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Sustainable Soil Stabilization Techniques for Enhancing Rural Road Infrastructure in Developing Regions

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ABSTRACT

The development of sustainable rural road infrastructure is crucial for enhancing accessibility and fostering socio-economic growth in developing regions. Challenges arise due to weak soils, such as expansive clays and loose granular deposits, which impede the load-bearing capacity of roads, causing premature failures. Soil stabilization techniques, including mechanical, chemical, and additive methods, improve soil strength, resistance to moisture, and stiffness, ensuring road durability. Alternative materials like industrial by-products—such as fly ash and GGBS—have gained attention for their environmental benefits. This study reviews various stabilization methods and their impact on mechanical properties, offering eco-friendly solutions for sustainable rural infrastructure.

Keywords: *Soil Stabilization, Rural Roads, Sustainable Infrastructure, Alternative Materials.*

I. INTRODUCTION

The development of sustainable rural road infrastructure has become a critical priority in transportation engineering, particularly in developing regions where accessibility, economic growth, and social inclusion are strongly dependent on road connectivity. Rural roads often traverse areas with weak or problematic soils such as expansive clays, lateritic soils, and loose granular deposits, which exhibit poor load-bearing capacity, high compressibility, and susceptibility to environmental degradation. These limitations frequently lead to premature pavement failures, increased maintenance costs, and reduced service life. Soil stabilization techniques have emerged as effective solutions to enhance the engineering properties of such soils, thereby improving the performance and durability of rural roads. Stabilization involves the modification of soil characteristics through mechanical, chemical, or additive-based methods, resulting in improved strength, stiffness, and resistance to moisture variations. Traditional stabilizers such as Portland cement and lime have been widely used; however, growing concerns about environmental sustainability, carbon emissions, and resource depletion have encouraged the exploration of alternative materials, including industrial by-products and locally available resources (Saurav & Sinha, 2026; López-González et al., 2026).

Recent research has increasingly focused on evaluating the performance of stabilized soil systems using both conventional and innovative materials under varying environmental and loading conditions. For instance, the incorporation of crushed bricks and fine sand stabilized with cement has demonstrated significant improvements in mechanical properties such as unconfined compressive strength (UCS), California bearing ratio (CBR), and tensile strength, making them viable alternatives to natural aggregates (Saurav & Sinha, 2026). Similarly, studies comparing cement stabilization with low-impact materials like kaolin have highlighted the trade-offs between rapid strength gain and environmental sustainability, suggesting that material selection should be context-specific based on project requirements and ecological considerations (López-González et al., 2026). The utilization of industrial by-products such as ground granulated blast furnace slag (GGBS), sugarcane bagasse ash (SCBA), and bottom ash has further demonstrated promising results in enhancing soil strength while reducing waste disposal issues and environmental footprints (Marathe et al., 2025; Farooq & Hasan, 2025). Additionally, chemical stabilization using alkali activators and sodium hydroxide has shown potential in improving soil performance, particularly in lateritic soils commonly found in tropical regions (Abdulkarim & Sa'eed, 2020). These approaches not only contribute to improved pavement performance but also align with sustainable construction practices.

Despite the advancements in stabilization techniques, challenges remain in selecting the most appropriate method for specific soil types, climatic conditions, and traffic demands. The effectiveness of stabilization is influenced by factors such as stabilizer type and dosage, curing time, moisture content, and soil mineralogy. Furthermore, long-term durability, environmental impact, and cost-effectiveness must be carefully evaluated to ensure sustainable implementation. Life cycle assessment (LCA) studies have indicated that while chemical stabilization methods may offer superior strength, mechanical stabilization techniques often result in lower environmental impacts (Albuquerque et al., 2024). Additionally, the integration of rural road development with broader sustainability goals, including agricultural growth and regional development, underscores the socio-economic importance of optimized stabilization strategies (Zhou et al., 2021). Therefore, a comprehensive performance evaluation of stabilized soil techniques is essential to identify efficient, cost-effective, and environmentally sustainable solutions for rural road construction. This study aims to critically analyze various soil stabilization methods, assess their mechanical and durability performance, and highlight their potential contributions to sustainable rural infrastructure development.

II. RESEARCH BACKGROUND

Saurav and Sinha (2026) had examined the development of sustainable pavement layers using mechanically stabilised mixtures of crushed bricks (CB) and fine sand (FS). The study had prepared experimental mixes at an FS–CB ratio of 1:1.6 with cement contents varying from 2% to 12% by weight. The mechanical performance of the mixtures had been evaluated through unconfined compressive strength (UCS), California bearing ratio (CBR), modulus of rupture (MOR), indirect tensile strength (ITS), and indirect tensile stiffness modulus (ITSM) tests. Their findings had revealed that the inclusion of cement significantly improved the UCS, CBR, MOR, and ITS values of the FS–CB mixtures. A UCS of 2.2 MPa had been attained at 4% cement content, while stable strength development had been observed up to 8% cement. The durability assessment had shown that mass loss remained below 10% for mixes containing 4% or more cement, thereby satisfying standard requirements. Additionally, drying and autogenous shrinkage strains had remained limited, and microstructural analysis had confirmed the formation of ettringite and calcium silicate hydrate, which had been associated with enhanced strength. Overall, the study had concluded that cement-stabilised FS–CB mixtures could serve as an environmentally sustainable alternative to conventional pavement materials.

López-González et al. (2026) had conducted a performance-based comparative evaluation of fine-grained soils stabilized with Portland cement and kaolin in order to assess their suitability for sustainable road subgrade improvement. The study had noted that soil stabilization was widely adopted in transportation engineering to improve the mechanical performance and serviceability of moisture-sensitive subgrades, while also recognizing the environmental concerns associated with Portland cement due to its high energy demand and CO_2 emissions. Using stabilizer dosages of 3%, 5%, and 7% by dry soil mass, the authors had carried out soil characterization, Standard Proctor compaction tests, and unconfined compressive strength (UCS) tests at curing periods ranging from 0 to 180 days. Their findings had revealed that cement-stabilized soils developed strength more rapidly at early ages and achieved higher long-term UCS values, making them suitable for applications requiring early load-bearing capacity. In contrast, kaolin-stabilized soils had shown gradual but stable strength improvement due to densification and particle rearrangement. The study had concluded that kaolin could serve as a viable low-impact alternative stabilizer for low-volume and secondary road infrastructure, thereby supporting sustainability-oriented and context-sensitive material selection in subgrade design.

Marathe et al. (2025) investigated the feasibility of stabilizing lateritic soil subgrades using alkali-activated ground granulated blast furnace slag (GGBS) and sugarcane bagasse ash (SCBA). They conducted a series of compaction experiments to determine the optimal maximum density, varying SCBA content while maintaining a constant slag dosage of 10% of the soil weight. An alkali-activator solution was prepared using caustic soda and water glass, and both unstabilized and stabilized soils were tested through unconfined compressive strength (UCS) and California bearing ratio (CBR) methods. The study revealed that the subgrade strength increased with SCBA addition up to a 10% threshold, beyond which it declined, under a uniform slag proportion. Microstructural analysis was performed to assess hydration development due to alkali-activated binder stabilization, and a correlation between UCS and CBR was established, resulting in a linear regression model linking these parameters. Extended 56-day testing confirmed enhanced mechanical performance. The research further proposed a pavement design for low-volume roads, demonstrating a 17% reduction in overall thickness while maintaining performance, and a comparative cost analysis highlighted both economic and sustainability advantages of the stabilization approach.

Farooq and Hasan (2025) investigated the use of sustainable materials, specifically bottom ash and lime, for stabilizing expansive clayey soils. They discussed the potential of incorporating bottom ash and lime as subgrade materials to improve the geotechnical properties of clayey soil. Laboratory experiments, including cost analyses, were conducted on various combinations and ratios of clayey soil (S), bottom ash (BA), and lime (L). The study found that adding 15% BA to clayey soil reduced its liquid limit and plasticity index, while the maximum dry unit weight decreased with the inclusion of BA. Subsequent addition of 6% lime to the S:BA (79:15) mixture further increased the maximum dry unit weight. The S:BA:L mixture in the ratio of 79:15:6 demonstrated the highest California Bearing Ratio (CBR) of 11.2%, indicating optimal subgrade properties. Moreover, the use of this mixture reduced the overall pavement thickness for a 15-year design life by approximately 37% and lowered construction costs by nearly 24% compared to clayey soil alone. The study emphasized the environmental and economic benefits of using the S:BA:L combination, highlighting its potential to mitigate waste impact and reduce reliance on natural aggregates and sand.

Albuquerque et al. (2024) investigated laboratory tests to identify granulometric stabilization and chemical improvement techniques applied to an experimental segment of the unpaved BR-030 highway in the Maraú Peninsula, Bahia. The study examined the performance of primary coating sections stabilized with sand, clayey gravel, reclaimed asphalt pavement (RAP), and simple graded crushed stone (GCS), alongside chemical improvements using Portland cement and hydrated lime. The laboratory campaign focused on evaluating mechanical resistance, resilient modulus, and permanent deformation. The authors reported that chemical improvement with 2% Portland cement yielded the most promising outcomes for potential application in the unpaved segment of the BR-030. Furthermore, a life cycle assessment (LCA) indicated that mechanical stabilization of the primary coating exhibited the lowest environmental impacts, highlighting its suitability and sustainability as a stabilization method.

Mustafa et al. (2023) investigated the use of earth materials in building construction in Saudi Arabia, noting their historical application and renewed global interest as low-energy alternatives to conventional construction materials. They aimed to assess the applicability of locally available soils in the Najd area as potential replacements for conventional materials. Four distinct soils were collected and characterized to determine their physical and chemical properties. The soils were stabilized with varying dosages of cement or hydrated lime (0–15% by dry weight) and evaluated for unconfined compressive strength and durability. The study found that cement stabilization produced stronger and more durable soil mixtures suitable for construction, while the addition of stabilizers generally enhanced soil durability. Comparisons with existing standards confirmed that the tested soils met both strength and durability requirements. Moreover, statistical analyses were used to develop correlations predicting mechanical properties such as modulus of elasticity, density, and stabilizer content, providing a basis for analyzing the behavior of stabilized earth materials in construction applications.

Roshan et al. (2022) investigated lateritic soil, a residual soil commonly found in tropical regions, noting that while it generally exhibited acceptable engineering properties for construction, it required treatment for transportation infrastructure, particularly in its fine-grained form. They selected cement as a stabilising agent to examine its effects on lateritic soil at both macro- and micro-levels. To achieve this, they conducted UCS, durability, FESEM, and EDX tests. The study reported that UCS increased with higher cement content and longer curing times, and that shear modulus similarly improved. Durability tests indicated that 3% cement was insufficient for stabilisation in areas exposed to cyclic wetting-drying, while 6% cement reduced UCS, but 9% and 12% cement enhanced it. FESEM analysis revealed microstructural changes with cement addition and curing, and EDX results demonstrated chemical composition variations. Overall, the study concluded that cement-stabilised lateritic soil could be suitable for road construction, with optimal cement percentages varying according to standards.

Vikas et al. (2021, December) investigated the sustainability of cementitious construction materials, noting their high energy intensity and contribution to CO_2 emissions, and reviewed approaches to develop alternative construction materials. They observed that rammed earth construction, which utilizes soil as a building material, had gained attention but suffered from lower durability. The study attempted to stabilize three locally available soils with varying engineering characteristics to assess their viability for rammed earth wall construction. It was reported that natural soils alone did not meet the required strength for construction, necessitating stabilization. The authors adopted admixture stabilization, examining the effects of Portland cement as a binder and lime as a pre-stabilizer for black cotton soil, while also incorporating polypropylene fiber to enhance tensile properties. Unconfined compressive strength and split tension tests were conducted on wet and soaked specimens after 14 and 28 days of curing. The results indicated that stabilized soils achieved adequate durability and satisfied a 2 MPa strength standard, with black cotton soil requiring 3% lime pre-stabilization, and fiber addition allowing target strength to be reached at 14 days with 0.4% fiber content.

Zhou et al. (2021) examined the role of rural road construction in promoting the sustainable development of regional agriculture in China, highlighting its significance for natural resource conservation, ecological protection, food security, and poverty alleviation. They selected five-dimensional indices encompassing population, society, economy, resources, and environment and employed the entropy method to calculate the agricultural sustainable development index for each province. A spatial econometric model was then constructed using panel data from 31 provinces between 2002 and 2018 to analyze the effects. The study found that rural road construction had significantly promoted agricultural sustainable development overall, although it exerted a negative influence on environmental sustainability with a lagged effect. The impact varied regionally, with positive effects observed in eastern and central provinces, while western regions showed no significant improvement due to a siphoning effect that caused a loss of talent and capital, undermining population and resource sustainability. The study was noted to have important policy implications for rural revitalization and agricultural development.

Abdulkarim and Sa'eed (2020) investigated the potential of sodium hydroxide (NaOH) to enhance the properties of lateritic soil (LS) for rural road construction in North-eastern Nigeria. They classified the soil as A-6(13) and CL according to AASHTO M 145-2012 and ASTM D 2487-2011, respectively, and treated it with 1, 3, and 7 molar concentrations of NaOH. The study examined the effects of compaction methods, specifically the British Standard Light (BSL) and British Standard Heavy (BSH), on the soil performance. Unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were performed on the compacted specimens. The findings indicated that increasing the molar concentration of NaOH generally improved the soil's engineering properties, particularly under the BSH compaction. Maximum 7-day UCS values of 909 kN/m² and 1106 kN/m² were reported at 7 molar concentration for BSL and BSH, meeting the 750–1500 kN/m² UCS range specified by the Nigerian General Specification (2013). For CBR, values of 33% and 38% were achieved at 3 and 7 molar concentrations under BSH, while 34% was observed at 7 molar under BSL, all exceeding the 30% minimum requirement for sub-base construction.

III. KEY FINDINGS FROM STUDY

Author & Year	Materials Used	Methodology	Key Findings	Significance
Saurav & Sinha (2026)	Crushed brick + fine sand + cement	UCS, CBR, MOR, ITS, ITSM tests	Strength improved with cement; optimum ~4–8%	Sustainable alternative to natural aggregates
López-González et al. (2026)	Cement vs kaolin	Compaction + UCS tests (0–180 days)	Cement = high early strength; kaolin = gradual strength	Eco-friendly stabilizer alternative
Marathe et al. (2025)	GGBS + SCBA	Compaction, UCS, CBR	Strength improved up to 10% SCBA; 17% thickness reduction	Cost-effective and sustainable
Farooq & Hasan (2025)	Bottom ash + lime	Geotechnical tests + cost analysis	CBR improved to 11.2%; 37% thickness reduction	Waste utilization and cost savings
Albuquerque et al. (2024)	Sand, RAP, cement, lime	Mechanical + LCA analysis	Cement best strength; mechanical stabilization lowest impact	Sustainability trade-off identified
Mustafa et al. (2023)	Cement + lime	UCS, durability tests	Cement improved strength; correlations developed	Predictive modeling potential
Roshan et al. (2022)	Cement (lateritic soil)	UCS, FESEM, EDX	Strength improved with curing; optimal % required	Microstructural validation
Vikas et al. (2021)	Cement, lime, fiber	UCS, tensile tests	2 MPa strength achieved; fiber improved durability	Sustainable construction material
Zhou et al. (2021)	Rural road systems	Econometric modelling	Roads improve agriculture but impact environment	Policy implications
Abdulkarim & Sa'eed (2020)	NaOH stabilization	UCS, CBR tests	Strength improved with molarity; met standards	Chemical stabilization viability

IV. CONCLUSION

The performance evaluation of stabilized soil techniques clearly demonstrates their critical role in enhancing the structural integrity, durability, and sustainability of rural road infrastructure. The reviewed studies highlight that both traditional stabilizers (cement and lime) and alternative materials (industrial by-products, agricultural waste, and chemical additives) significantly improve soil properties such as strength, stiffness, and resistance to environmental degradation. Cement stabilization consistently provides high early and long-term strength, making it suitable for high-load applications, whereas alternative stabilizers like kaolin, GGBS, SCBA, and bottom ash offer environmentally sustainable and cost-effective solutions. Mechanical stabilization techniques exhibit lower environmental impacts, while chemical stabilization ensures superior performance in challenging soil conditions. Overall, the integration of waste materials in soil stabilization not only enhances engineering performance but also supports sustainable development by reducing environmental pollution and conserving natural resources.

V. FUTURE SCOPE

- **Development of Hybrid Stabilization Techniques** combining chemical and mechanical methods for optimized performance.
- **Advanced Microstructural Analysis** using AI and imaging techniques to better understand soil-stabilizer interactions.
- **Life Cycle Cost and Carbon Footprint Analysis** for large-scale implementation of sustainable stabilization methods.
- **Field Performance Studies** to validate laboratory findings under real traffic and environmental conditions.
- **Use of AI and Machine Learning Models** for predicting stabilized soil behavior and optimizing mix design.
- **Exploration of New Eco-Friendly Materials** such as bio-enzymes, nanomaterials, and geopolymers.
- **Climate-Resilient Stabilization Strategies** to address extreme weather conditions and long-term durability.

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