06° for the untreated soil. This increase indicates a substantial improvement in frictional resistance and suggests that the treated material developed greater resistance to particle displacement under loading. The increase can be associated with the greater proportion of sand and the cementitious bonding generated by the foam mortar within the soil matrix. The development of stronger particle interaction is consistent with the behavior of cementitious lightweight soil, in which binder content and mixture composition influence the resulting mechanical properties (Chen et al., 2024). The shear-strength improvement therefore supports the CBR results by demonstrating that the enhanced bearing performance of MB25 was accompanied by a stronger resistance mechanism at the particle level.

The compaction results provide another basis for evaluating the relative effectiveness of the treatment levels. MB15 reduced the OMC from 34.00% to 16.10% and increased the MDD from 1.27 g/cm³ to 1.65 g/cm³, while MB20 reduced the OMC to 17.85% and increased the MDD to 1.69 g/cm³. These changes indicate that the treated mixtures could achieve higher dry densities with substantially lower moisture requirements than the untreated soil. MB25 recorded an OMC of 24.00%, which was higher than the values of MB15 and MB20, indicating that its compaction response did not follow the same trend as its CBR improvement. Nevertheless, MB25 achieved the highest CBR value, showing that maximum bearing performance was not determined solely by optimum moisture content. The combined effects of particle rearrangement, cementitious bonding, and the composition of the treated mixture can influence the final engineering response (Wibowo, 2022). The results suggest that MB20 may provide a favorable compaction response, whereas MB25 provides superior bearing performance.

From an engineering selection perspective, the optimum foam-mortar content depends on whether the primary objective is maximum mechanical performance or a balance between performance and material efficiency. MB15 already increased the CBR from 5.10% to 15.97%, demonstrating that a relatively lower foam-mortar content can produce a substantial improvement in bearing capacity. MB20 further increased the CBR to 20.05% and produced the highest documented MDD of 1.69 g/cm³ among the tested mixtures with available density data. MB25 produced the highest CBR of 25.70% and the highest documented internal friction angle of approximately 34.5%, making it the strongest mixture in terms of the principal mechanical indicators evaluated in this study. The progressive improvement in CBR is consistent with previous studies reporting the effectiveness of foam mortar and lightweight foamed materials for improving soft-ground performance (Kim et al., 2022). Therefore, MB25 can be considered the optimum mixture when maximum bearing capacity and shear resistance are prioritized, whereas MB15 and MB20 remain viable alternatives when lower treatment content or more favorable compaction characteristics are considered.

CONCLUSION

The experimental results demonstrate that the addition of foam mortar substantially improved the physical and mechanical performance of the soft clay obtained from Kelurahan Sawah Besar, Gayamsari District, Semarang City. The untreated soil was dominated by clay-sized particles at 89.88% and exhibited a specific gravity of 2.487, liquid limit of 53.21%, plastic limit of 29.82%, and plasticity index of 23.39%. The initial mechanical characteristics consisted of a cohesion value of 0.247 kg/cm², an internal friction angle of 11.06°, an optimum moisture content of 34.00%, a maximum dry density of 1.27 g/cm³, and an unsoaked CBR of 5.10%. These characteristics indicate that the untreated material had limited shear resistance and bearing performance and therefore required improvement for applications involving significant structural loading. Foam mortar addition substantially modified the grain-size composition, with the clay fraction decreasing from 89.88% in the untreated soil to 13.74%, 36.46%, and 24.88% for MB15, MB20, and MB25, respectively. The sand fraction simultaneously increased from 2.79% in MB0 to 72.25%, 56.10%, and 68.06% for MB15, MB20, and MB25, respectively. The results confirm that foam mortar can modify the particle composition and mechanical characteristics of soft clay and provide a substantial improvement in its engineering performance.

The mechanical evaluation showed that foam mortar increased the bearing capacity and shear resistance of the treated soil, with MB25 providing the highest documented overall mechanical performance. The unsoaked CBR increased progressively from 5.10% for MB0 to 15.97% for MB15, 20.05% for MB20, and 25.70% for MB25, corresponding to an approximately 5.04-fold increase at the MB25 treatment level. The internal friction angle also increased from 11.06° in the untreated soil to approximately 34.5° in MB25, indicating substantially greater resistance to particle movement and shear deformation. The Standard Proctor results showed that MB15 and MB20 achieved higher maximum dry densities of 1.65 and 1.69 g/cm³, respectively, compared with 1.27 g/cm³ for MB0, while their optimum moisture contents decreased to 16.10% and 17.85%. MB25 recorded an optimum moisture content of 24.00%, although its maximum dry density was not available in the reported experimental results. Among the tested mixtures, MB25 is therefore considered the most effective composition when maximum bearing capacity and shear resistance are prioritized, while MB15 and MB20 provide technically relevant alternatives with favorable compaction characteristics and lower foam-mortar contents. Future research should investigate a wider range of foam-mortar contents, including 5%, 10%, 30%, and 35%, together with additional tests such as the Unconfined Compression Test, triaxial test, and consolidation test and different curing periods of 7, 14, 28, and 56 days to identify the optimum mixture and better evaluate strength development over time.

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