Mechanical and Bearing Performance of Cement–Fly Ash Stabilized Clay Subgrade

Denny B. Pinasang
Civil Engineering Department, Manado State Polytechnic, Manado, Indonesia
dennyboypinasang@yahoo.com (corresponding author)

Miswar Tumpu
Disaster Management Study Program, The Graduate School, Hasanuddin University, Indonesia
tumpumiswar@gmail.com

Don R. G. Kabo
Civil Engineering Department, Manado State Polytechnic, Manado, Indonesia
donkabo74@gmail.com

Carter Kandou
Civil Engineering Department, Manado State Polytechnic, Manado, Indonesia
ckandou@yahoo.com

Herman Tumengkol
Civil Engineering Department, Manado State Polytechnic, Manado, Indonesia
tumengkolherman@yahoo.co.id

Hoong Pin-Lee
Civil Engineering Department, Faculty of Engineering and Quantity Surveying, INTI International University, Negeri Sembilan, Malaysia
hoongpin.lee@newinti.edu.my

Received: 25 January 2026 | Revised: 5 March 2026 | Accepted: 13 March 2026

ABSTRACT

Clay soils with low bearing capacity pose significant challenges for road pavement subgrade performance, especially in moisture-sensitive environments. This study evaluates the effectiveness of cement–fly ash mixtures for soil stabilization to improve the engineering properties of clay used as a subgrade layer. Laboratory experiments varied the fly ash content (0%, 5%, 10%, 15%, and 20%) while keeping the cement proportion fixed. The stabilized soils were evaluated using Atterberg limits, compaction characteristics, and California Bearing Ratio (CBR) tests. The results show that using cement–fly ash mixtures reduces soil plasticity while increasing maximum dry density and bearing capacity. Optimal performance was observed at 15% fly ash, which produced a significant improvement in CBR compared with untreated soil, whereas higher fly ash contents yielded diminishing strength gains. This study identifies an optimal cement–fly ash combination that improves mechanical performance while maintaining material efficiency, supporting sustainable pavement design. The findings also demonstrate the potential to use industrial by-products to reduce dependence on conventional materials, contributing to the Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production). The results provide practical guidance for engineers and policymakers in developing cost-effective and environmentally responsible road infrastructure.

Keywords-clay soil stabilization; cement–fly ash stabilization; subgrade improvement; CBR; sustainable pavement design; industrial waste management; SDGs

I. INTRODUCTION

Clay soil is widely used as a natural subgrade material in road pavement construction. However, its inherently low bearing capacity, high plasticity, and sensitivity to moisture variations often lead to premature pavement distress [1]. These unfavorable characteristics can cause excessive deformation, cracking, and a reduced service life of pavement structures, particularly in tropical regions with high rainfall intensity [2]. Consequently, soil stabilization has become an important engineering approach for improving subgrade performance and maintaining pavement durability. Among the various stabilization methods, chemical treatment using cement and industrial by-products has gained attention because of its effectiveness and its potential contribution to sustainable infrastructure development. Cement-based stabilization can significantly improve the mechanical behavior of weak soils by increasing strength, stiffness, and durability. Authors in [3] reported that incorporating fly ash and agricultural waste ash in geopolymer-based systems can enhance durability while reducing dependence on ordinary Portland cement. Authors in [4] found that the addition of soluble silicates and limestone improves compressive strength and soil stiffness, highlighting the importance of binder composition in soil stabilization. Moreover, the utilization of waste-derived materials has been explored as an environmentally responsible stabilization approach. Authors in [5] demonstrated that waste tire shreds can enhance soil strength and durability, while authors in [6] showed that waste marble dust and corncob ash improve both the engineering and microstructural properties of expansive soils used in road subgrades.

The construction industry has explored the use of industrial by-products and waste materials to enhance the mechanical and environmental performance of construction materials. Materials such as steel waste, Ground Granulated Blast Furnace Slag (GGBS), graphene, and other additives can improve concrete strength, durability, and overall sustainability [7-11]. These innovations are particularly relevant in developing countries, where industrial by-products, such as fly ash, are readily available. Incorporating these materials into pavement and subgrade stabilization systems provides opportunities to reduce environmental impacts while enhancing structural performance and extending infrastructure service life. Despite the growing number of studies on alternative stabilizers, many investigations emphasize geopolymer systems, unconventional additives, or microstructural analysis, while limited attention is given to the systematic optimization of conventional cement–fly ash mixtures for pavement subgrade applications. In many cases, fly ash is introduced only as a supplementary material without evaluating its interaction with cement across different mixture proportions. As a result, practical guidance for determining the optimum fly ash content for subgrade stabilization remains limited. This limitation is particularly relevant for regions with locally available clay soils whose mineralogical characteristics and environmental conditions may influence stabilization performance.

Therefore, this study systematically investigates the influence of cement–fly ash mixture variations on the engineering properties of clay soil used as a pavement subgrade layer. The research evaluates changes in plasticity characteristics, compaction behavior, and CBR values to identify the optimal fly ash proportion that balances mechanical improvement and material efficiency. The investigation focuses on locally sourced clay and fly ash under environmental conditions representative of South Sulawesi, Indonesia, providing practical insights for context-specific stabilization strategies. From a sustainability perspective, the use of fly ash as a partial stabilizing material contributes to the SDGs, particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production), by reducing reliance on Portland cement and promoting the reuse of industrial by-products while improving the load-bearing performance of pavement subgrades.

II. MATERIALS AND METHODS

A. *Fly Ash*

Fly ash is a by-product of coal combustion in thermal power plants and is commonly employed as a stabilizing material in geotechnical engineering because of its pozzolanic and cementitious properties. According to [12], fly ash is classified into Class C (high-calcium) and Class F (low-calcium) based on the coal source and calcium oxide (CaO) content [13, 14]. Class C fly ash, typically produced from sub-bituminous coal, contains more than 20% CaO and exhibits self-cementing properties. In contrast, Class F fly ash, derived from bituminous or anthracite coal, contains less than 10% CaO and generally requires an external activator for strength development [15]. High-calcium fly ash can contribute more effectively to both early-age and long-term strength gain in soil stabilization applications [16]. The fly ash used in this study was obtained from the Jayapura Thermal Power Plant and classified as Class F fly ash according to [12]. Its chemical composition, presented in Table I, is dominated by silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), confirming its pozzolanic nature. The relatively low CaO content (2%) indicates limited self-cementing capability; therefore, cement was used as an activator to enhance the stabilization reaction [15, 16].

From a geotechnical perspective, fly ash has been applied to improve the engineering properties of clay soils used in subgrade and embankment construction. The addition of fly ash can reduce soil plasticity, improve compaction characteristics, and increase Unconfined Compressive Strength (UCS) and shear strength of fine-grained soils [17]. Fly ash–stabilized soils also exhibit lower swelling potential and higher load-bearing capacity compared to untreated clay, making them suitable for pavement subgrade applications. Fly ash contents ranging from 10% to 20% can significantly improve soil performance, particularly when combined with hydraulic binders such as cement [18]. The effectiveness of fly ash stabilization depends on factors such as soil mineralogy, fly ash content, moisture condition, compaction delay time, and curing conditions, which influence the development of pozzolanic reactions [19, 20]. Compared to other waste-based stabilizers, such as rice husk ash, marble dust, and tire shreds, fly ash offers a balanced combination of engineering performance, availability, and environmental benefits while supporting sustainable construction practices [21]. The physical appearance of the fly ash used in this study is shown in Figure 1.

TABLE I. CHEMICAL COMPOSITION OF CLASS F FLY ASH

Component	**Content (%)**
SiO_2	55.2
Al_2O_3	26.8
Fe_2O_3	12
CaO	2
MgO	2.5
SO_3	1.5
Fineness (cm²/g)	–
Loss on ignition (%)	–

Fig. 1. Physical appearance of class F fly ash.

B. Cement

Cement is one of the most widely used hydraulic binders for soil stabilization because it can significantly improve the mechanical properties of fine-grained soils. In geotechnical engineering, cement stabilization reduces plasticity, limits volumetric changes, and increases the strength and stiffness of clay soils through hydration and cementation reactions [22]. Unlike fly ash, which primarily exhibits pozzolanic behavior, cement reacts directly with water to form Calcium Silicate Hydrate (C–S–H) and Calcium Aluminate Hydrate (C–A–H) compounds that bind soil particles into a dense and stable matrix [23]. As a result, cement-stabilized soils have been utilized in road subgrade construction because they provide substantial improvements in unconfined compressive strength, bearing capacity, and durability [24]. However, the use of cement alone is often associated with higher construction costs and increased carbon emissions due to its energy-intensive manufacturing process. Therefore, research has explored the partial replacement of cement with supplementary materials such as fly ash to improve sustainability while maintaining engineering performance [25]. In blended stabilization systems, cement acts not only as a primary stabilizer but also as an activator that enhances the pozzolanic reactions of low-calcium fly ash. Calcium ions released during cement hydration react with silica and alumina in fly ash to form additional cementitious compounds, resulting in a denser and stronger soil structure [25]. Cement–fly ash mixtures can significantly improve compressive strength, stiffness, and durability while reducing brittleness compared with cement-only stabilization systems [26, 27]. The effectiveness of this method depends on several factors, including cement dosage, curing time, and soil mineralogy, as excessive cement content may lead to brittle behavior and economic inefficiency [28]. Accordingly, this study evaluates the effectiveness of 8% cement combined with varying proportions of locally sourced Class F fly ash to stabilize clay subgrade soils typical of Indonesian tropical regions. The objective is to identify an optimal cement–fly ash mixture that maximizes mechanical performance, particularly the UCS and CBR values, while improving material efficiency and supporting sustainable engineering practices [29].

C. Methodology

This study employed a laboratory experimental approach to evaluate the influence of cement–fly ash mixtures on the engineering properties of clay soil used as a road pavement subgrade. The behavior of untreated natural soil was compared with that of soils stabilized using varying fly ash proportions and a constant cement content. All experimental procedures followed relevant standards to ensure the reliability and repeatability of results. The clay soil was first tested in its natural state to determine baseline physical and mechanical properties before stabilization. Soil classification and index property tests were conducted following [30], while the Liquid Limit (LL) and Plastic Limit (PL) were determined based on [31]. Specific gravity was measured according to [32], and Particle Size Distribution (PSD) was analyzed based on [33]. Compaction characteristics were evaluated using the Standard Proctor [34] and Modified Proctor [35] methods, while mechanical performance was assessed using the UCS test [36] and the CBR test [37].

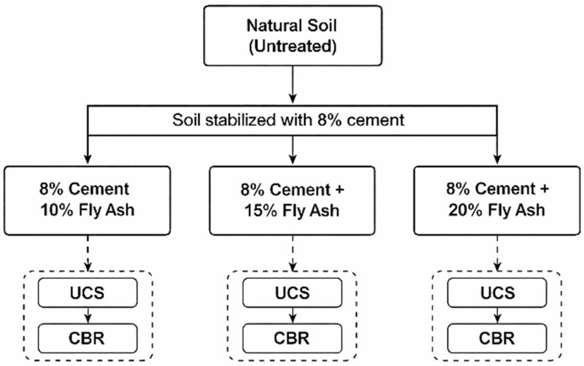

Fig. 2. Variation of test specimens and experimental program.

Soil stabilization was performed utilizing a dry mixing method to ensure uniform distribution of cement and fly ash before adding water to achieve the target moisture content for compaction. Cement content was maintained at 8% to act as a chemical activator, while fly ash was varied at 0%, 10%, 15%, and 20% by dry weight of soil based on recommendations from previous stabilization studies. The stabilized mixtures were compacted following standard laboratory procedures and cured at 25 ± 2°C and 95% relative humidity for 7, 14, and 28 days before testing. UCS specimens were wrapped with plastic film to minimize moisture loss, whereas CBR specimens were soaked in water for 24 h before testing and subjected to an additional soaked condition after 96 h of immersion to simulate critical moisture conditions in pavement subgrades. Statistical analysis was performed using one-way Analysis of Variance (ANOVA) at a significance level of 5% (α = 0.05), assuming normality and homogeneity of variance. Five identical specimens were prepared for each mixture, and the results are presented as mean values ± Standard Deviation (SD). The overall experimental workflow is summarized in Figure 2, while the composition of each specimen is presented in Table II, which includes untreated soil and stabilized mixtures with 8% cement and fly ash contents of 10%, 15%, and 20%.

TABLE II. COMPOSITION OF CEMENT–FLY ASH STABILIZED SOIL SPECIMENS

Sample code	Fly ash content (% by weight of soil)	Cement content (% by weight of soil)	Description
S0	0%	0%	Natural clay soil (untreated)
S1	0%	8%	Soil stabilized with cement only
S2	10%	8%	Soil stabilized with 10% fly ash + cement
S3	15%	8%	Soil stabilized with 15% fly ash + cement
S4	20%	8%	Soil stabilized with 20% fly ash + cement

III. RESULTS AND DISCUSSION

A. Physical Properties of Untreated Clay Soil

The physical properties of the untreated clay soil were determined through laboratory testing to establish baseline characteristics before stabilization. These properties are important for evaluating the suitability of the soil as a pavement subgrade and for assessing the effectiveness of fly ash–cement treatment in subsequent analyses. The results indicate that the natural soil exhibits relatively high plasticity and sensitivity to moisture variations, which are typical characteristics of clayey subgrade soils and have been reported in previous studies on expansive clays used in pavement structures [38, 39]. The natural water content of the soil is 21.53%, indicating a moderately moist condition commonly observed in expansive soils influenced by tropical climatic conditions [1, 2]. The specific gravity (Gs) value of 2.78 suggests that the soil matrix is dominated by clay minerals and silicate-based constituents, which are typical of fine-grained soils with relatively high plasticity and low structural stability [3, 19]. The physical properties of the untreated clay soil are detailed in Table III.

The PSD results presented in Figure 3 indicate that the soil is predominantly composed of fine particles, consisting of silt (48.8%), clay (33.8%), sand (16.6%), and a minor gravel fraction (0.8%). In this study, clay is defined as particles smaller than 2 μm, while silt refers to particles ranging from 2 μm to 75 μm, according to the USDA soil texture classification system. Therefore, the fraction passing the No. 200 sieve (75 μm) includes both silt and clay components. The Atterberg limit results show an LL of 45.09%, a PL of 25.71%, and a PI of 19.08%, indicating medium to high plasticity. Such characteristics are commonly associated with low bearing capacity, high compressibility, and significant shrink–swell potential [1, 25]. Based on the AASHTO classification system, the soil is categorized as A-7-6, which is generally considered poor to fair for subgrade applications. This classification is consistent with the measured compaction characteristics, including a maximum dry density of 1.73 g/cm³, an optimum moisture content of 21.82%, and a relatively low UCS value of 11.73 kg/cm². Soils within the A-7-6 category often require chemical or pozzolanic stabilization to improve strength, reduce plasticity, and enhance durability in pavement structures [5, 14, 16, 19, 24, 25, 41]. Therefore, the baseline characteristics presented in Table III provide a justification for investigating the effectiveness of cement–fly ash stabilization in improving the engineering performance of the clay subgrade.

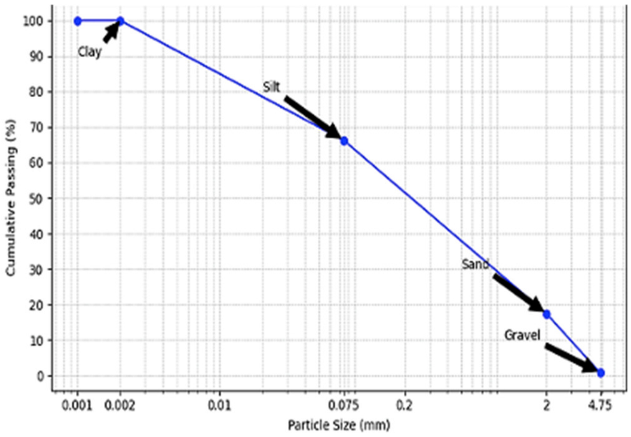

Fig. 3. PSD of untreated clay soil.

TABLE III. PROPERTIES OF UNTREATED CLAY SOIL

Property	Obtained value	Unit
Water content	21.53	%
Specific gravity (G_s)	2.78	–
Atterberg limits		
Shrinkage limit	9.37	%
LL	45.09	%
PL	25.71	%
PI	19.08	%
Grain size distribution		
Passing No. 200 sieve	48.8	%
Gravel	0.8	%
Sand	16.6	%
Silt (2–75 μm)	15	%
Clay (<2 μm)	33.8	%
Soil classification (AASHTO)	A-7-6	–
Mechanical characteristics		
Maximum dry density (γdry)	1.73	g/cm³
Optimum moisture content (ωopt)	21.82	%
UCS	11.73	kg/cm²

B. The Effect of Fly Ash and Cement on Atterberg Limits of Subgrade Soil

The modification of Atterberg limits is an important indicator for evaluating the effectiveness of chemical stabilization in clayey subgrade soils. Adding fly ash and cement alters the physicochemical interactions among clay particles, resulting in changes to the LL, PL, and PI. As outlined in Table IV, the untreated soil (S0) exhibits the highest plasticity, whereas the stabilized samples show progressively lower plasticity with increasing fly ash content combined with cement. Similar reductions in plasticity have been reported in expansive and soft clays treated with stabilizing agents, leading to improved soil workability and reduced moisture sensitivity [1, 6, 19]. These improvements are particularly important for pavement subgrades, since lower plasticity is closely associated with greater volumetric stability and reduced susceptibility to moisture-induced deformation [25, 42]. During the early stages of stabilization, the LL and PL values may initially increase slightly due to flocculation–agglomeration processes. In this stage, calcium ions released from cement and fly ash interact with clay particle surfaces, temporarily increasing the soil's water-holding capacity [24, 37].

TABLE IV. ATTERBERG LIMITS OF SUBGRADE SOIL STABILIZED WITH FLY ASH AND CEMENT

Sample code	LL (%)	PL (%)	PI (%)
S0	45.09	25.71	19.38
S1	42.6	28.4	14.2
S2	40.2	30.8	9.4
S3	38.1	31.6	6.5
S4	36.4	32.1	4.3

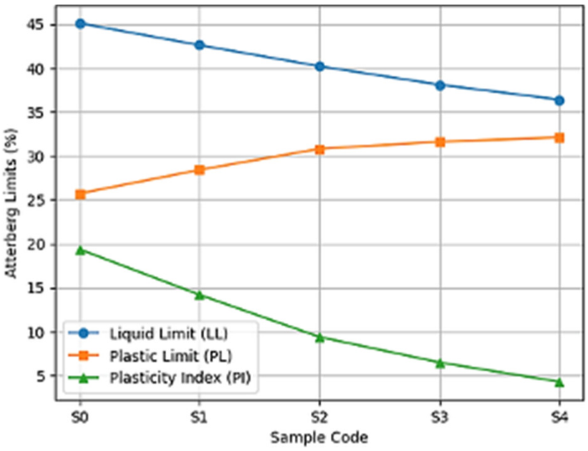

Fig. 4. Effect of fly ash and cement addition on the LL, PL, and PI of subgrade soil.

With further addition of stabilizers, pozzolanic reactions become dominant, producing cementitious compounds, such as C–S–H and C–A–H, which bind soil particles into a denser and more stable structure while consuming free water. Consequently, the LL and PL gradually decrease as the fly ash–cement content increases, indicating a transition from highly plastic soil to a more stable and less compressible material [16, 29]. The reduction in PI, illustrated in Figure 4, represents one of the most significant outcomes of the stabilization process because lower PI values indicate reduced plasticity and compressibility under repeated traffic loading. Similar findings were reported in [5, 6], where cementitious binders reduced PI by modifying the diffuse double layer surrounding clay particles. The combined use of fly ash and cement further enhances this effect because fly ash supplies reactive silica and alumina, while cement provides calcium hydroxide that accelerates pozzolanic reactions within the soil matrix [17, 19, 26]. The trends demonstrated in Figure 4 are consistent with previous stabilization studies in which blended binders produced greater reductions in soil plasticity than cement-only treatments [16, 22]. Overall, these results confirm that the untreated A-7-6 clay soil becomes less plastic and more stable after stabilization, thereby reducing shrink–swell behavior and improving pavement performance under varying environmental conditions [1, 3, 29].

C. Effect of Fly Ash and Cement on UCS and CBR

The influence of fly ash and cement addition on the mechanical performance of subgrade soil was evaluated using UCS and CBR tests. As summarized in Table V, both parameters show substantial improvement compared with untreated soil, confirming the effectiveness of fly ash–cement stabilization. The untreated clay soil (S0) exhibits low UCS and CBR values, indicating poor bearing capacity and limited suitability for pavement subgrade applications, which is typical for A-7-6 soils reported in [1, 6]. Table V presents the comparative UCS and CBR values of untreated and stabilized samples, where the results are expressed as mean ± SD (e.g., UCS = 1.85 ± 0.12 MPa; CBR = 24.5 ± 1.3%).

TABLE V. COMPARISON OF UCS AND CBR RESULTS FOR SOIL SAMPLES WITH FLY ASH AND CEMENT MIXTURES

Sample code	UCS (kg/cm²)	CBR (%)
S0	11.73	3.57
S1	18.45	7.62
S2	22.68	10.14
S3	25.94	11.89
S4	27.12	10.85

The UCS values show an increasing trend with higher fly ash content at a constant cement content of 8%, rising from 11.73 kg/cm² for untreated soil to 27.12 kg/cm² for the mixture containing 20% fly ash and 8% cement (S4). This strength improvement is mainly attributed to pozzolanic reactions between fly ash, cement hydration products, and clay minerals, which generate cementitious compounds such as C–S–H and C–A–H that enhance particle bonding and densify the soil matrix [16, 17, 29]. During UCS testing, untreated specimens generally showed ductile failure with noticeable deformation. In contrast, stabilized samples exhibited more brittle failure patterns characterized by vertical or inclined cracks due to stronger cementitious bonding. In contrast, the CBR results indicate the presence of an optimum fly ash content rather than a continuous strength increase. As illustrated in Figure 5, the CBR value rises significantly from 3.57 for the untreated soil to a maximum of 11.89 at 15% fly ash and 8% cement (S3), before slightly decreasing at 20% fly ash (S4). This behavior suggests that excessive fly ash may introduce unreacted particles or reduce effective bonding within the soil matrix, which weakens the load-bearing structure. Similar findings were reported in [6, 16], where it was observed that soil strength improves only up to an optimum stabilizer dosage. In addition to the calculated CBR values, the load–penetration curves obtained from the CBR tests are also presented in Figure 5 to illustrate the penetration resistance of the stabilized clay. The untreated soil shows a gradual increase in load with penetration, whereas stabilized specimens exhibit steeper curves, indicating higher stiffness and improved resistance to deformation. The improvement in mechanical performance can be explained by physicochemical interactions within the soil–binder matrix. Cement hydration releases calcium ions that initiate reactions forming C–S–H and C–A–H gels, which fill voids and strengthen interparticle bonding, while the reactive silica and alumina in fly ash participate in pozzolanic reactions with calcium hydroxide to produce additional cementitious compounds. The comparison between UCS and CBR responses indicates that different mechanisms influence these parameters; UCS tends to increase continuously with higher fly ash content due to ongoing pozzolanic reactions, whereas CBR is more sensitive to compaction efficiency, particle interlocking, and short-term stiffness under penetration loading. As shown in Figure 5, this difference underscores the importance of identifying an optimal stabilizer dosage for pavement applications rather than relying solely on compressive strength indicators, consistent with pavement engineering recommendations that emphasize CBR as a key design parameter [25, 42]. Strength development is also influenced by curing time because hydration and pozzolanic reactions continue beyond the selected curing period, potentially producing additional strength gains. From a practical perspective, partial replacement of cement with fly ash provides economic and environmental benefits by reducing cement consumption and associated carbon emissions. Overall, the results confirm that the mixture containing 15% fly ash and 8% cement provides the optimum balance between strength improvement and bearing capacity for clay subgrade stabilization, consistent with previous studies on sustainable soil stabilization using industrial by-products [14, 19, 22].

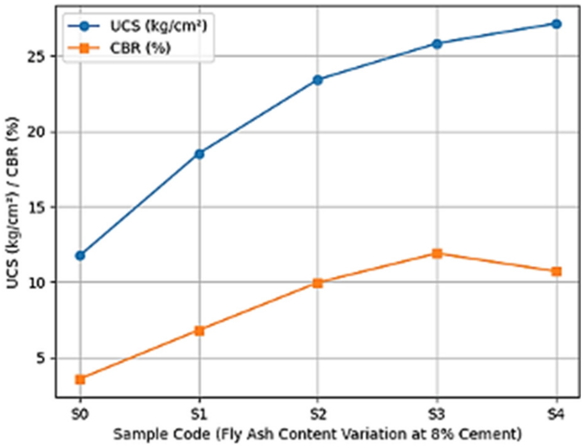

Fig. 5. UCS and CBR of fly ash–cement stabilized subgrade soil.

D. Environmental Benefits and Sustainability Implications of Fly Ash Utilization

To evaluate the statistical significance of the stabilization materials on the mechanical properties of the treated clay soil, a one-way ANOVA was conducted. Before the analysis, the main ANOVA assumptions, independence of observations, normality of residuals, and homogeneity of variances, were verified. The stabilizer dosage was treated as a single factor with multiple levels corresponding to the different cement–fly ash mixtures used in this study, while UCS and CBR were used as the dependent variables. Post-hoc Tukey's HSD tests were performed to identify pairwise differences among dosage levels. All analyses were carried out using statistical software (e.g., SPSS v.26) with a significance level of $p < 0.05$. The ANOVA results, outlined in Table VI, indicate significant differences in UCS and CBR values among the tested mixtures ($p < 0.05$), confirming that cement–fly ash dosage has a statistically significant influence on the mechanical performance of the clay subgrade. Beyond the statistical evaluation, the utilization of fly ash in soil stabilization provides important environmental benefits by improving infrastructure durability and service life. Fly ash enhances long-term mechanical performance and resistance to environmental degradation, thereby reducing maintenance frequency and material consumption in pavement systems [13, 19]. Improved durability of stabilized subgrades also increases resistance to moisture damage and cyclic loading conditions [6, 22]. Furthermore, partial replacement of Portland cement with fly ash reduces energy consumption and greenhouse gas emissions because cement production is highly energy-intensive and a major contributor to global CO_2 emissions. The reuse of fly ash also supports waste reduction and resource conservation by diverting coal combustion by-products from landfills while decreasing the demand for virgin raw materials [13, 19]. Considering that ordinary Portland cement typically emits approximately 0.8–0.9 tons of CO_2 per ton of production, the use of fly ash contributes to lower carbon footprints and supports circular economy principles in sustainable geotechnical engineering and infrastructure development [14, 15, 25-27, 41].

TABLE VI. ANOVA RESULTS FOR CLAY SUBGRADE STABILIZATION (UCS AND CBR)

Source of variation	**df**	**SS**	**MS**	**F-value**	**p-value**	**Significance**
UCS (MPa)						
Between groups	5	12.45	2.49	15.32	0.002	Yes
Within groups	12	1.95	0.16	-	-	-
Total	17	14.4	-	-	-	-
CBR (%)						
Between groups	5	430.8	86.16	18.45	0.001	Yes
Within groups	12	56	4.67	-	-	-
Total	17	486.8	-	-	-	-

df = degrees of freedom
SS = sum of squares
MS = mean square
F-value = MS(Between)/MS(Within)
p-value = probability value for F-test
Significance = indicates if $p < 0.05$ (Yes = statistically significant)

IV. CONCLUSIONS

This study confirms that the combined use of cement and fly ash is an effective approach for improving the engineering performance of problematic clay subgrade soils while supporting a lower-carbon stabilization strategy through partial cement replacement and the utilization of industrial by-products. The experimental results show that fly ash–cement mixtures modify the soil's plasticity characteristics, Liquid Limit (LL), Plastic Limit (PL), and PI, which initially increase and subsequently decrease, resulting in reduced swelling potential and improved stability. Compaction behavior also improves, as indicated by a reduction in optimum moisture content and an increase in maximum dry density, reflecting the formation of a denser soil structure. Mechanical performance is substantially enhanced, with both Unconfined Compressive Strength (UCS) and CBR values increasing significantly compared to the untreated soil. The optimum mixture identified in this study is 15% fly ash with 8% cement, which produced the highest CBR value, while higher fly ash contents further improved UCS. Although the direct economic benefit of fly ash replacement may be moderate, the improved mechanical performance together with the reuse of industrial by-products demonstrates that cement–fly ash stabilization is a technically viable and environmentally beneficial alternative for pavement subgrade improvement, consistent with sustainable construction goals. Despite these promising findings, several limitations should be acknowledged. The experiments were conducted under controlled laboratory conditions using a specific clay soil type and limited stabilization proportions, which may not fully represent the variability of field conditions. In addition, the investigation primarily focused on short-term mechanical performance, particularly UCS and CBR behaviour, without assessing long-term durability aspects such as cyclic loading, environmental exposure, or moisture fluctuations. Future research should investigate a wider variety of soil types and stabilization ratios, as well as long-term durability performance under conditions such as wet–dry cycling and freeze–thaw action, supported by field-scale validation. It should also include environmental assessments, such as leaching tests and life-cycle analysis, to better quantify sustainability benefits. In addition, combining microstructural analysis with in situ performance studies would improve the understanding of stabilization mechanisms and strengthen the practical application of cement–fly ash mixtures in sustainable subgrade engineering.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known financial interests, personal relationships, or affiliations that could have influenced the work reported in this paper.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the laboratory staff and technicians who provided valuable assistance during sample preparation and experimental testing. Appreciation is also extended to the supporting institutions for providing facilities and technical resources that enabled the successful completion of this study.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to limitations related to data ownership and institutional restrictions.

AI USE AND DECLARATION OF GENERATIVE AI USE

During the preparation of this work, the authors used generative AI tools to assist in language refinement and improve the clarity of the manuscript. After using these tools, the authors carefully reviewed and edited the content as needed and take full responsibility for the final content of the publication.

REFERENCES

[1] S. Y. O. Amakye, S. J. Abbey, and C. A. Booth, "Road pavement defect investigation using treated and untreated expansive road subgrade materials with varying plasticity index," *Transportation Engineering*, vol. 9, Sept. 2022, Art. no. 100123, https://doi.org/10.1016/j.treng.2022.100123.

[2] A. A. Latif, M. F. Muda, M. R. Zainudin, and H. Dao, "Review of Asphalt Pavement Adaptation to Climate Change: Enhancing Resilience and Sustainability," *CONSTRUCTION*, vol. 5, no. 2, Dec. 2025, https://doi.org/10.15282/construction.v5i2.12670.

[3] P. R. Rangan, M. Tumpu, M. Mansyur, and D. S. Mabui, "Assessment of Fly Ash-Rice Straw Ash-Laterite Soil Based Geopolymer Mortar Durability," Civil Engineering Journal, vol. 9, no. 06, pp. 1456–1470, June 2023, https://doi.org/10.28991/CEJ-2023-09-06-012.

[4] P. R. Rangan, M. Tumpu, and M. Mansyur, "Study of the effect of soluble silicates (waterglass) and limestone on the compressive strength test, cohesion and modulus of soil stiffness," *AIP Conference Proceedings*, vol. 3110, no. 1, Mar. 2024, Art. no. 020026, https://doi.org/10.1063/5.0205399.

[5] I. M. K. Artoshi, L. A. Abdulateef, I. H. Farman, and A. M. Ahmed, "Efficiency and Durability Assessment of Soil Stabilization using Waste Tire Shreds," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 13012–13016, Feb. 2024, https://doi.org/10.48084/etasr.6740.

[6] L. Z. Wongbae, C. Kabubo, and A. Owayo, "The Effect of Waste Marble Dust and Corncob Ash on the Engineering and Micro-Structural Properties of Expansive Soil for Use in Road Subgrades," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13765–13772, Apr. 2024, https://doi.org/10.48084/etasr.7034.

[7] N. Vig, S. Mor, and K. Ravindra, "The multiple value characteristics of fly ash from Indian coal thermal power plants: a review," *Environmental Monitoring and Assessment*, vol. 195, no. 1, Oct. 2022, Art. no. 33, https://doi.org/10.1007/s10661-022-10473-2.

[8] A. Jahami, F. Chamseddine, A. A. Salhab, M. Ibrahim, B. Zaiter, and H. F. Isleem, "Enhancing concrete properties with steel waste: a comprehensive review of GGBS, SS, and steel waste utilization," *Innovative Infrastructure Solutions*, vol. 9, no. 10, Sept. 2024, Art. no. 391, https://doi.org/10.1007/s41062-024-01717-w.

[9] A. Badran, W. Aldabbik, W. A. Agha, and R. Alzein, "Sustainable Pavement Materials: A Comprehensive Review of Performance, Environmental Impacts, and Implementation Challenges," *Steps For Civil, Constructions and Environmental Engineering*, vol. 1, no. 2, pp. 1–26, Oct. 2023, https://doi.org/10.61706/sccee12011187.

[10] A. Jahami, L. Dayaa, J. J. Assaad, O. Baalbaki, and J. Khatib, "Flexural Strength of Structural Beams Cast Using Combined Normal-Weight and Lightweight Concrete Mixtures," *Buildings*, vol. 14, no. 12, Nov. 2024, https://doi.org/10.3390/buildings14123787.

[11] ASTM C618-22 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. USA: ASTM International, 2023.

[12] A. Jahami, H. Mouzanar, S. Mahfouz, J. Khatib, and M. Sonebi, "Effect of graphene as additive on the mechanical properties of concrete," *Nanoworld Journal*, vol. 9, no. Special Issue 2, pp. S87–S92, Sept. 2023, https://doi.org/10.17756/nwj.2023-s2-015.

[13] A. Ndukwe *et al.*, "Metal Corrosion in High Temperature Conditions: A Review," *Zastita Materijala*, vol. 66, no. 2, pp. 292–312, June 2025, https://doi.org/10.62638/ZasMat1203.

[14] H. M. Alqawasmeh, "Enhancing the sustainability of geotechnical engineering with utilization of fly Ash," *Discover Materials*, vol. 5, no. 1, Jan. 2025, Art. no. 11, https://doi.org/10.1007/s43939-025-00183-0.

[15] Z. F. Akbulut, D. Yavuz, T. A. Tawfik, P. Smarzewski, and S. Guler, "Enhancing Concrete Performance through Sustainable Utilization of Class-C and Class-F Fly Ash: A Comprehensive Review," *Sustainability*, vol. 16, no. 12, June 2024, https://doi.org/10.3390/su16124905.

[16] A. M. Seidu, S. Sun, A. O. S. Alnur, and S. Li, "Stabilization of Expansive Soil Using High-Calcium Fly Ash, Lime, and Basalt Fiber

Blends," *Geotechnical and Geological Engineering*, vol. 43, no. 7, Aug. 2025, Art. no. 377, https://doi.org/10.1007/s10706-025-03348-z.

[17] Z. Chen, Y. Gao, W. Wei, Y. Lv, and Z. Wu, "Stabilization of Soft Clay by a Low-Calcium Fly Ash Geopolymer," *Journal of Materials in Civil Engineering*, vol. 35, no. 11, Nov. 2023, Art. no. 04023398, https://doi.org/10.1061/JMCEE7.MTENG-15403.

[18] L. Long, Y. Zhao, G. Lv, Y. Duan, X. Liu, and X. Jiang, "Improving stabilization/solidification of MSWI fly ash with coal gangue based geopolymer via increasing active calcium content," *Science of The Total Environment*, vol. 854, Jan. 2023, Art. no. 158594, https://doi.org/10.1016/j.scitotenv.2022.158594.

[19] C. Turan, A. A. Javadi, R. Vinai, and R. B. Zali, "Geotechnical Characteristics of Fine-Grained Soils Stabilized with Fly Ash, a Review," *Sustainability*, vol. 14, no. 24, Dec. 2022, https://doi.org/10.3390/su142416710.

[20] M. Swamynaidu and A. Tyagi, "Hydraulic conductivity of cement and fly ash stabilised clay mixes – Application to soil mixing techniques for seepage barrier construction," *Construction and Building Materials*, vol. 431, June 2024, Art. no. 136533, https://doi.org/10.1016/j.conbuildmat.2024.136533.

[21] W. Ahmad, G. Yu, Y. Mao, S. Ahmad, K. Nawaz, and B. Alibrahim, "Mechanical and Microstructural Behavior of Clay Soil Stabilized with Metallic Tailing Powder," *Geotechnical and Geological Engineering*, vol. 43, no. 8, Sept. 2025, Art. no. 444, https://doi.org/10.1007/s10706-025-03414-6.

[22] Z. Zimar *et al.*, "Performance of industrial fly ash based stabilized mine haul roads under seasonal moisture changes," *Transportation Geotechnics*, vol. 48, Sept. 2024, Art. no. 101295, https://doi.org/10.1016/j.trgeo.2024.101295.

[23] A. Öz, H. Çil, A. Benli, and G. Kaplan, "Enhanced mechanical and durability properties of alkali-activated composites through the use waste tire aggregates, brick powder, and marble powder," *Journal of Sustainable Cement-Based Materials*, vol. 15, no. 5, pp. 1673–1701, May 2026, https://doi.org/10.1080/21650373.2026.2612726.

[24] M. J. Roshan and A. S. B. A. Rashid, "Geotechnical characteristics of cement stabilized soils from various aspects: A comprehensive review," Arabian Journal of Geosciences, vol. 17, no. 1, Dec. 2023, Art. no. 1, https://doi.org/10.1007/s12517-023-11796-1.

[25] P. Sinha and K. K. R. Iyer, "Effect of Stabilization on Characteristics of Subgrade Soil: A Review," in *Advances in Computer Methods and Geomechanics*, 2020, pp. 667–682, https://doi.org/10.1007/978-981-15-0886-8_54.

[26] M. Alharthai, A. M. Maglad, K. Alharthi, and Y. I. A. Aisheh, "Towards sustainable concrete pavements: a critical review on fly ash as a supplementary cementitious material," *REVIEWS ON ADVANCED MATERIALS SCIENCE*, vol. 64, no. 1, Jan. 2025, https://doi.org/10.1515/rams-2025-0198.

[27] A. Fauzi, M. F. Nuruddin, A. B. Malkawi, and M. M. A. B. Abdullah, "Study of Fly Ash Characterization as a Cementitious Material," *Procedia Engineering*, vol. 148, pp. 487–493, Jan. 2016, https://doi.org/10.1016/j.proeng.2016.06.535.

[28] ASTM D2487-17 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). USA: ASTM International, 2020.

[29] ASTM D4318-17e1 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. USA: ASTM International, 2018.

[30] ASTM D854-14 Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (Withdrawn 2023). USA: ASTM International, 2023.

[31] ASTM D6913/D6913M-17(2025) Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. USA: ASTM International, 2025.

[32] ASTM D698-12e2 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3)). USA: ASTM International, 2021.

[33] ASTM D1557-12(2021) Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2700 kN-m/m^3)). USA: ASTM International, 2021.

[34] ASTM D2166/D2166M-16 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. USA: ASTM International, 2016.

[35] ASTM D1883-16 Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. USA: ASTM International, 2021.

[36] M. S. Kırgız *et al.*, "Modification mechanism of silver nanoparticles-functionalized MW-CNT and GGBFS and CQDs on the structural properties of geopolymer reinforced-composite beam," *Scientific Reports*, vol. 15, no. 1, July 2025, Art. no. 27997, https://doi.org/10.1038/s41598-025-08910-6.

[37] P. Thannasi, M. S. Abid, and C. Pichaimuthu, "Experimental study on the strength improvement of cement fly ash stabilized Indian marine clay," *Journal of Building Pathology and Rehabilitation*, vol. 11, no. 1, Oct. 2025, Art. no. 40, https://doi.org/10.1007/s41024-025-00720-7.

[38] S. Chaiyaput, N. Arwaedo, N. Kingnoi, T. Nghia-Nguyen, and J. Ayawanna, "Effect of curing conditions on the strength of soil cement," *Case Studies in Construction Materials*, vol. 16, June 2022, Art. no. e01082, https://doi.org/10.1016/j.cscm.2022.e01082.

[39] H. F. H. Ali and A. S. Mohammed, "Modeling the effect of chemical additives on clay soil plasticity: novel analysis of oxide contributions in fly ash and cement treatments," *Modeling Earth Systems and Environment*, vol. 10, no. 6, pp. 7049–7078, Dec. 2024, https://doi.org/10.1007/s40808-024-02154-5.

[40] Z. Zimar, D. Robert, F. Giustozzi, A. Zhou, S. Setunge, and J. Kodikara, "Use of industrial wastes for stabilizing expansive clays in pavement applications: durability and microlevel investigation," *Acta Geotechnica*, vol. 19, no. 9, pp. 6259–6287, Sept. 2024, https://doi.org/10.1007/s11440-024-02298-9.

[41] M. Liu, M. Saberian, J. Li, A. Tajaddini, and R. Roychand, "Improving expansive soil subgrade using sustainable green polymer-based admixture," *Case Studies in Construction Materials*, vol. 23, Dec. 2025, Art. no. e05090, https://doi.org/10.1016/j.cscm.2025.e05090.

[42] M. Widiastuti, S. Widodo, M. Tumpu, M. P. Hatta, and I. Alimuddin, "Landslide Hazard Index Assessment Using GIS and AHP in Tapalang, Mamuju, West Sulawesi Province, Indonesia," *Engineering, Technology & Applied Science Research*, vol. 15, no. 4, pp. 24857–24863, Aug. 2025, https://doi.org/10.48084/etasr.10835.