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The Effect of Stabilizing the California Bearing Ratio (CBR) and Unconfined Compression Strength (UCS) of Clay Soil Using Fly Ash and Slacked Lime

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Abstract

Clay soil is frequently encountered in road and building construction, yet its low bearing capacity, high plasticity, and sensitivity to moisture variations can limit its suitability as a subgrade material. This study aims to characterize clay soil from the Kaligawe area of Semarang and evaluate the effects of fly ash, hydrated lime, and their combination on California Bearing Ratio (CBR) and Unconfined Compression Strength (UCS). An experimental laboratory approach was employed using untreated soil and stabilized specimens with additive contents of 2%, 4%, 6%, 8%, 10%, 12%, 15%, and 20% based on dry soil weight. The testing program comprised Atterberg limits, Standard Proctor compaction, soaked and unsoaked CBR, and UCS tests. The untreated soil exhibited a Liquid Limit of 65.375%, Plastic Limit of 27.611%, Plasticity Index of 37.764%, unsoaked CBR of 4.80%, soaked CBR of 3.10%, and UCS of 0.867 kg/cm². Fly ash achieved optimum CBR values at 15%, reaching 12.20% unsoaked and 8.80% soaked, whereas hydrated lime achieved 19.60% unsoaked and 17.00% soaked at 10%. The combined treatment produced the highest unsoaked CBR of 21.20% and UCS of 2.284 kg/cm² at 10% fly ash + 10% hydrated lime. UCS values for fly ash and hydrated lime individually reached 1.725 and 2.198 kg/cm², respectively. The findings demonstrate that combined stabilization effectively enhances clay performance, with 10% + 10% identified as the optimum composition.

Keywords: *Clay Soil, CBR, Fly Ash, Hydrated Lime, Soil Stabilization.*

INTRODUCTION

Every civil engineering construction project, ranging from highways and buildings to embankments and other infrastructure, fundamentally depends on soil as the primary supporting medium, making the engineering characterization and improvement of problematic soils an increasingly important issue in sustainable infrastructure development. The diversity of soil types encountered in construction, including boulders, sand, gravel, silt, clay, and colloidal materials, results in substantially different engineering responses because their physical, mineralogical, and hydraulic properties govern bearing capacity, compressibility, deformation, and strength behavior. Fine-grained soils, particularly clay, are among the most challenging materials because their very small particle size and large specific surface area generate strong interactions with water, resulting in substantial changes in consistency and mechanical performance under varying environmental conditions (Bowles, 1989). The fundamental principles of geotechnical engineering indicate that clayey soils can exhibit low shear strength, high compressibility, and significant volume changes, particularly when subjected to changes in moisture content and loading conditions (Das, 2021). These characteristics become particularly consequential in areas formed by sedimentary and former wetland deposits, such as the Kaligawe area of Semarang, where the presence of soft and fine-grained deposits can constrain the performance of soil as a construction subgrade. From a geotechnical perspective, wet clay generally becomes soft and exhibits low bearing capacity, whereas drying may induce shrinkage and cracking, creating a recurring challenge for infrastructure subjected to seasonal or operational moisture variations (Hardiyatmo, 2002).

Chemical soil stabilization has consequently developed as a technically practical approach for modifying problematic soil properties through the controlled incorporation of binders or stabilizing agents, with lime and fly ash receiving considerable attention because of their complementary mechanisms of soil modification. Hydrated lime, or calcium hydroxide [$Ca(OH)_2$], can alter the physicochemical behavior of clay through cation exchange and flocculation-agglomeration, reducing plasticity and improving soil workability while initiating longer-term cementitious reactions (Little et al., 2021). Fly ash, by contrast, contains reactive silica and alumina that can participate in pozzolanic reactions in the presence of calcium, promoting the formation of cementitious compounds that contribute to increased stiffness and strength. The effectiveness of this combined stabilization mechanism has been demonstrated for low-plasticity kaolin, where fly ash and hydrated lime improved the mechanical properties of the treated soil through changes associated with pozzolanic activity and cementitious bonding (Abdelbaset et al., 2024). Earlier research also established that fly ash can improve the bearing capacity of problematic clayey subgrades, although the magnitude of improvement depends strongly on soil characteristics and the proportion of stabilizing material incorporated (Utami et al., 2021). The engineering response is therefore not governed simply by the presence of a stabilizer but by the interaction between soil mineralogy, additive composition, dosage, moisture condition, and curing process. This interaction makes mixture optimization essential when the objective is to obtain a stabilization treatment that is mechanically effective while remaining technically and economically feasible.

The performance of stabilized clay is commonly evaluated through the California Bearing Ratio (CBR) and Unconfined Compression Strength (UCS), two complementary indicators that capture different aspects of soil improvement and are directly relevant to geotechnical and pavement engineering applications. The CBR test evaluates the resistance of compacted soil to penetration and is widely employed to characterize subgrade bearing capacity for pavement design, whereas the UCS test measures the compressive resistance of cohesive soil without lateral confinement and provides an indication of the internal strength and bonding developed during stabilization (ASTM International, 2021). Indonesian testing standards similarly establish laboratory CBR and unconfined compressive strength as important procedures for evaluating the engineering performance of compacted soils and cohesive materials (Badan Standardisasi Nasional, 2012a, 2012b). Previous studies have shown that lime-based stabilization can substantially modify the CBR behavior of clay, although the magnitude and direction of improvement may vary with additive content and curing conditions (Abdurrahim, 2023). Research involving cement and lime has likewise demonstrated that stabilization can increase the CBR of clay soils, confirming the relevance of chemical treatment for improving weak subgrades (Miswar et al., 2017). Recent investigations have further shown that variations in lime content and curing duration can produce markedly different CBR responses in expansive clay, indicating that stabilization effectiveness cannot be generalized across soil types or mixture proportions (Wardani et al., 2026). Consequently, CBR and UCS should be considered jointly because CBR primarily reflects resistance to external penetration loading, while UCS provides insight into the internal strength and cohesion generated by stabilization.

The existing literature demonstrates substantial potential for fly ash and lime stabilization, yet important inconsistencies remain regarding the optimum combination of materials and the extent to which improvements in bearing capacity correspond with gains in compressive strength. Fly ash-based stabilization has been reported to improve CBR in problematic soils, but the resulting performance is highly dependent on the characteristics of the original soil and the dosage of fly ash used (Harwadi et al., 2022). Similarly, the addition of fly ash to expansive or organic clay has produced measurable changes in UCS, confirming that pozzolanic stabilization can contribute to strength development but also suggesting that the response is not uniform across different clay systems (Yacub et al., 2025). Studies combining lime with supplementary materials have reported increases in strength, while research on highly reactive clay has shown that moisture and clay content can significantly influence the UCS achieved after lime treatment (Muhmed et al., 2022). More recent work has expanded the analytical perspective by examining relationships between chemical oxides and the prediction of CBR and UCS in fine-grained soils stabilized with fly ash and cement, demonstrating that chemical composition may provide an important basis for understanding and predicting mechanical performance (Ali & Mohammed, 2026). Research has also demonstrated that stabilized soil performance can be evaluated through predictive relationships involving both UCS and CBR, yet such approaches do not eliminate the need for experimentally determining suitable material proportions for site-specific soils (Salehi et al., 2023). The literature therefore indicates a persistent empirical gap concerning how a specific clay soil, particularly one originating from a locally distinctive depositional environment, responds simultaneously in terms of CBR and UCS to controlled combinations of fly ash and hydrated lime.

The unresolved issue carries both scientific and practical significance because an inappropriate stabilizer proportion may produce insufficient strength development, inefficient material utilization, or an improvement in one engineering parameter without a corresponding improvement in another. The economic dimension is particularly relevant because the use of fly ash and lime as stabilization materials must be evaluated not only in terms of mechanical performance but also in relation to the cost implications of constructing pavement subgrades with treated clay soils (Sharif et al., 2025). Fly ash also represents a potentially valuable industrial by-product, making its incorporation into soil stabilization relevant to resource efficiency and the reduction of waste associated with conventional construction materials, provided that its engineering performance is adequately established. The importance of selecting suitable material combinations is reinforced by research showing that the use of lime and fly ash can modify the CBR and swelling characteristics of clay, although the optimum dosage remains dependent on the specific soil and treatment conditions (Setiyono, 2022). Experimental evidence from clay stabilized with lime and fly ash has similarly confirmed that CBR can be enhanced through combined treatment, supporting the feasibility of the approach while leaving room for more site-specific optimization (Yulianti et al., 2023). The interpretation of these responses must also remain consistent with accepted soil classification and laboratory testing principles, because reliable stabilization assessment depends on correctly identifying the engineering characteristics of the untreated soil and applying standardized testing procedures (ASTM International, 2022). These considerations establish a need for an experimentally grounded investigation that connects the initial properties of local clay with the mechanical response produced by systematic addition of fly ash and hydrated lime.

Within this scientific landscape, the present study positions itself as a site-specific experimental investigation of clay soil from Kaligawe, Semarang, focusing on the comparative response of untreated and chemically stabilized soil through CBR and UCS measurements. The study is designed to characterize the initial engineering properties of the clay before stabilization and subsequently evaluate changes produced by controlled proportions of fly ash and hydrated lime. Particular attention is given to identifying the mixture proportion that provides the most favorable improvement in bearing capacity and unconfined compressive strength, rather than assuming that increasing stabilizer content necessarily produces proportional mechanical gains. The research addresses the practical problem of improving the suitability of locally available clay soil as a construction subgrade while simultaneously contributing empirical evidence concerning the interaction between fly ash, hydrated lime, and clay under laboratory-controlled conditions. Methodologically, the study integrates standardized CBR and UCS testing to provide complementary evidence of external load-bearing performance and internal strength development. The theoretical contribution lies in strengthening the empirical understanding of how combined pozzolanic and lime-based stabilization modifies the mechanical behavior of clay soil, while the methodological contribution lies in establishing an experimentally comparable basis for determining an optimal stabilizer composition. The study therefore aims to analyze the characteristics of Kaligawe clay soil, quantify the changes in CBR and UCS resulting from the addition of fly ash and hydrated lime, and determine the optimum mixture proportion capable of improving the engineering performance of the soil for construction applications.

RESEARCH METHODS

This study employed an empirical experimental design to investigate the effect of fly ash and slaked lime stabilization on the California Bearing Ratio (CBR) and Unconfined Compression Strength (UCS) of clay soil collected from the Kaligawe area of Semarang and tested at the Soil Mechanics Laboratory, Faculty of Engineering, Universitas Islam Sultan Agung (UNISSULA). The experimental materials consisted of naturally air-dried clay soil, fly ash, slaked lime, and water, with untreated clay serving as the control material, while lime stabilization was based on physicochemical modification through cation exchange, flocculation, and subsequent cementitious reactions (Little et al., 2021). The soil was air-dried, disaggregated, and passed through a No. 4 sieve with a nominal opening of 4.75 mm, after which fly ash and slaked lime were weighed according to the predetermined percentages based on the dry weight of the soil and mixed until homogeneous. The treatments consisted of untreated soil, fly ash alone, slaked lime alone, and a combined fly ash–slaked lime mixture at additive levels of 2%, 4%, 6%, 8%, 10%, 12%, 15%, and 20%, with the combined treatment using equal proportions of fly ash and slaked lime at each selected level. Water was added to each mixture until the optimum moisture content (OMC) obtained from the Standard Proctor test was reached, followed by specimen molding and curing for the predetermined curing period to facilitate stabilization reactions. The experimental configuration was supported by previous evidence that fly ash and hydrated lime can improve the mechanical properties of fine-grained soils through physicochemical modification and pozzolanic reactions (Abdelbaset et al., 2024).

Table 1. Percentage of Fly Ash and Slaked Lime Mixtures

Variation (%)	Soil (%)	Fly Ash (%)	Slaked Lime (%)
0	100	0	0
2	98	2	2
4	96	4	4
6	94	6	6
8	92	8	8
10	90	10	10
12	88	–	12
15	85	–	15
20	80	–	20

The experimental evaluation comprised Atterberg limits, Standard Proctor compaction, laboratory CBR, and UCS tests, with Atterberg-limit testing performed using a Casagrande apparatus and related equipment to determine the liquid limit, plastic limit, and plasticity index in accordance with applicable soil classification procedures (ASTM International, 2022). Standard Proctor compaction was conducted to establish the relationship between moisture content and dry unit weight and to determine the OMC used for preparation of stabilized specimens. Laboratory CBR testing was performed using a CBR machine, CBR molds, penetration piston, proving ring, dial gauge, and soaking equipment in accordance with SNI 1744:2012, with specimens tested under unsoaked conditions and after 4 × 24 h of soaking to represent high-moisture conditions. UCS testing was conducted using cylindrical specimens and a compression-testing apparatus in accordance with SNI 3638:2012, with the maximum axial stress at failure recorded as the unconfined compressive strength of each treatment. Measurement validity was maintained through standardized specimen preparation, controlled stabilizer dosage, consistent moisture conditioning, identical compaction procedures, and uniform loading procedures across control and stabilized specimens, while the CBR and UCS responses were compared quantitatively across all mixtures. Performance was evaluated by calculating and comparing CBR and UCS values relative to untreated clay, presenting the results through tables and graphs, and identifying the optimum mixture as the composition producing the highest mechanical improvement before a subsequent decline, consistent with previous findings that fly ash stabilization can improve the CBR performance of problematic clayey subgrades (Harwadi et al., 2022).

RESULTS AND DISCUSSION

Characteristics of the Untreated Clay Soil

The characterization of untreated clay soil was conducted to establish the initial physical and mechanical properties of the material collected from the Kaligawe area of Semarang before stabilization with fly ash and slaked lime. The parameters examined comprised liquid limit (LL), plastic limit (PL), plasticity index (PI), unconfined compression strength (UCS), unsoaked California Bearing Ratio (CBR), soaked CBR, and degree of saturation. These parameters were selected because they collectively describe the consistency, plasticity, compressive resistance, bearing capacity, and moisture condition of the soil. The results provide a quantitative baseline for assessing the magnitude of improvement generated by the stabilization treatment. The measured properties of the untreated soil are presented in Table 2, which serves as the reference condition for subsequent comparisons.

Table 2. Physical and Mechanical Properties Test Results of Untreated Soil

No.	Property	Value	Unit
1	Liquid Limit (LL)	65.375	%
2	Plastic Limit (PL)	27.611	%
3	Plasticity Index (PI)	37.764	%
4	UCS Value	0.867	kg/cm²
5	Unsoaked CBR Value	4.80	%
6	Soaked CBR Value	3.10	%
7	Degree of Saturation	92.255	%

The data in Table 2 show that the untreated soil has an LL of 65.375%, a PL of 27.611%, and a PI of 37.764%, indicating a substantial plastic range and a pronounced response to changes in moisture content. The high LL and PI values are characteristic of fine-grained soils with considerable plastic behavior, where the interaction between clay particles and water strongly influences consistency and deformation characteristics (Das, 2021). The PI value of 37.764% also indicates that the soil has a relatively broad moisture interval within which plastic deformation can occur. Such behavior can reduce the reliability of clay as a construction material when moisture conditions fluctuate during service. The high-plasticity condition is particularly relevant to subgrade applications because changes in water content can influence both volume stability and mechanical resistance. The physical appearance of the untreated material used in the experimental program is shown in Figure 1.

Figure 1. Visual Condition of the Original Clay Soil Sample from the Kaligawe Area, Semarang

The physical condition shown in Figure 1 represents the untreated clay material before the incorporation of stabilization agents and provides visual documentation of the specimen used as the experimental reference. The material was prepared through air drying and disaggregation before being processed for laboratory testing, ensuring that the initial soil condition could be reproduced during specimen preparation. The high plasticity indicated by the laboratory results is consistent with the engineering behavior expected from clay-rich soils whose mechanical response is strongly affected by water content (Hardiyatmo, 2002). The UCS value of 0.867 kg/cm² indicates that the untreated soil has limited resistance to axial compressive loading without lateral confinement. This relatively low strength condition is important because insufficient compressive resistance may contribute to deformation under sustained structural or traffic loading. The combination of the visual condition and measured mechanical properties establishes the untreated soil as a weak reference material requiring further engineering treatment.

The CBR results provide additional evidence of the limited bearing performance of the untreated clay, with the unsoaked CBR reaching only 4.80% and decreasing to 3.10% after soaking. The reduction corresponds to approximately 35.42%, indicating that exposure to water produces a substantial decrease in penetration resistance of the untreated material. CBR is widely used to assess the bearing capacity of compacted soil intended for pavement subgrade applications, making this reduction particularly relevant for evaluating soil performance under moisture-sensitive field conditions (Badan Standardisasi Nasional, 2012a). The high degree of saturation of 92.255% further indicates that the soil was already close to a saturated condition during characterization. Under such conditions, the availability of water within the soil structure can weaken interparticle resistance and contribute to a reduction in strength. The contrast between unsoaked and soaked CBR values therefore provides an important baseline for determining whether stabilization can improve the resistance of the clay to moisture-induced weakening.

The combined results indicate that the Kaligawe clay possesses three interrelated engineering limitations, namely high plasticity, relatively low compressive strength, and low bearing capacity under both unsoaked and soaked conditions. The high PI indicates substantial sensitivity to moisture-related changes in consistency, while the UCS value reflects limited internal resistance of the untreated soil under axial loading. The reduction in CBR following soaking further demonstrates that water exposure can adversely affect the load-bearing behavior of the material, which is consistent with the known influence of moisture and clay content on the strength characteristics of treated and untreated fine-grained soils (Muhmed et al., 2022). These characteristics are important for the selection of an appropriate stabilization strategy because improvement must address both the physical behavior and mechanical performance of the soil. A treatment that increases dry-state bearing capacity but remains highly vulnerable to moisture would provide limited practical benefit for a moisture-sensitive subgrade. The untreated results consequently provide a comprehensive reference against which changes in plasticity, CBR, and UCS can be evaluated after the addition of fly ash and slaked lime.

The initial condition of the Kaligawe clay establishes the need for stabilization because its high plasticity and low strength may restrict its direct application as a supporting layer for construction. Chemical stabilization is particularly relevant because lime can modify clay particle interactions through physicochemical processes, while reactive components of fly ash can contribute to cementitious bonding within the treated soil matrix (Little et al., 2021). The baseline CBR values of 4.80% in the unsoaked state and 3.10% in the soaked state provide measurable reference points for quantifying subsequent improvements in bearing capacity. Similarly, the initial UCS of 0.867 kg/cm² provides a reference for evaluating changes in compressive resistance following treatment. The degree of saturation of 92.255% highlights the importance of considering moisture-related performance when interpreting the effectiveness of stabilization. These baseline characteristics form the empirical foundation for examining how different proportions of fly ash and slaked lime alter the plasticity and mechanical behavior of the clay in the subsequent tests.

Effect of Fly Ash and Slaked Lime on Atterberg Limits

The Atterberg-limit tests were conducted to evaluate changes in the consistency characteristics of Kaligawe clay following the incorporation of fly ash and slaked lime. The untreated soil recorded a liquid limit (LL) of 65.38%, a plastic limit (PL) of 27.61%, and a plasticity index (PI) of 37.76%, indicating a broad plastic range and substantial sensitivity to changes in moisture content. These initial values provide the reference condition for assessing the modification of soil plasticity after stabilization. The reduction in plasticity is an important indicator in clay stabilization because changes in the clay–water interaction can influence volume stability and deformation behavior under field conditions. The effectiveness of stabilization can therefore be assessed not only from strength improvement but also from the extent to which the consistency characteristics of the soil are modified. Lime is known to induce cation exchange and flocculation of clay particles, producing changes in the diffuse double layer and reducing the plastic behavior of fine-grained soils (Little et al., 2021).

The addition of fly ash resulted in a progressive reduction in the LL and PI of the clay compared with the untreated condition. The LL decreased from 65.38% in the untreated soil to 49.04% at 2% fly ash and continued to decline to 40.75% at 20% fly ash, while the PI decreased from 37.76% to 15.17% over the same range. The decrease in PI indicates that the fly ash treatment reduced the range of moisture contents within which the soil behaved plastically. The response suggests that the incorporation of fly ash modified the active clay fraction and reduced the intensity of interaction between clay particles and water. Similar behavior has been reported for problematic clayey soils stabilized with fly ash, where the reduction in plasticity was accompanied by improvements in engineering performance (Utami et al., 2021). The reduction was not completely proportional to the increase in fly ash content, indicating that the effectiveness of additional material depends on the extent of interaction between the stabilizer and the available reactive components of the soil.

The slaked-lime treatment generated a comparable but more pronounced modification of the plasticity characteristics at several tested contents. At 2% slaked lime, the LL decreased to 52.09% and the PI decreased to 25.62%, while at 10% and 12% slaked lime the PI decreased further to 14.56% and 12.43%, respectively. The relatively large reduction in PI reflects the capacity of lime to rapidly alter the physicochemical condition of clay through cation exchange and particle flocculation, followed by longer-term cementitious reactions. Experimental research on clay treated with lime has demonstrated that the resulting UCS response is strongly affected by the interaction between lime content, clay characteristics, and moisture conditions (Muhmed et al., 2022). The measured values for the individual fly ash and slaked-lime treatments are summarized in Table 3 to facilitate direct comparison among the stabilization conditions.

Table 3. Atterberg Limits Values for Different Mixture Variations

Sample	LL (%)	PL (%)	PI (%)
Untreated soil	65.38	27.61	37.76
Fly ash 2%	49.04	23.04	26.00
Fly ash 10%	42.64	25.45	17.19
Fly ash 15%	41.85	25.03	16.82
Fly ash 20%	40.75	25.58	15.17
Slaked lime 2%	52.09	26.67	25.62
Slaked lime 10%	41.52	26.96	14.56
Slaked lime 12%	39.89	27.45	12.43
Fly ash 10% + slaked lime 10%	38.23	26.32	11.91
Fly ash 11% + slaked lime 11%	36.35	27.21	9.14

As shown in Table 3, the combined treatment produced the lowest LL and PI values among the reported mixtures, with the 10% fly ash + 10% slaked lime mixture reaching an LL of 38.23% and a PI of 11.91%. Increasing the combined proportion to 11% fly ash + 11% slaked lime reduced the LL further to 36.35% and the PI to 9.14%, representing a reduction of approximately 75.82% in PI compared with the untreated soil. This response indicates that the simultaneous incorporation of the two stabilizers generated a stronger modification of the clay consistency than the individual treatments reported in the table. The mechanism can be associated with the complementary functions of lime and fly ash, in which calcium supplied by lime promotes physicochemical modification while reactive silica and alumina from fly ash contribute to pozzolanic reactions. The combined use of hydrated lime and fly ash has been shown to improve the mechanical properties of fine-grained soil through these interacting stabilization mechanisms (Abdelbaset et al., 2024). The substantial reduction in PI also indicates a shift toward a less plastic soil condition, which is favorable for controlling moisture-related deformation.

The comparison among the mixtures demonstrates that the reduction in LL was generally more substantial than the change in PL, indicating that stabilization primarily affected the upper moisture boundary associated with the transition from plastic to liquid behavior. For fly ash, the PI reduction from 37.76% to 15.17% corresponds to a decrease of approximately 59.85%, whereas the 12% slaked-lime mixture produced a reduction of approximately 67.11%. The combined 11% + 11% treatment generated the largest reduction, suggesting that the interaction between the two stabilizing materials was particularly effective in altering the consistency behavior of the clay. Research on lime and fly ash stabilization has similarly indicated that changes in soil plasticity are closely associated with modifications in particle arrangement and physicochemical interaction between the stabilizer and clay minerals (Yulianti et al., 2023). The results indicate that increasing stabilizer content generally improves plasticity characteristics within the investigated range, although the optimum engineering mixture cannot be established from Atterberg limits alone. Mechanical performance must be considered because a mixture producing the lowest PI may not necessarily produce the highest CBR or UCS.

The Atterberg-limit results establish a clear modification of the Kaligawe clay from a highly plastic untreated condition toward a substantially less plastic state following stabilization. The PI decreased from 37.76% in the untreated soil to 15.17% with 20% fly ash, 12.43% with 12% slaked lime, and 9.14% with the 11% + 11% combined treatment. This progressive reduction indicates that the stabilizers altered the soil structure and reduced the intensity of clay–water interaction. The findings are consistent with the established role of lime in reducing plasticity through physicochemical reactions and particle flocculation, while fly ash contributes reactive components that can support subsequent cementitious development. From an engineering perspective, the reduction in PI indicates improved consistency characteristics and potentially greater resistance to moisture-induced deformation, but the final suitability of each mixture requires confirmation through CBR and UCS performance. The subsequent CBR analysis therefore focuses on whether the observed improvement in plasticity translates into increased bearing capacity under both unsoaked and soaked conditions.

Effect of Fly Ash and Slaked Lime on California Bearing Ratio

The California Bearing Ratio (CBR) test was conducted to evaluate the bearing capacity of the untreated and stabilized clay soil under unsoaked and soaked conditions. The untreated clay recorded a CBR value of 4.80% in the unsoaked condition and 3.10% after soaking, indicating that water exposure substantially reduced the penetration resistance of the soil. This behavior is consistent with the high plasticity characteristics identified in the initial soil characterization, where the PI reached 37.76%, making the soil susceptible to moisture-induced weakening. CBR provides an important engineering indicator for evaluating subgrade performance because it measures the resistance of compacted soil to penetration under standardized loading conditions (ASTM International, 2021). The difference between the unsoaked and soaked values indicates that the original soil had limited resistance to saturation, which is particularly relevant for construction areas exposed to prolonged wet conditions. The initial CBR values therefore establish a relatively weak baseline against which the effectiveness of fly ash and slaked lime stabilization can be quantitatively assessed.

The addition of fly ash increased the CBR of the clay compared with the untreated condition, although the improvement was dependent on the stabilizer content. The optimum fly ash content was identified at 15%, producing an unsoaked CBR of 12.20% and a soaked CBR of 8.80%, compared with 4.80% and 3.10% for untreated soil, respectively. These values represent increases of approximately 154.17% for the unsoaked condition and 183.87% for the soaked condition relative to the untreated material. The improvement can be associated with the reactive silica and alumina contained in fly ash, which can participate in pozzolanic reactions and contribute to the formation of cementitious products within the soil matrix (Ahmed et al., 2024). The higher CBR obtained at the optimum content indicates that an appropriate quantity of fly ash can increase penetration resistance by improving interparticle bonding and modifying the soil structure. The subsequent reduction at excessive fly ash content indicates that increasing the amount of additive beyond the effective reaction range does not necessarily produce proportional mechanical improvement.

Slaked lime generated a stronger CBR response than fly ash when evaluated at their respective optimum contents. The 10% slaked-lime mixture achieved an unsoaked CBR of 19.60% and a soaked CBR of 17.00%, representing increases of approximately 308.33% and 448.39%, respectively, relative to the untreated soil. The relatively small difference between the unsoaked and soaked values indicates that lime stabilization substantially improved the resistance of the clay to strength deterioration under water exposure. The effectiveness of lime can be attributed to cation exchange and flocculation-agglomeration processes that modify the arrangement of clay particles and reduce the thickness of the diffuse double layer (Abdurrahim, 2023). The comparative results of the untreated soil, fly ash, slaked lime, and combined treatment are presented in Table 4 to demonstrate the relative performance of each stabilization system. The data provide a basis for determining whether the combined use of fly ash and slaked lime offers an additional mechanical benefit beyond the individual stabilizers.

Table 4. Summary of Optimum CBR and UCS Values for Each Stabilization Material

Stabilization Material	Optimum Content	Unsoaked CBR (%)	Soaked CBR (%)	UCS (kg/cm²)
Untreated soil (without mixture)	–	4.80	3.10	0.867
Fly ash	15%	12.20	8.80	1.725
Slaked lime	10%	19.60	17.00	2.198

Fly ash + slaked lime	10% + 10%	21.20	–	2.284

The combined fly ash and slaked-lime treatment produced the highest reported unsoaked CBR, reaching 21.20% at a composition of 10% fly ash + 10% slaked lime. This value represents an increase of approximately 341.67% compared with the untreated CBR of 4.80%, demonstrating a substantial improvement in penetration resistance. The superior response of the combined mixture indicates that the two stabilizers produced complementary effects, with lime promoting early physicochemical modification while fly ash supplied reactive silica and alumina for subsequent pozzolanic reactions. Similar improvement from combined lime and fly ash stabilization has been reported for fine-grained soil, where the interaction between lime-induced modification and pozzolanic activity contributes to the development of a stronger soil matrix (Abdelbaset et al., 2024). The CBR comparison also shows that the combined mixture exceeded the optimum unsoaked CBR obtained from fly ash alone and slaked lime alone. The observed response suggests that the mechanical benefit of the combined treatment was not merely additive but was associated with the interaction between the two stabilizing mechanisms.

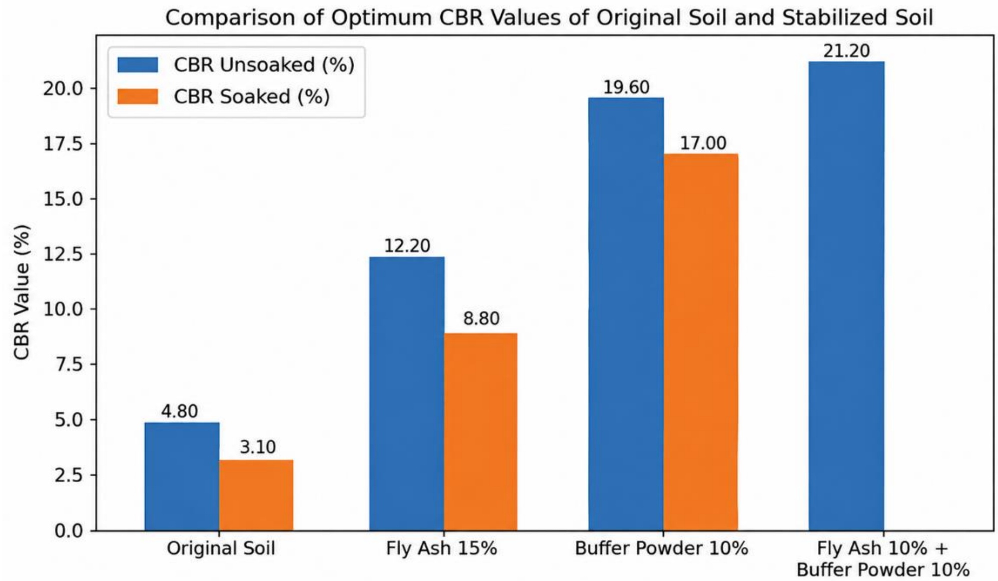

Figure 2. Comparison of Optimum CBR Values of Untreated and Stabilized Clay Soil

The pattern illustrated in Figure 2 confirms the substantially higher bearing capacity obtained after stabilization compared with the untreated condition. The unsoaked CBR increased from 4.80% for untreated soil to 12.20% with 15% fly ash, 19.60% with 10% slaked lime, and 21.20% with the combined 10% + 10% treatment. Under soaked conditions, the slaked-lime mixture maintained the highest reported value at 17.00%, while the fly ash mixture reached 8.80%, demonstrating that lime provided stronger resistance to water-induced reduction in penetration resistance within the tested individual treatments. The improved soaked performance of lime-treated clay is consistent with evidence that lime-induced physicochemical reactions can modify highly reactive clay and influence its strength response under different moisture conditions (Muhmed et al., 2022). The difference between the individual and combined treatments also indicates that the optimum composition cannot be determined solely from the performance of one stabilizer because the interaction between stabilizing agents can produce a distinct mechanical response. The absence of a reported soaked CBR value for the 10% + 10% combination prevents direct quantitative comparison of its soaked performance with the other treatments and avoids introducing an unsupported value into the analysis.

The occurrence of an optimum CBR rather than a continuously increasing response demonstrates that stabilizer dosage must be controlled according to the characteristics of the clay and the reaction capacity of the additives. The fly ash treatment reached its optimum at 15%, while the slaked-lime treatment reached its optimum at 10%, indicating different levels of additive demand for achieving effective soil modification. Excessive stabilizer can reduce the efficiency of the stabilization process when the available reactive soil constituents are insufficient to utilize the additional material, potentially affecting particle arrangement and compacted density. Previous research on clay stabilized with lime and fly ash has shown that stabilization effectiveness depends strongly on the selected additive proportion and that an optimum content must be established experimentally rather than assumed from a fixed dosage (Yulianti et al., 2023). The present CBR results support this principle because the highest additive percentage does not correspond to the highest measured bearing capacity. The 10% fly ash + 10% slaked-lime composition therefore represents the most effective combined treatment within the tested range based on the available CBR data.

The CBR findings demonstrate that chemical stabilization substantially improved the penetration resistance of the Kaligawe clay, with the combined fly ash and slaked-lime treatment producing the highest reported unsoaked CBR. The increase from 4.80% in untreated soil to 21.20% in the 10% + 10% mixture indicates a pronounced improvement in subgrade bearing performance. The results also reveal that slaked lime was more effective than fly ash when each material was considered individually at its optimum content, particularly under soaked conditions. This behavior is consistent with the role of lime in rapidly modifying clay particle interactions and reducing plasticity, while fly ash contributes additional pozzolanic material to the stabilized matrix (Setiyono, 2022). The combined treatment produced the strongest unsoaked response, supporting the interpretation that physicochemical modification and pozzolanic activity can operate synergistically in improving clay behavior. Evaluation of UCS is subsequently required to determine whether the increase in CBR is accompanied by a corresponding improvement in the internal compressive strength of the stabilized soil.

Effect of Fly Ash and Slaked Lime on Unconfined Compression Strength

The Unconfined Compression Strength (UCS) test was conducted to evaluate the improvement in the internal strength of the clay following stabilization with fly ash, slaked lime, and their combination. The untreated clay exhibited a UCS value of 0.867 kg/cm², indicating relatively low compressive resistance before stabilization. The addition of stabilizing materials produced a clear increase in UCS, although the magnitude of improvement varied according to the type and proportion of additive. This increase reflects changes in particle interaction and the development of stronger interparticle bonding within the stabilized soil matrix. UCS is particularly relevant for assessing the strength and stiffness of cohesive soil because the test measures the maximum axial stress sustained by a specimen without lateral confinement (ASTM International, 2020). The UCS response therefore complements the CBR results by providing an indication of the internal strength development generated by the stabilization process.

The fly ash treatment increased the UCS from 0.867 kg/cm² for untreated soil to 1.725 kg/cm² at the optimum content of 15% fly ash. This represents an increase of approximately 98.96% relative to the untreated soil, demonstrating that fly ash substantially enhanced the compressive resistance of the clay. The UCS value subsequently decreased slightly to 1.713 kg/cm² at 20% fly ash, indicating that increasing the additive content beyond the optimum did not provide additional strength development. The improvement can be associated with pozzolanic reactions involving reactive silica and alumina in fly ash, which contribute to the formation of cementitious compounds within the stabilized soil structure (Yacub et al., 2025). The observed optimum at 15% indicates that sufficient reactive material was available at this dosage to improve interparticle bonding without producing the adverse effects associated with excessive additive content. The response is consistent with previous research showing that fly ash can increase the UCS of clay soils, although the optimum content is dependent on soil composition and stabilization conditions.

Slaked lime generated a greater increase in UCS than fly ash at its optimum treatment level. The UCS increased from 0.867 kg/cm² in the untreated soil to 2.198 kg/cm² at 10% slaked lime, representing an increase of approximately 153.63%. The value then decreased slightly to 2.114 kg/cm² at 12% slaked lime, indicating that the optimum strength was achieved before the highest tested lime content. The stronger response of lime can be attributed to cation exchange, flocculation-agglomeration, and subsequent cementitious reactions that alter the structure and bonding characteristics of clay particles (Hardiyatmo, 2020). The UCS response confirms that the strength improvement observed in the CBR test was accompanied by a corresponding increase in compressive resistance. The comparison between the individual treatments indicates that slaked lime generated a greater UCS improvement than fly ash within the optimum proportions investigated.

The combined treatment produced the highest UCS value among the investigated stabilization systems, reaching 2.284 kg/cm² at 10% fly ash + 10% slaked lime. This value represents an increase of approximately 163.44% compared with the untreated UCS of 0.867 kg/cm², confirming the substantial strengthening effect of the combined stabilizers. The UCS subsequently decreased to 2.247 kg/cm² at the 12% + 12% composition, indicating that the maximum strength was achieved at the 10% + 10% combination rather than at the higher dosage. The superior performance of the combined treatment can be explained by the complementary contribution of lime-induced physicochemical modification and fly ash-based pozzolanic reactions. Similar research has demonstrated that the UCS of stabilized fine-grained soils is influenced by the interaction between stabilizer content, moisture conditions, and the development of cementitious bonds within the soil matrix (Salehi et al., 2023). The results indicate that the 10% + 10% combination provided the most favorable balance between particle modification and cementitious strength development within the investigated range.

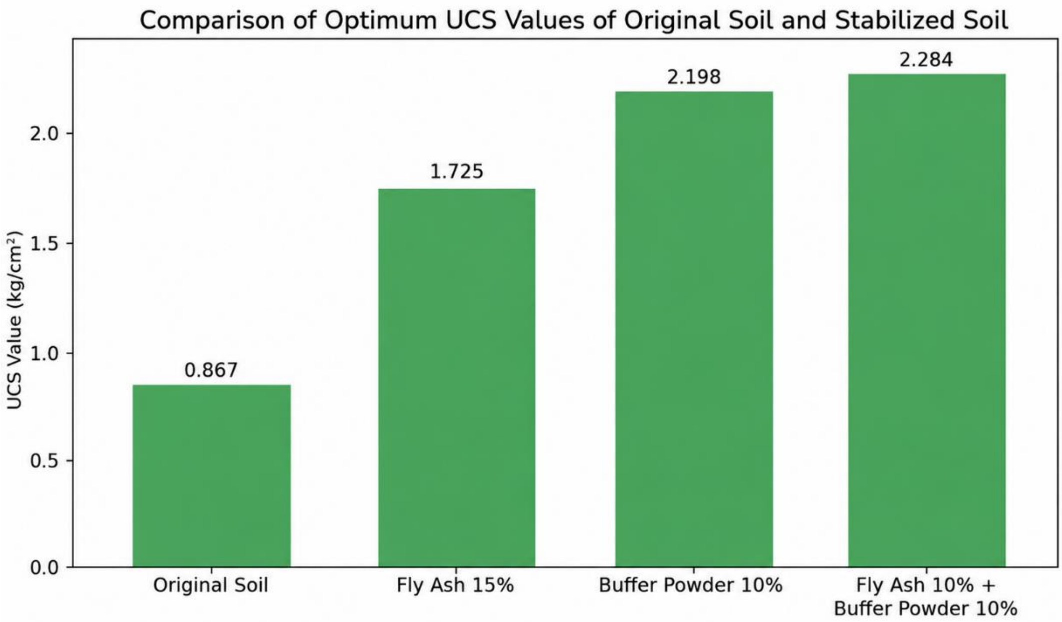

Figure 3. Comparison of Optimum UCS Values of Untreated and Stabilized Clay Soil

As illustrated in Figure 3, the UCS increased substantially for all optimum stabilization treatments compared with untreated clay. The untreated soil recorded only 0.867 kg/cm², whereas the optimum fly ash, slaked lime, and combined treatments reached 1.725, 2.198, and 2.284 kg/cm², respectively. The combined mixture therefore produced the highest compressive strength, exceeding the optimum fly ash treatment by approximately 32.41% and the optimum slaked-lime treatment by approximately 3.91%. The relatively small difference between the combined and slaked-lime treatments indicates that lime contributed strongly to the strength development, while the addition of fly ash provided an additional contribution to the cementitious matrix. This interpretation agrees with evidence that lime can enhance the reactivity of fine-grained soils while fly ash supplies pozzolanic constituents that participate in strength development (Abdelbaset et al., 2024). The graphical comparison confirms that the mechanical response cannot be attributed solely to the quantity of additive, because the combined 20% total additive content produced a higher UCS than the individual treatments containing comparable or lower stabilizer quantities.

The decrease in UCS observed after the optimum content provides evidence that stabilization efficiency was not linearly proportional to additive dosage. For fly ash, the UCS declined from 1.725 kg/cm² at 15% to 1.713 kg/cm² at 20%, while for slaked lime it declined from 2.198 kg/cm² at 10% to 2.114 kg/cm² at 12%. A similar decline occurred in the combined treatment, where UCS decreased from 2.284 kg/cm² at 10% + 10% to 2.247 kg/cm² at 12% + 12%. Such behavior indicates that the availability of reactive soil constituents and the resulting particle arrangement impose practical limits on the beneficial effect of additional stabilizer. Previous investigations have shown that excessive stabilizer content may fail to generate proportional strength gains because the additional material cannot be fully incorporated into effective cementitious bonding (Nugroho et al., 2022). The optimum UCS values therefore represent the dosage range in which the stabilization reactions and compacted soil structure produce the most effective strength development. This finding is important for engineering applications because increasing stabilizer content beyond the optimum would increase material consumption without providing a corresponding improvement in compressive performance.

The UCS results confirm that fly ash and slaked lime substantially improved the compressive resistance of the Kaligawe clay, with the combined 10% fly ash + 10% slaked lime mixture producing the highest measured value of 2.284 kg/cm². The increase from 0.867 kg/cm² in the untreated condition demonstrates that stabilization significantly enhanced the internal strength of the soil matrix. The stronger performance of the combined treatment indicates that the physicochemical effects of lime and the pozzolanic contribution of fly ash operated in a complementary manner. The observed strength development is consistent with previous findings that lime-pozzolan stabilization can improve both UCS and CBR by developing stronger bonding within treated fine-grained soils (Salehi et al., 2023). The decrease in UCS at higher dosages further confirms that optimum stabilization must be established experimentally for the specific soil and stabilizer combination. Taken together with the CBR findings, the UCS results reinforce the 10% fly ash + 10% slaked lime mixture as the most effective treatment among the tested combinations.

CONCLUSION

The clay soil collected from the Kaligawe area of Semarang exhibited relatively low bearing capacity in its untreated condition, as indicated by an unsoaked CBR of 4.80%, a soaked CBR of 3.10%, and a UCS of 0.867 kg/cm². These values indicate that the original soil has limited mechanical performance and requires stabilization before being utilized as a construction subgrade. Fly ash stabilization increased the CBR to an optimum unsoaked value of 12.20% and a soaked value of 8.80% at a 15% dosage. Slaked lime produced a greater improvement, with optimum unsoaked and soaked CBR values of 19.60% and 17.00%, respectively, at a 10% dosage. The combined treatment of fly ash and slaked lime generated the highest unsoaked CBR, reaching 21.20% at a composition of 10% fly ash and 10% slaked lime. A comparable response was observed in the UCS results, where the optimum values reached 1.725 kg/cm² for 15% fly ash, 2.198 kg/cm² for 10% slaked lime, and 2.284 kg/cm² for the combined 10% + 10% treatment. The results establish the 10% fly ash + 10% slaked lime composition as the most effective stabilization treatment among the investigated mixtures based on the simultaneous improvement of bearing capacity and unconfined compressive strength.

The findings indicate that the combined application of fly ash and slaked lime provides a technically effective alternative for improving the engineering performance of clay soil in the Kaligawe area of Semarang. The 10% + 10% mixture achieved the highest measured CBR and UCS performance, demonstrating that the interaction between the two stabilizing materials can provide greater mechanical improvement than their individual applications within the tested proportions. The treatment is particularly relevant for subgrade applications where both resistance to penetration and internal compressive strength are important performance considerations. The experimental results also indicate that increasing stabilizer content beyond the optimum does not necessarily produce further strength improvement, emphasizing the importance of determining dosage based on the specific characteristics of the soil. Future research should incorporate soil samples collected directly from road sections experiencing settlement to obtain data that more accurately represent in-situ conditions and the mechanisms contributing to field deformation. Field-scale verification, including evaluation under actual moisture, loading, and drainage conditions, would further strengthen the applicability of the laboratory findings to infrastructure design. Such investigations could provide a more comprehensive basis for assessing the long-term performance and practical implementation of fly ash and slaked lime stabilization in problematic clayey subgrades.

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