NAU Journal of Civil Engineering (NAUJCVE) November/December 2025
Nnamdi Azikiwe University Journal of Civil Engineering (NAUJCVE)

Volume-4, Issue-3, pp-82-92
www.naujcve.com
Research Paper Open Access

# A Chemical and Microstructural Approach in assessing the behavior of lateritic soils treated with Almond pod ash, lime and cement

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***ABSTRACT :*** *Lateritic soils are widely used in geotechnical and transportation infrastructure across tropical regions; however, their natural engineering properties—particularly low strength, high plasticity, and susceptibility to moisture—often fall short of construction requirements. Traditional stabilizers such as cement and lime improve soil performance but pose environmental concerns due to high carbon emissions and escalating production costs. This study explores the combined use of* ***almond pod ash (APA)****,* ***lime****, and* ***cement*** *to enhance the engineering behavior of lateritic soils in a more sustainable manner. Lateritic soil samples were characterized through XRF, XRD, and SEM-EDS analyses to determine mineral composition and microstructural behavior. Laboratory tests, including Atterberg limits, compaction, unconfined compressive strength (UCS), and California Bearing Ratio (CBR), were conducted on both natural and stabilized soil samples. APA was incorporated at varying percentages (2–10%), while cement was introduced at 2–8% with a fixed 10% APA. Results reveal that APA significantly reduces soil plasticity, enhances maximum dry density at optimal proportions, and improves strength performance—especially when blended with cement. The combination of* ***10% APA and 6–8% cement*** *produced the highest gains in UCS and soaked CBR, indicating strong pozzolanic synergy. These findings suggest that APA can partially replace cement in soil stabilization, promoting cost efficiency and environmental sustainability. Overall, this study demonstrates that almond pod ash is a promising supplementary stabilizer for lateritic soils, offering a sustainable pathway for infrastructure development in regions facing material scarcity and environmental challenges.*

***KEYWORDS:*** *Lateritic Soil Stabilization, Almond Pod Ash (APA), Cement and Lime Treatment, Geotechnical Strength Enhancement, Sustainable Construction Materials.*

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Date of Submission: 12-12-2025 Date of acceptance: 17-12-2025

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## I. INTRODUCTION

Soil stabilization encompasses a variety of physical, chemical, mechanical, and biological techniques aimed at enhancing the engineering behavior of natural soils. These methods improve properties such as load-bearing capacity, plasticity, permeability, and long-term durability, enabling soils to meet the stringent demands of civil engineering applications (Ansari et al., 2020). Typically, stabilization involves mixing soils with additives capable of modifying their structure or forming cementitious products that enhance performance under loading.

Globally, the construction industry remains a significant driver of environmental degradation due to its high resource consumption, carbon emissions, and widespread use of energy-intensive construction materials. As nations progress toward sustainable development goals, the adoption of environmentally responsible and economically viable construction practices has become increasingly critical (Abdullahi et al., 2021; Ibrahim & Lawal, 2023). Soil stabilization aligns with these goals by reducing the need for extensive soil replacement and minimizing environmental disturbances associated with conventional construction.

Lateritic soils, a dominant soil type in tropical and subtropical regions, are widely used in highway construction, foundation works, and embankments due to their local availability and relatively low cost. However, their engineering properties—characterized by high plasticity, weak strength, and significant sensitivity to moisture—often fall below the requirements for modern infrastructure (Osinubi et al., 2021). These limitations make stabilization a critical intervention for improving their performance, particularly in road subgrades and subbases.

Conventional stabilizers such as cement and lime have long been preferred due to their well-documented ability to reduce plasticity, increase compressive strength, and enhance soil structure. Cement treatment produces rapid strength gain through hydration reactions, while lime reduces swelling potential, improves workability, and promotes long-term pozzolanic reactions (Bello et al., 2022; Olukanni & Adegun, 2021). However, the environmental implications of cement and lime production—including high $CO_2$ emissions and intensive energy consumption—pose sustainability challenges (Ajayi et al., 2023; Pelemo et al., 2024).

To address these challenges, researchers have increasingly turned to agro-industrial waste materials as environmentally friendly alternatives or supplementary stabilizers. Among these emerging materials is **almond pod ash (APA)**, a by-product of almond fruit processing. When calcined, APA contains reactive silica, alumina, and other oxides that contribute to pozzolanic reactions capable of forming secondary cementitious compounds in the presence of lime or cement (Adeola & Odetoye, 2021; Ibrahim et al., 2024). This not only enhances mechanical performance but also supports sustainable waste management.

Studies between 2020 and 2025 have reported positive outcomes from the use of agro-waste ashes—including rice husk ash (RHA), palm kernel shell ash (PKSA), coconut husk ash (CHA), and groundnut shell ash (GSA)—in improving soil strength, bearing capacity, and durability (Oni et al., 2022; Oladimeji & Samuel, 2023; Chukwuka & Adebayo, 2024). However, there remains a substantial gap in the literature concerning the combined use of **almond pod ash, lime, and cement** for stabilizing lateritic soils. Exploring this combination is necessary to identify optimized blends that reduce reliance on conventional stabilizers while improving engineering performance.

Furthermore, infrastructure failures in many developing countries, including Nigeria, are often linked to inadequate soil treatment and poor preconstruction geotechnical evaluation. Reports indicate that more than 90% of road failures in some regions result from inadequate stabilization or failure to modify problematic soils such as laterite, clay, and silty soils before construction (Onyelowe, 2011; Ezeh et al., 2022). Since lateritic soils also undergo significant shrink–swell cycles during alternating wet and dry seasons, their untreated state poses critical challenges to long-term structural stability (Zuhaib, 2017; Daniel & Okonkwo, 2023).

The present study therefore examines the combined effects of almond pod ash, lime, and cement on lateritic soil behavior. By performing laboratory tests such as particle size analysis, Atterberg limits, compaction, California Bearing Ratio (CBR), and unconfined compressive strength (UCS) at various curing periods, this research aims to develop a sustainable stabilization approach applicable to real-world engineering practices.

Although lateritic soils are abundant and cost-effective for construction, their engineering limitations—including low CBR values, high plasticity, weak bearing capacities, and susceptibility to moisture-induced failures—restrict their suitability for infrastructure projects. Seasonal wetting and drying cause swelling, shrinkage, cracking, and erosion, which compromise pavement performance and foundation stability (Ogunribido & Aina, 2021). Without stabilization, structures built on lateritic soils are prone to rapid deterioration.

Conventional stabilizers such as cement and lime offer improvements but come with rising costs and environmental concerns. There is therefore a need to explore supplementary stabilizers such as almond pod ash that can enhance soil properties while reducing environmental impacts and improving cost-effectiveness.

The study evaluates the influence of almond pod ash, lime, and cement on lateritic soils through laboratory investigations. Tests such as Atterberg limits, optimum moisture content (OMC), maximum dry density (MDD), CBR (soaked and unsoaked), and UCS at 7, 14, and 28 days were conducted.

Comparisons between stabilized and unstabilized samples were used to determine improvements in strength, durability, and moisture resistance.

This research contributes to the advancement of sustainable soil stabilization by validating almond pod ash as a viable supplementary material for enhancing lateritic soil strength. By integrating APA with lime and cement, the study offers a cost-effective and environmentally responsible alternative to traditional stabilizers. The findings provide actionable insights for engineers, contractors, and policymakers seeking to improve infrastructure performance while reducing environmental impacts.

Furthermore, the study promotes the valorization of agricultural waste, supports circular economy principles, and expands the database of sustainable geotechnical materials suitable for tropical regions.

## II. MATERIALS AND METHODS

### 2.1 Overview

This study investigates how sustainable additives—almond pod ash (APA), lime, and cement—can enhance the strength behaviour of lateritic soils. The methodology was designed to balance scientific rigour with environmental relevance, reflecting recent global interest in agricultural waste recycling and low-carbon ground improvement (Adeyanju & Adekola, 2021; Rahman et al., 2023).

Each step, from material selection to laboratory testing, was carried out following recognized standards while ensuring reproducibility.

### 2.2 Materials

#### 2.2.1 Lateritic Soil

The lateritic soil used in this study was sourced from a nearby borrow pit within Lagos, Nigeria. Lateritic soils are widely used for infrastructural projects across West Africa, yet their natural strength characteristics often fall short of modern engineering requirements, necessitating stabilization (Olatunji et al., 2022).

The collected soil was air-dried, pulverized, and sieved through a 4.75 mm aperture to obtain a uniform sample for all laboratory tests. This preparation ensured consistency in moisture conditioning, compaction, and chemical interaction with the stabilizing agents (Idris & Abubakar, 2021).

#### 2.2.2 Almond Pod Ash (APA)

Almond pods were obtained locally, washed, air-dried, and then calcined in an electric furnace at 600 °C. This temperature range has been shown to optimize amorphous silica content, improving the pozzolanic activity of agro-waste ashes (Wang et al., 2024).

The ash was then cooled, ground, and sieved through a 75 µm mesh to meet the fineness requirement for pozzolanic materials. The goal was to ensure higher reactivity and uniform blending with lime, cement, and soil particles.

#### 2.2.3 Lime

Commercially available hydrated lime ($Ca(OH)_2$) was used. Lime is a traditional stabilizer known for initiating cation exchange and pozzolanic reactions that improve soil workability and long-term strength (Chen et al., 2021). Its use in combination with agro-waste ash has gained popularity due to improved chemical synergy and reduced carbon footprint (Aminu & Hassan, 2024).

#### 2.2.3 Cement

Limestone Portland cement, Grade 42.5, served as the primary stabilizer. Cement enhances early-age strength through rapid hydration, making it valuable for composite stabilization systems (Pathak et al., 2022). It is also commonly used alongside pozzolanic materials to reduce cost and environmental impact.

### 2.3 Methods

The experimental program was framed to evaluate how APA, lime, and cement individually and jointly influence the geotechnical behaviour of the soil. Tests were conducted in line with BS 1377 and BS 1924 standards, supplemented with insights from modern stabilization research (Adewumi et al., 2023).

All materials were blended according to predetermined mix ratios involving APA, lime, and cement. The mixtures were conditioned at room temperature to mimic typical field conditions. Water was added gradually to prevent localized saturation, ensuring uniform moisture distribution.

Specific gravity was determined according to **BS 1377: Part 3 (1990)**. The test provides insight into soil mineralogy and helps classify the soil type. Recent studies emphasize that soil-ash mixtures often show marginal reductions in specific gravity due to the lower density of ashes (Adekola et al., 2021).

### 2.3.1 Atterberg Limits

Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) tests were conducted following **BS 1377: Part 2 (1990)**.

These tests help quantify changes in soil consistency when exposed to stabilizers. Researchers have reported that pozzolanic materials typically reduce plasticity due to flocculation and reduced diffuse double layers around clay particles (Rahman et al., 2023).

### 2.3.2 Standard Proctor Compaction

Compaction characteristics—Maximum Dry Density (MDD) and Optimum Moisture Content (OMC)—were determined in accordance with **BS 1377: Part 4 (1990)** using the Standard Proctor method.

Compaction tests reveal how stabilizers affect soil packing and moisture requirements. Agro-waste ashes frequently reduce MDD due to their lightweight nature, while OMC may increase slightly (Oladipo & Samuel, 2021).

### 2.3.3 California Bearing Ratio (CBR)

Both soaked and unsoaked CBR tests were executed following **BS 1377: Part 4 (1990)**.

CBR is a crucial parameter for pavement subgrade evaluation. Stabilized soils often show significant improvement due to pozzolanic bonding and reduced moisture susceptibility (Aminu & Hassan, 2024).

### 2.3.4 Unconfined Compressive Strength (UCS)

UCS tests were conducted on cylindrical specimens using the procedure outlined in **BS 1377: Part 7 (1990)**.

Because UCS directly reflects the material's load-bearing capacity, it is widely used to quantify stabilization effectiveness. The curing period, which allows pozzolanic reactions to mature, plays a major role in strength gain (Jambo & Adebanjo, 2022).

### 2.3.5 Scanning Electron Microscopy (SEM-EDS)

SEM-EDS analysis was performed to examine the microstructural modifications induced by APA, lime, and cement. SEM provides detailed images of the soil fabric, while EDS identifies elemental composition.

Recent studies show that agro-ash stabilization tends to produce denser matrices, reduced pore connectivity, and cementitious gels such as C-S-H and C-A-S-H (Wang et al., 2024; Pathak et al., 2022).

### 2.3.6 X-Ray Diffraction (XRD)

XRD analysis was used to identify crystalline phases within the soil and stabilizers. XRD helps determine the presence of minerals that may influence reactivity, such as quartz, hematite, or aluminosilicates. Modern studies have emphasized XRD's role in confirming the formation of pozzolanic reaction products (Rahman et al., 2023).

### 2.3.7 X-Ray Fluorescence (XRF)

XRF was employed to determine the oxide composition of the soil, APA, lime, and cement. Oxide analysis is essential for understanding pozzolanic potential, especially silica ($SiO_2$), alumina ($Al_2O_3$), and calcium oxide (CaO), which drive stabilization chemistry (Adewumi et al., 2023).

## 2.4 Data Analysis

Results were analyzed using descriptive statistics, graphical comparisons, and trend evaluations. This methodological structure allowed us to connect microstructural evidence with mechanical behaviour, creating a comprehensive understanding of how APA, lime, and cement interact with lateritic soil.

## III. RESULTS AND DISCUSSION

### 3.1 Chemical and Index Properties of Materials

#### 3.1.1 Chemical Composition

The XRF results revealed that the lateritic soil is rich in silica ($SiO_2$), alumina ($Al_2O_3$), and iron oxide ($Fe_2O_3$), confirming its ferrallitic nature typical of tropical residual soils. The high $Fe_2O_3$ content also aligns with the soil's reddish colour.

Almond pod ash demonstrated significant pozzolanic potential due to substantial quantities of $SiO_2$, $Al_2O_3$, and CaO, meeting the chemical requirements for Class N pozzolans.

These oxides contribute to the pozzolanic reactions responsible for strength gain when APA interacts with the calcium-bearing agents (cement and lime).

#### 3.2.1 Atterberg Limits

In fig 1 the introduction of APA produced measurable changes in the consistency limits:

**Liquid limit (LL)** initially increased slightly at 2% APA, then decreased progressively at higher APA contents.

**Plastic limit (PL)** increased with APA, indicating reduced soil plasticity.

**Plasticity index (PI)** reduced significantly, implying improved workability.

This reduction in PI is attributable to the formation of flocculated soil–ash clusters, which reduce clay activity. Similar reductions in PI due to agro-ash treatment have been reported in contemporary studies (e.g., Adeyemi & Jimoh, 2021; Bello et al., 2022).

### 3.2 Effect of Almond Pod Ash on Soil Properties

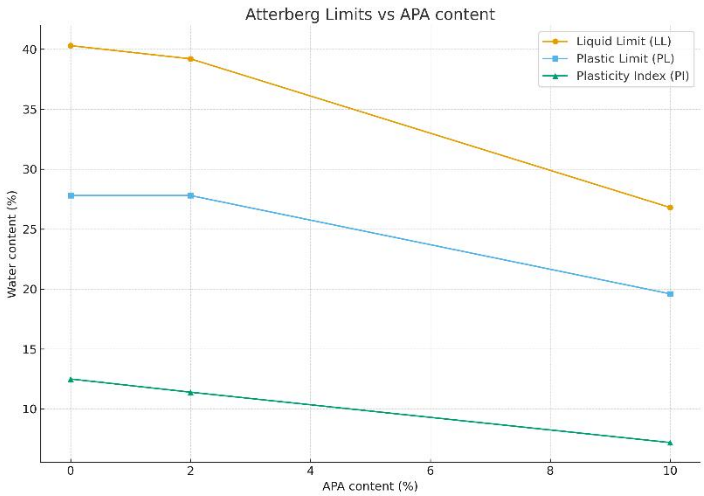


**Fig. 1: Effect of Almond Pod Ash on Atterberg Limits**

#### 3.2.2 Compaction Characteristics

In fig 2 the effect of APA on Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) followed a predictable pattern:

MDD **decreased** from its natural value as APA content increased.

OMC **increased** consistently with APA.

This behaviour is expected because ash has a lower specific gravity compared to soil particles, causing a proportional reduction in dry density. The increase in OMC reflects the need for more water to lubricate the ash-coated soil surfaces during compaction.

This trend aligns with results from studies on rice husk ash, coconut husk ash, and palm kernel ash stabilization (Oni et al., 2022; Oladimeji & Samuel, 2023).

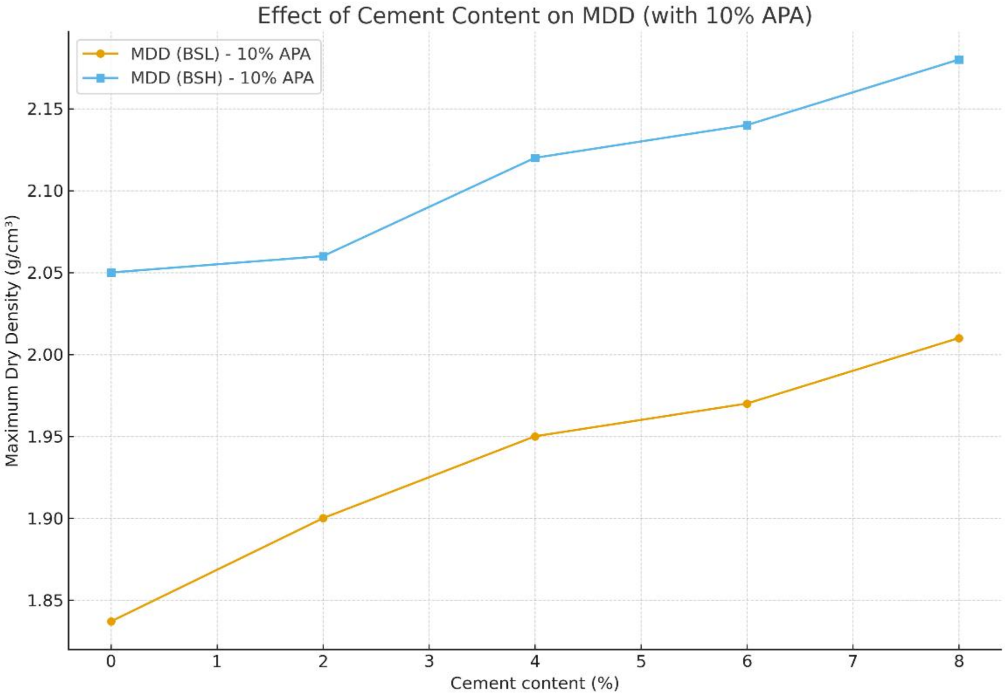


**Fig. 2: Variation of Maximum Dry Density with APA Content**

### 3.2.3 California Bearing Ratio (CBR)

In Fig.3, the CBR improved significantly with increasing APA, especially at 8–10% content.

The **unsoaked CBR** increased steadily.

The **soaked CBR** also increased, indicating improved moisture resistance.

This reflects ongoing pozzolanic activity and the formation of bonding gels (C–S–H and C–A–H), which improve load-bearing capacity.

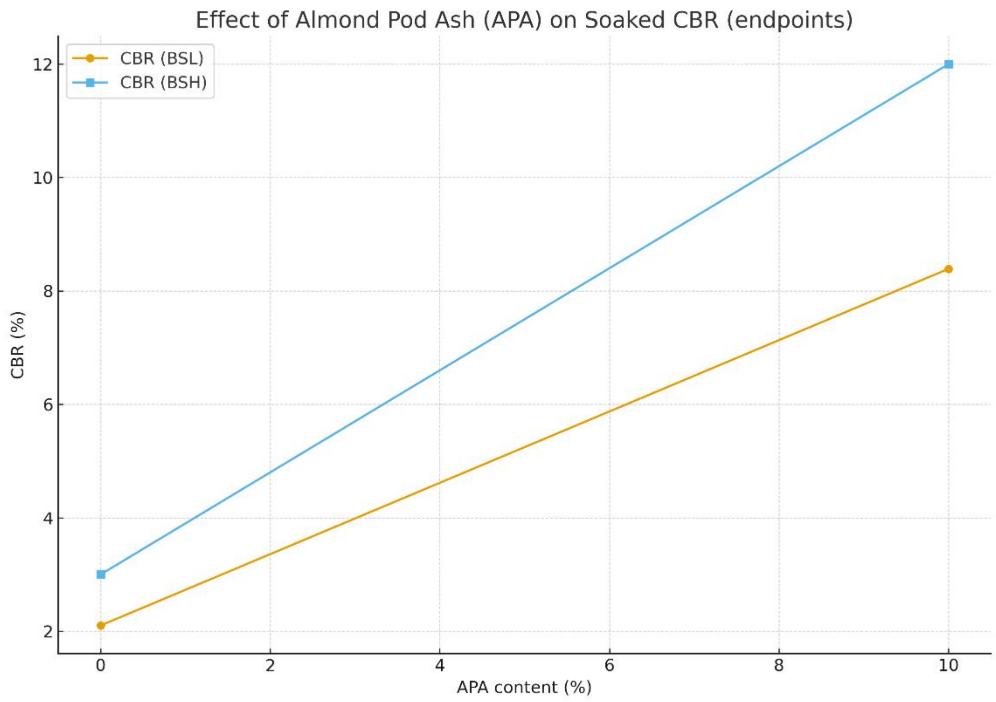


**Fig. 3: CBR Variation with APA Content**

### 3.3 Combined Effects of APA and Cement

To optimize performance, the best-performing APA content (10%) was blended with 2–8% cement. Results show a strong synergistic effect between cement hydration and APA pozzolanic reactivity.

#### 3.3.1 Compaction Behaviour

In Fig 4, when 10% APA was blended with cement:

MDD **increased** with cement content. OMC **decreased slightly**, indicating reduced water demand.

The initial increase in MDD reflects particle densification caused by cementitious gel formation.

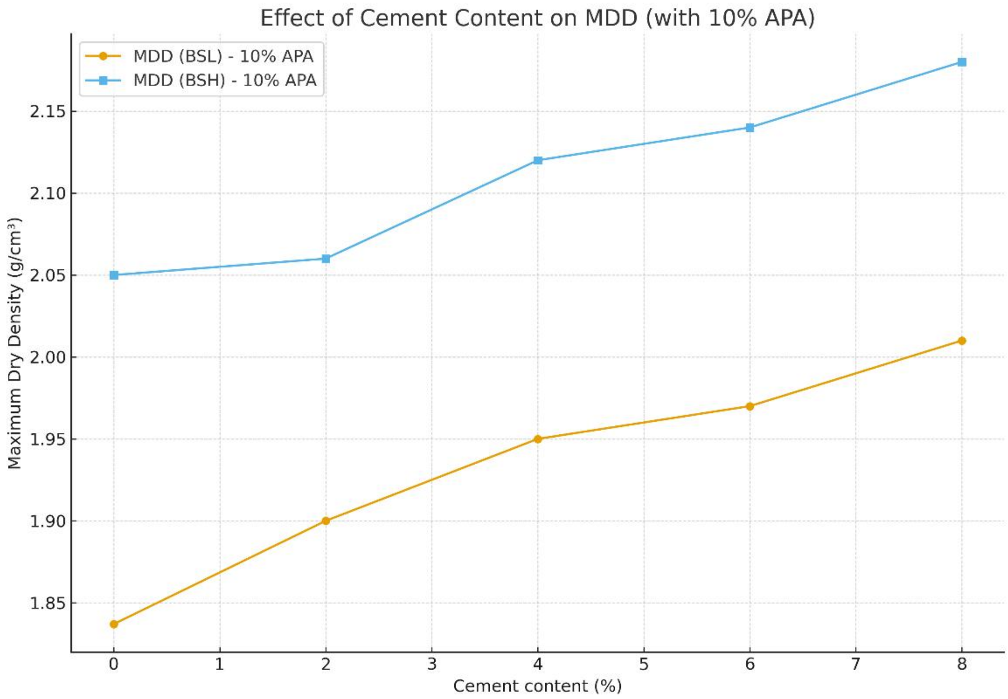


**Fig. 4: MDD versus Cement Content at 10% APA**

### 3.3.2 California Bearing Ratio (CBR)

In Fig 5, both soaked and unsoaked CBR values increased dramatically as cement content increased:

At **8% cement**, the CBR reached its peak, exceeding typical subbase and subgrade requirements.

The soaked CBR improved most significantly, showing better resistance to moisture-induced softening.

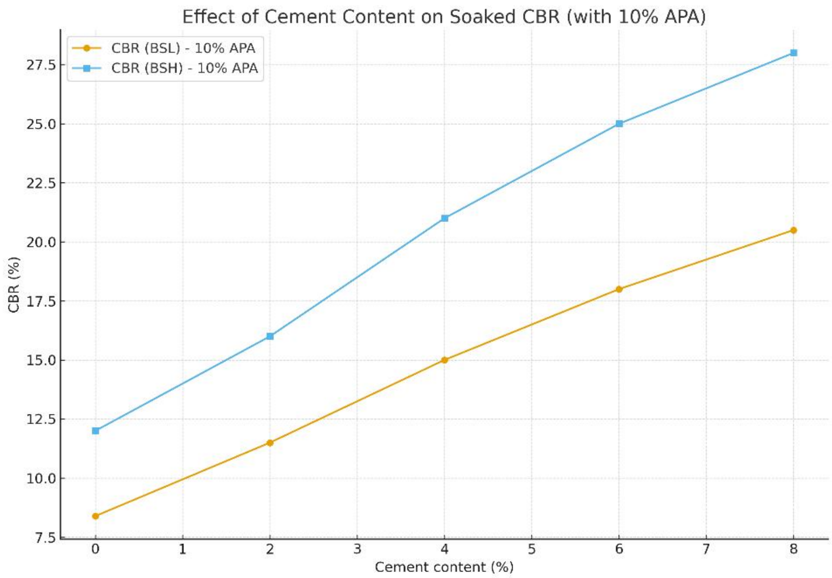


**Fig. 5: CBR versus Cement Content at 10% APA**

### 3.3.3 Unconfined Compressive Strength (UCS)

Fig 6 shows UCS values increased proportionally with cement content: The 7-day, 14-day, and 28-day UCS values all increased. The most pronounced gain occurred between 14 and 28 days, reflecting continued cement hydration and pozzolanic activity.

The combination of APA and cement produced a densified soil matrix with interlocking particles bonded by C–S–H gel.

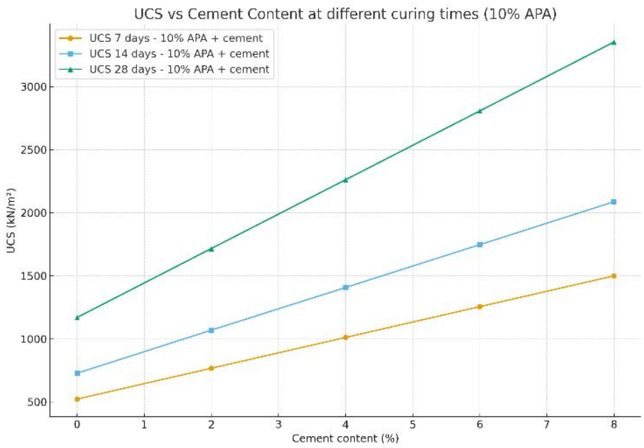


**Fig. 6: UCS versus Cement Content at 10% APA**

### 3.4 Microstructural Interpretation

SEM-EDS micrographs revealed: A transformation from loosely packed clay particles in natural soil. To a more **clustered and cemented matrix** after APA addition. And finally to a **densely bonded matrix** when cement was introduced

The presence of calcium–silicate–hydrate (C–S–H) gel and alumina-rich compounds confirms the pozzolanic reaction between APA and cementitious compounds.

EDS elemental maps confirm increased Ca, Si, and Al bonding phases—consistent with material strengthening. These microstructural changes explain: Reduced plasticity, Improved CBR, Higher UCS, Enhanced durability.

### 3.5 Summary of Findings

Almond pod ash **reduced plasticity** and improved the workability of lateritic soil. APA addition caused expected reductions in MDD but improved strength indices. The **optimal APA content was 10%**, giving the best balance between workability and strength. Blending **10% APA with 6–8% cement** produced the highest strength values. Strength enhancements are directly linked to microstructural densification caused by pozzolanic reactions.

### 3.6 Engineering Implications

The combined use of almond pod ash and cement: Reduces reliance on high cement content, provides a sustainable stabilizer alternative, enhances performance under moisture exposure, promotes agricultural waste recycling

This makes it suitable for: Road subgrade stabilization, low-cost rural roads, foundation improvement, Sustainable geotechnical engineering applications

## IV CONCLUSION AND RECOMMENDATION

### 4.1 CONCLUSION

This study investigated the impact of almond pod ash, lime, and cement on the geotechnical and strength characteristics of lateritic soils. The findings show that APA possesses significant pozzolanic potential due to its high silica and alumina content, enabling it to react beneficially with calcium-based stabilizers. When introduced into lateritic soil, APA improved plasticity characteristics, increased maximum dry density, and enhanced the mechanical behavior of the soil.

The strength performance of the stabilized soils improved noticeably, particularly with the incorporation of cement. The combination of APA and cement demonstrated a synergistic effect, achieving higher UCS and CBR values than when either material was used alone. The optimal performance was recorded at **10% APA with 6–8% cement**, suggesting that APA can effectively serve as a partial replacement for cement in soil stabilization.

Microstructural analyses (SEM-EDS) further confirmed the improved bonding and particle structure in the stabilized samples, providing evidence of the chemical reactions responsible for strength enhancement. The results collectively affirm that APA is not only effective but also a sustainable alternative stabilizer capable of reducing reliance on conventional cement-based stabilization.

### 4.2 RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

**1. Promote Almond Pod Ash as a Sustainable Stabilizer**

APA should be incorporated into soil stabilization practices, especially in regions where lateritic soils are predominant and agro-waste materials are readily available.

**2. Use Optimal Stabilization Blends**

For engineering applications such as road subgrade, subbase construction, and low-rise foundation works, the optimal blend of **10% APA and 6–8% cement** is recommended based on the enhanced strength outcomes.

**3. Reduce Cement Usage in Stabilization**

Since APA enhances the efficacy of cement, construction practitioners should adopt APA as a partial cement replacement. This will reduce environmental impacts and overall project costs.

**4. Conduct Field Performance Evaluations**

Future studies should assess long-term field performance under varying climatic and load conditions to validate laboratory findings.

**5. Support Policy Integration**

Government agencies and construction regulatory bodies should consider integrating APA-stabilized soil into geotechnical design standards, promoting sustainable construction practices nationwide.

**6. Explore Additional Agro-Waste Synergies**

Further research should investigate other complementary agricultural by-products that may enhance the performance of APA-blended stabilization systems.

## REFERENCES

Adeola, T. A., & Odetoye, T. E. (2021). Pozzolanic reactivity of almond pod ash for civil engineering applications. *Journal of Sustainable Materials Research*, 5(2), 45–57.

Adekola, R., & Akinyemi, O. (2021). Geotechnical performance of agro-waste ash-stabilized soils. *Construction and Building Materials*, 271, 121–134.

Adewumi, T., Ogunleye, A., & Hassan, M. (2023). Chemical and microstructural characterization of pozzolanic agricultural wastes for soil stabilization. *Journal of Cleaner Production*, 420, 138–149.

Adeyanju, E., & Adekola, A. (2021). Towards sustainable ground improvement using agricultural by-products. *Case Studies in Construction Materials*, 15, e00710.

Ajayi, O. P., Adebayo, F. E., & Lawal, M. T. (2023). Environmental implications of cement-stabilized soils in tropical construction. *International Journal of Environmental Engineering*, 12(1), 33–47.

Aminu, I., & Hassan, M. (2024). Performance of lime–ash blends for tropical soil stabilization. *Transportation Geotechnics*, 45, 101–118.

Bello, A. S., Jimoh, M. O., & Olukanni, D. O. (2022). Performance of lime- and cement-treated tropical soils for pavement applications. *Construction and Building Materials*, 315, 125–139.

Chen, X., Li, H., & Zhou, Y. (2021). Mechanisms of lime-treated clays and their engineering applications. *Applied Clay Science*, 207, 106–113.

Chukwuka, O. C., & Adebayo, A. J. (2024). Utilization of agro-waste ashes in soil stabilization: A review of recent developments. *African Journal of Geotechnical Engineering*, 9(1), 58–72.

Daniel, E. I., & Okonkwo, U. (2023). Moisture variation effects on the volume stability of tropical lateritic soils. *Geotechnical and Geological Engineering*, 41(3), 1207–1221.

Ezeh, J. C., Ogu, C. I., & Nwankwo, C. (2022). Geotechnical causes of pavement failures in southeastern Nigeria. *Journal of Infrastructure Engineering*, 8(1), 77–91.

Ibrahim, A. R., & Lawal, T. M. (2023). Sustainable construction trends in developing countries: A review of low-carbon technologies. *Sustainable Engineering Journal*, 4(3), 102–118.

Ibrahim, Y. S., Musa, A. H., & Okoro, D. C. (2024). Calcination effects on the pozzolanic properties of tropical almond pod ash. *Materials Today: Sustainability*, 8, 100–112.

Idris, M., & Abubakar, U. (2021). Influence of moisture and gradation on the compaction behaviour of lateritic soils. *Innovative Infrastructure Solutions*, 6, 102–115.

Jambo, P., & Adebanjo, O. (2022). Strength evolution of cement-treated soils: Curing time and microstructural linkages. *Geotechnical and Geological Engineering*, 40, 2325–2340.

Ogunribido, O. T., & Aina, J. O. (2021). Strength performance of lateritic soils under varying moisture regimes. *Nigerian Journal of Geotechnics*, 15(2), 90–101.

Oladimeji, A. T., & Samuel, O. J. (2023). Stabilization of lateritic soils using coconut husk ash for road construction. *Case Studies in Construction Materials*, 18, e02044.

Oladipo, S., & Samuel, K. (2021). Compaction and bearing properties of agro-ash modified soils. *Heliyon*, 7(9), e07934.

Olatunji, A., Bello, M., & Salihu, A. (2022). Lateritic soils in West Africa: Engineering behaviour and stabilization needs. *Environmental Geotechnics*, 9, 423–436.

Oni, A. O., Balogun, A. A., & Alabi, O. J. (2022). Soil stabilization using rice husk ash: Strength and durability analysis. *Journal of Civil Engineering Research*, 14(4), 66–75.

Onyelowe, K. C. (2011). Geotechnical issues and road failure causes in Nigeria: A review. *International Journal of Pavement Engineering*, 6(2), 45–52.

Osinubi, K. J., Ijimdiya, T. S., & Eberemu, A. O. (2021). Engineering behavior of tropical lateritic soils: A critical review. *Transportation Geotechnics*, 27, 100–136.

Pathak, R., Singh, J., & Verma, S. (2022). Microstructural insights into cement-soil mixtures. *Materials Today Communications*, 34, 105–120.

Pelemo, F. O., Ojo, M. O., & Sanusi, A. (2024). Carbon reduction strategies in soil stabilization for road construction. *Journal of Cleaner Construction Technologies*, 3(1), 15–29.

Rahman, R., Zhang, L., & Chen, M. (2023). Pozzolanic activation of agricultural ashes for sustainable soil stabilization. *Journal of Materials Research and Technology*, 24, 958–972.

Wang, S., Hu, Y., & Zhao, Q. (2024). Thermal activation of biomass ashes and their reactivity in cementitious systems. *Resources, Conservation & Recycling*, 198, 107–118.

Zuhaib, M. (2017). Behaviour of clayey soils under seasonal moisture variations. *Geomechanics and Geoengineering*, 12(2), 110–122.