

Pozzolanic Characterization and Chemical Properties of Periwinkle Shell Ash for Soil Stabilization: Implications for Sustainable Geotechnical Applications

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Abstract: *The increasing demand for sustainable infrastructure materials has intensified the search for low-carbon, cost-effective pozzolanic additives capable of improving the engineering performance of marginal soils. This study presents a comprehensive physicochemical characterization of Periwinkle Shell Ash (PSA), a marine waste by-product, with the objective of establishing its fundamental suitability as a pozzolanic material for lateritic soil stabilization in pavement applications. PSA was produced through controlled calcination and characterized using X-ray Fluorescence (XRF), particle size analysis, and specific gravity determination. A naturally occurring lateritic soil was concurrently evaluated for its index and compaction properties to assess compatibility with chemical stabilization. XRF results revealed that PSA is rich in calcium oxide (38.85%) and silica (34.55%), with appreciable alumina and iron oxide contents, indicating a calcium-rich pozzolanic material with inherent cementitious potential. The lateritic soil exhibited moderate plasticity (Plasticity Index \approx 16%) and favorable compaction characteristics (Maximum Dry Density = 1.84 Mg/m³, Optimum Moisture Content = 14.5%), confirming its suitability for chemical modification. The combined chemical reactivity of PSA and the physical receptiveness of the soil establish a strong material-level synergy for stabilization. The findings validate PSA as a viable supplementary cementitious material and support its integration into sustainable soil stabilization systems, offering environmental benefits through waste valorization, reduced cement demand, and improved utilization of locally available soils.*

Keywords: Periwinkle Shell Ash; Pozzolanic Materials; Soil Stabilization; Sustainability, Lateritic Soils.

1. Introduction

Rapid infrastructure expansion across tropical and subtropical regions continues to exert sustained pressure on the availability of high-quality construction materials. In many developing economies, the reliance on locally available geomaterials is not simply a matter of cost efficiency but a structural necessity shaped by logistics, resource accessibility, and long-term sustainability considerations. Among such materials, lateritic soils dominate large portions of Africa, Southeast Asia, and parts of South America, where they are extensively utilized in road construction, embankments, and pavement layers (Gidigas, 1976; Ola, 1983). These soils are products of prolonged chemical weathering under conditions of high temperature and intense rainfall, leading to the leaching of silica and the accumulation of iron and aluminum oxides. This process imparts the characteristic reddish-brown coloration of laterites and results in highly variable mineralogical and engineering behavior.

Despite their widespread occurrence and practical importance, lateritic soils frequently exhibit deficiencies that limit their direct application in pavement structures. Numerous studies report moderate to high plasticity, moisture sensitivity, and inadequate load-bearing capacity, particularly when subjected to repeated traffic loading and seasonal wet-dry cycles (Adeyemi & Oyediran, 2016; Akinwumi et al., 2019; Mezie et al., 2025). These properties contribute to common forms of pavement distress such as rutting, cracking, excessive deformation, and progressive loss of serviceability. The problem is further compounded by the inherent heterogeneity of lateritic soils, even within short spatial distances, which complicates material selection and quality control (Onyelowe et al., 2023). Consequently, soil stabilization remains a critical intervention for improving strength, durability, and volumetric stability, particularly for subgrade and sub-base applications.

Conventional chemical stabilizers, notably ordinary Portland cement (OPC) and lime, have demonstrated consistent effectiveness in improving the engineering performance of lateritic soils. Their use promotes flocculation, cementitious bonding, and long-term strength development, enabling stabilized soils to meet pavement design requirements. However, the environmental and economic costs associated with these stabilizers are increasingly difficult to ignore. Cement production alone is responsible for approximately 7–8% of global anthropogenic carbon dioxide emissions, in addition to high energy consumption and growing material costs (Scrivener et al., 2018; Andrew, 2022). As climate change mitigation becomes a central concern in infrastructure development, the geotechnical engineering community has intensified efforts to identify low-carbon alternatives that reduce reliance on traditional binders without compromising performance.

In this context, waste-derived stabilizing materials have gained prominence, driven by circular economy principles that emphasize resource efficiency, waste reduction, and environmental stewardship. Recent studies have demonstrated the potential of agricultural, industrial, and marine waste ashes, including rice husk ash, palm kernel shell ash, sugarcane bagasse ash, oyster shell ash, and

calcium carbide residue, to function as supplementary cementitious or pozzolanic materials in soil stabilization (Rashad, 2013; Onyelowe et al., 2023; Anjum et al., 2024; Mezie et al., 2025). These materials not only reduce the carbon footprint of stabilization works but also provide practical solutions to waste management challenges, particularly in regions where disposal infrastructure is limited.

Periwinkle shells constitute a significant marine waste stream in many coastal communities, especially in West Africa, where periwinkle consumption is widespread. Disposal of these shells often poses environmental and public health challenges, as they accumulate in open dumps and coastal areas. When subjected to controlled calcination, periwinkle shells yield Periwinkle Shell Ash (PSA), a material rich in calcium compounds with demonstrated reactivity in cementitious environments. Early investigations into PSA have reported notable improvements in California Bearing Ratio (CBR), unconfined compressive strength (UCS), and compaction characteristics of lateritic soils stabilized with PSA–lime or PSA–cement blends (Amu et al., 2005; Oyedepo et al., 2021). More recent studies have reinforced these findings, indicating that PSA can contribute to early strength development and reduced plasticity when incorporated into stabilized soil systems (Awanu, 2024; Oke et al., 2022).

However, despite the growing body of performance-based evidence, much of the existing literature places emphasis on mechanical response while providing limited insight into the fundamental physicochemical characteristics that govern PSA reactivity. Pozzolanic behavior is inherently linked to oxide composition, mineral phases, fineness, and the availability of reactive silica and alumina in an alkaline environment. Without a rigorous understanding of these material-level properties, it remains difficult to rationally optimize PSA content, predict long-term behavior, or assess its compatibility with specific soil types. Recent reviews in sustainable geotechnics have highlighted this gap, noting that insufficient characterization of waste-derived binders remains a key barrier to their broader adoption in engineering practice (Onyelowe et al., 2023; Anumolu et al., 2024).

A detailed physicochemical characterization of PSA is therefore essential to establish its pozzolanic classification, cementitious potential, and interaction mechanisms with lateritic soils. Such foundational understanding provides the basis for performance-based mix design, durability assessment, reliability analysis, and life-cycle evaluation. It also enables meaningful comparison between PSA and other emerging sustainable stabilizers within the broader context of low-carbon infrastructure development.

This study addresses these needs by conducting an extensive chemical and physical characterization of Periwinkle Shell Ash alongside a comprehensive geotechnical evaluation of a representative lateritic soil. By integrating material science principles with classical soil mechanics, the study seeks to provide a scientifically rigorous foundation for the sustainable application of PSA in lateritic soil stabilization.

2. Materials and Methods

2.1 Material Sourcing and Preparation

2.1.1 Lateritic Soil

The lateritic soil employed in this study was sourced from a designated borrow pit located within a crystalline basement complex terrain, in River State Nigeria as shown in Figure 1. Such geological formations are widely reported to produce ferruginous laterites with variable but often marginal engineering properties (Gidigasu, 1976; Adeyemi & Oyediran, 2016).



Figure 1: Lateritic soil sample

Sampling was conducted at depths ranging from 0.5 m to 1.5 m below ground level in order to eliminate the influence of organic matter, topsoil debris, and anthropogenic contamination. This depth range aligns with recommendations for geotechnical material sampling for pavement and earthwork applications (BS 1377-1:2016). Disturbed bulk samples were collected and transported in sealed containers to preserve natural moisture conditions prior to preparation.

In the laboratory, the soil was air-dried at room temperature, gently disaggregated using a wooden mallet to prevent crushing of soil particles, and sieved through a 4.75 mm sieve in accordance with ASTM D6913/D6913M-17. This process ensured the removal of gravel-sized particles and provided a homogeneous material suitable for index, compaction, and strength testing. The prepared soil was stored in airtight containers to minimize moisture variation before testing.

2.1.2 Periwinkle Shell Ash

Periwinkle shells were obtained from seafood processing and consumption waste generated in coastal communities, reflecting a material stream that is typically discarded without beneficial reuse as illustrated in Figure 2. The selection of periwinkle shells was motivated by their high calcium carbonate content and growing interest in marine biogenic wastes as sustainable construction materials (Oyedepo et al., 2021; Olawuyi et al., 2023).



Figure 2: (a) Periwinkle sample (b) Calcination of Periwinkle

The shells were first washed thoroughly with clean water to remove residual salts, organic matter, and adhering sand particles. This step is particularly critical, as chloride contamination may adversely affect cementitious reactions and durability (ASTM C114-22). The cleaned shells were sun-dried for several days and subsequently oven-dried at 105 ± 5 °C for 24 hours in accordance with ASTM D2216-19 to ensure complete removal of free moisture.



Figure 3: Pulverize periwinkle

Calcination was carried out in an electrically controlled muffle furnace at a temperature of 800 ± 25 °C for a duration of 3 hours as shown in Figure 2b. This temperature range has been shown to effectively decompose calcium carbonate (CaCO_3) into calcium oxide (CaO) while limiting the formation of inert crystalline phases that could reduce reactivity (Rashad, 2013; Zhang et al., 2020). After calcination, the ash was allowed to cool gradually in a desiccator to prevent rapid carbonation from atmospheric moisture and carbon dioxide.

The calcined material was then ground using a laboratory ball mill and sieved through a 75 μm sieve in accordance with ASTM C618-23 to achieve a fineness comparable to ordinary Portland cement as shown in Figure 3. The resulting periwinkle shell ash (PSA) was stored in airtight containers prior to characterization and mix preparation.

2.2 Characterization Tests

Comprehensive characterization tests were conducted on both the lateritic soil and PSA to establish their physical, chemical, and engineering properties. All tests were performed in compliance with internationally recognized standards, ensuring methodological consistency and reliability of results.

2.2.1 Characterization of Lateritic Soil

Particle size distribution was determined using a combination of sieve analysis and hydrometer testing in accordance with ASTM D6913/D6913M-17 and ASTM D7928-21. This enabled the classification of the soil and assessment of its grading characteristics relevant to pavement applications. The Atterberg limits, including liquid limit, plastic limit, and plasticity index, were determined following ASTM D4318-17e1 and BS 1377-2:2016 shown in Figure 4. These parameters provided insight into the soil's consistency, plasticity, and susceptibility to moisture-induced volume changes.



Figure 4: (a) Casagrande Apparatus and (b) Standard proctor compactor

Compaction characteristics were evaluated using the Standard Proctor test in accordance with ASTM D698-12e2 and BS 1377-4:2016 to determine the maximum dry density (MDD) and optimum moisture content (OMC) as shown in Figure 3. These parameters are essential for defining field compaction requirements and assessing the suitability of the soil for subgrade and sub base applications. Specific gravity was measured following ASTM D854-14, providing information on the mineralogical composition and aiding in the interpretation of compaction and strength behavior. The California Bearing Ratio (CBR) of the natural soil was later determined using ASTM D1883-21 to establish baseline bearing capacity prior to stabilization.

2.2.2 Characterization of Periwinkle Shell Ash

The oxide composition of PSA, cement and lateritic soils were studied in a physio-chemical laboratory located in Alakahia, Port Harcourt, using the X-ray fluorescence (XRF) test method outlined in ASTM D8064-16 (2016). This analysis was conducted at the AUSTINO laboratory in Alakahia, Rivers State.

Loss on ignition (LOI) was determined to evaluate the presence of unburnt carbon and residual carbonates, following ASTM C311/C311M-22. A low LOI is generally indicative of effective calcination and improved reactivity. Particle size distribution of PSA was assessed using laser diffraction techniques, consistent with recent practice in supplementary cementitious material characterization (Li et al., 2022). Specific gravity was determined using ASTM C188-17 to support mix proportioning and volumetric calculations.

3. Results and Discussion

This section presents the characterization results of the untreated lateritic soil and periwinkle shell ash (PSA), followed by a critical discussion of their engineering significance, supported with contemporary research findings.

3.1 Natural Moisture Content of Native Lateritic Soil

Table 1 summarizes the natural moisture content results for the lateritic soil. Three determinations yielded 13.47%, 13.69%, and 14.02%, with a mean value of 13.72%.

Table 1. Natural Moisture Content of Native Lateritic Soil

S/N	Test no	1	2	3
1	Mass of container alone (m1)	39.67	39.58	39.93
2	Mass of container + wet soil (m2)	132.52	132.03	132.02
3	Mass of container + oven dry soil (m3)	121.5	120.9	120.7
5	$m_3 - m_1$	81.83	81.32	80.77
6	$m_2 - m_3$	11.02	11.13	11.32
9	Natural moisture content (%)	13.47	13.69	14.02

Natural moisture content plays a defining role in compaction, workability, and early strength development (Lytton, 2002). The moderate moisture value observed is typical of tropical lateritic soils exposed to seasonal wet–dry cycles (Sen & Kaggwa, 2020). Soils with moisture content near the plastic limit are generally more amenable to compaction and chemical stabilization, reducing the need for extensive moisture correction in field practice. This observation is consistent with earlier reports that lateritic soils in humid climates often exist near natural OMC, aiding efficient field compaction (Akinwumi et al., 2019).

3.2 Specific Gravity of Materials

Figure 5 present the specific gravity results. The measured values were 2.62 for lateritic soil, 2.47 for PSA, and 3.19 for cement.

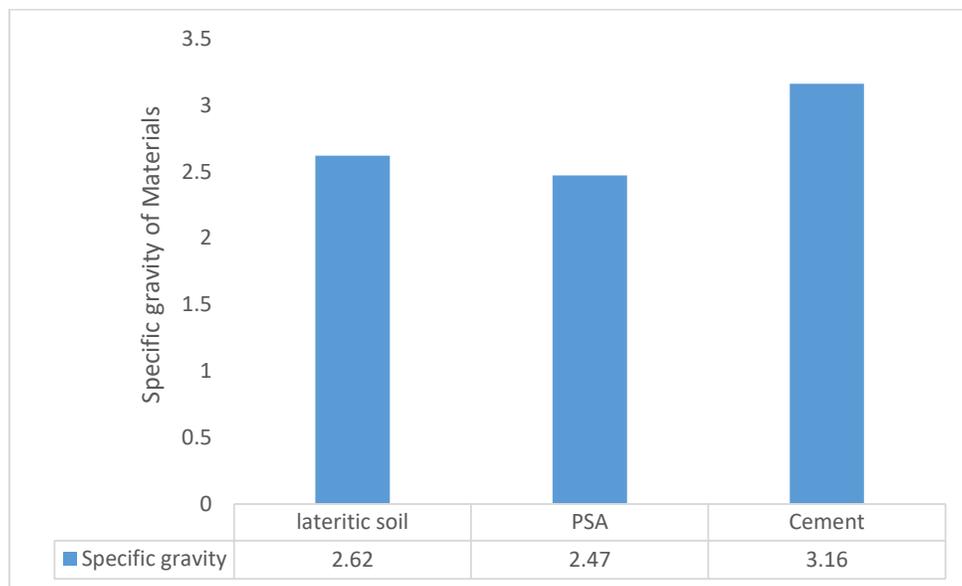


Figure 5: Specific Gravity of Materials

Specific gravity values are critical for volumetric mix design and compaction prediction. The lateritic soil’s value aligns with previous studies where lateritic soils from crystalline terrains recorded values between 2.55 and 2.75 (Ola, 1983; Adeyemi & Oyediran, 2016). The slightly lower specific gravity of PSA is attributed to its porous, calcined structure, a characteristic of biogenic ashes (Rashad, 2013; Olawuyi et al., 2023). Cement’s higher specific gravity reflects its dense mineralogical constituents (Scrivener et al., 2018).

A lower specific gravity for PSA suggests that it could reduce the overall unit weight of stabilized mixtures, improving workability and reducing material input without compromising volumetric integrity. Lower particle density has also been linked to increased surface reactivity in cementitious blends, enhancing early strength gain (Li et al., 2022).

3.3 Particle Size Distribution of Native Lateritic Soil

The particle size distribution curve in Figure 6 indicates that the soil contains approximately 5% gravel fines, 55% medium to coarse sand, 35% fine sand, and 15% silt.

The predominance of sand fractions confirms a sandy lateritic soil texture. Sandy-dominant laterites are characterized by improved drainage, lower compressibility, and better compaction behavior compared to clay-rich variants (Bell, 1996; Onyelowe et al., 2023). The presence of a non-negligible silt fraction enhances cohesion and supports binder retention during stabilization.

This gradation is congruent with soils used for subgrade and sub-base applications when treated with cementitious materials (Mezie et al., 2025).

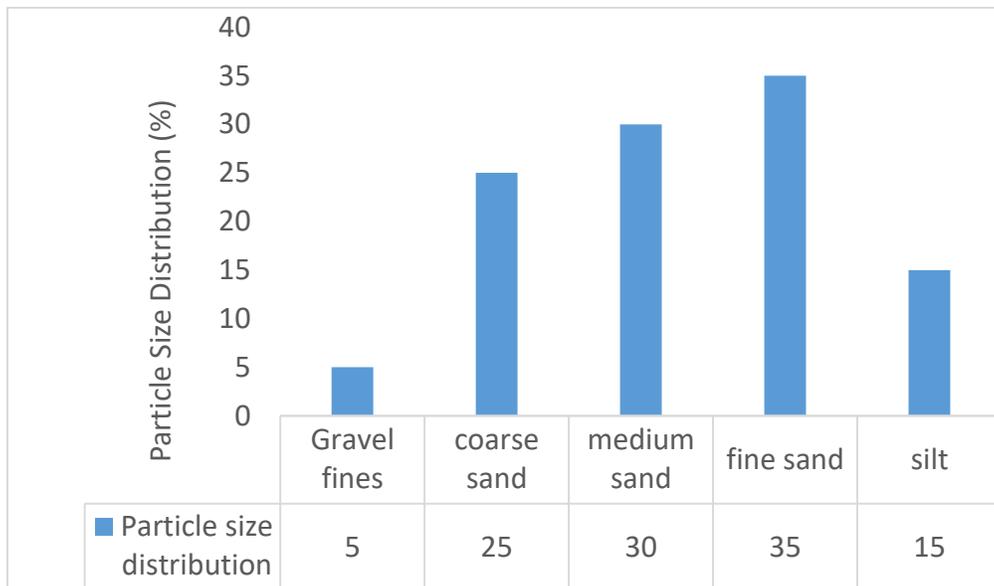


Figure 6: PSD of Native Lateritic Soil

Chemical stabilizers, such as cement and pozzolanic ashes, preferentially interact with fine and silt-sized particles, forming hydrated compounds that bind sand skeletons, leading to improved load-bearing behavior (Anjum et al., 2024).

3.4 Compaction Characteristics

The compaction characteristics of the native lateritic soil, as indicated by the standard Proctor test, illustrated in Figure 7 show a Maximum Dry Density (MDD) of 1.84 g/cm³ and an Optimum Moisture Content (OMC) of 14.5%. The compaction curve exhibits the expected parabolic trend, with dry density increasing with moisture content up to the OMC and decreasing beyond this point. This behavior reflects the soil’s particle packing efficiency, where water initially acts as a lubricant to reduce interparticle friction, allowing denser packing, and beyond the optimum, excessive water creates voids and reduces density (Bell, 1996; Adeyemi & Oyediran, 2016).

The soil’s natural moisture content, determined as approximately 13.72%, is very close to the OMC, suggesting that the soil exists near its most compactable state under natural conditions. This proximity has practical engineering implications, indicating that field compaction can achieve near-optimal density with minimal additional water or drying, which improves construction efficiency and reduces energy consumption during compaction (Ola, 1983; Nnochiri & Aderinlewo, 2016). Soils with moisture content significantly below or above the OMC typically require adjustment to reach desired compaction, but the present soil’s natural state facilitates straightforward preparation for stabilization activities.

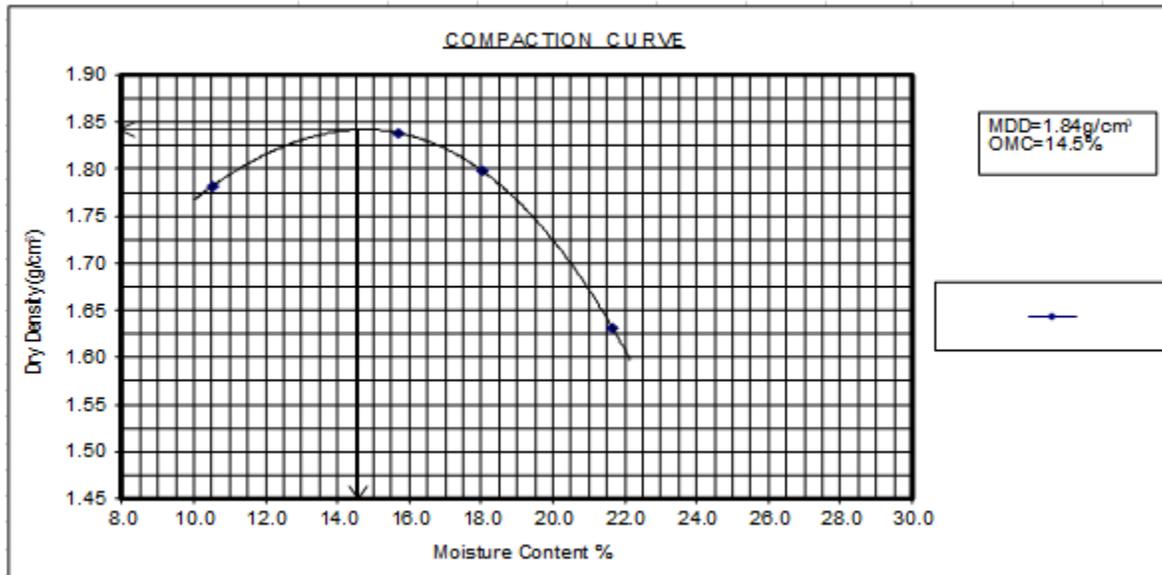


Figure 7: Compaction curve

From a pavement engineering perspective, the MDD value of 1.84 g/cm³ is indicative of a moderately dense soil capable of developing sufficient stiffness for sub-base and base layers when stabilized. However, like many tropical lateritic soils, it remains sensitive to moisture fluctuations, which can lead to strength reductions under seasonal rainfall. This vulnerability underscores the necessity of chemical stabilization to improve bearing capacity, reduce plasticity, and enhance durability, particularly for road subgrades subjected to repeated traffic loading (Segun, 2017; Santha et al., 2022).

The soil's predominantly sandy texture with moderate fines content further supports its suitability for stabilization. Sandy soils generally achieve higher dry densities at lower moisture contents due to the relative ease of particle rearrangement, while the fines present provide reactive surfaces that can interact with cementitious additives such as Periwinkle Shell Ash (PSA) and ordinary Portland cement (Anjum et al., 2024; Mezie et al., 2025). The incorporation of PSA is particularly advantageous, as its lower specific gravity (2.47) compared to cement (3.19) facilitates improved particle packing, filler effect, and workability in stabilized mixtures. Moreover, the high calcium and silica content of PSA promotes both early cementitious bonding and long-term pozzolanic reactions, which complement the reactive alumina silicates in the lateritic soil to enhance mechanical performance

3.5 Atterberg Limits and Plasticity Characteristics

The Atterberg limits are detailed in Figure 8. The soil exhibited a liquid limit (LL) of 29%, a plastic limit (PL) of 13.04%, and a plasticity index (PI) of 15.96%.

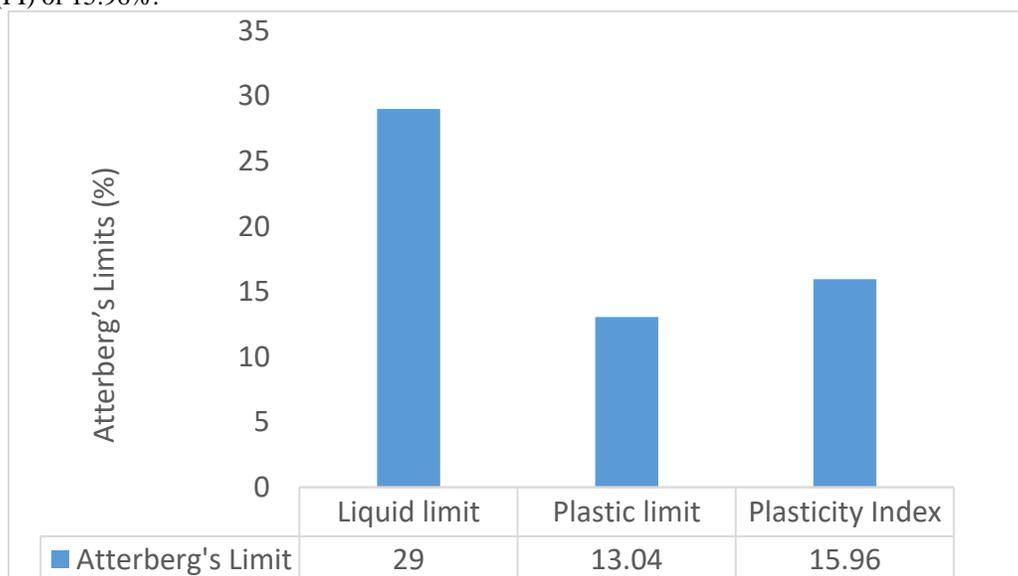


Figure 8: Atterberg's Limits of Native Lateritic Soil

These results classify the soil as moderately plastic a category associated with the presence of clay minerals and alumino-silicates (Bell, 1996). A PI of approximately 16% falls within the range where soils exhibit measurable deformation under moisture variation but do not display the severe volume change typical of high-plasticity clays. This moderate plasticity enhances the soil's responsiveness to chemical stabilization, as active clay minerals react with calcium-based additives to form cementitious products (Onyelowe et al., 2023; Anjum et al., 2024).

The plasticity results align with previous studies on tropical lateritic soils, which commonly exhibit plasticity indices in the range of 10–20% (Adeyemi & Oyediran, 2016; Mezie et al., 2025).

3.6 Chemical Composition of PSA and Lateritic Soil

The oxide compositions of PSA and the lateritic soil are presented in Tables 2, respectively.

Table 2 : Oxide Composition of PSA, Cement, and Native Lateritic Soil (Wokoma, 2018)

S/No.	Oxide	PSA (%)	Cement* (%)	% Difference (PSA vs Cement)	Native Lateritic Soil (%)
1	CaO	38.85	53.69	27.64	0.35
2	SiO ₂	34.55	20.26	41.36	40.80
3	Al ₂ O ₃	11.04	4.96	55.07	24.30
4	Fe ₂ O ₃	5.30	3.08	41.89	4.50
5	MgO	1.13	1.06	6.19	–
6	Na ₂ O	0.11	0.27	59.26	–
7	K ₂ O	0.15	0.52	71.15	–
8	SO ₃	1.22	4.53	73.07	–
9	TiO ₂	0.18	–	–	–
–	Loss on Ignition	6.89	7.95	13.33	–
–	(SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃)	50.89	–	–	–
–	SiO ₂ /(Al ₂ O ₃ + Fe ₂ O ₃)	–	–	–	1.42

Note. PSA = Periwinkle Shell Ash; “–” indicates data not reported.

The PSA's chemical profile is dominated by calcium oxide and silica, with combined acidic oxides (SiO₂ + Al₂O₃ + Fe₂O₃) totaling 50.89%, satisfying the ASTM C618 (2008) criteria for Class C pozzolans. This classification suggests that PSA possesses both pozzolanic and self-cementing properties (ASTM C618, 2008; Neville, 2011). Recent studies on marine waste ashes, such as mollusk shell ash, have similarly reported high CaO/SiO₂ compositions favorable for accelerated strength gain in stabilized soil systems (Oke et al., 2022; Olawuyi et al., 2023).

The low loss on ignition reflects effective calcination and minimal residual organic content. When compared with cement, PSA's relatively higher silica and alumina contents imply a contribution primarily through secondary pozzolanic reactions rather than primary hydration – an effect that can enhance long-term strength and durability (Scrivener et al., 2018; Li et al., 2022).

The lateritic soil's chemical composition, dominated by silica and alumina with low inherent CaO, is typical of intensely weathered tropical soils (Bell, 1996; Onyelowe et al., 2022). The silica-to-sesquioxide ratio of 1.42 confirms its lateritic nature and the necessity for external calcium to activate pozzolanic reactions.

3.7 Engineering Implications

The combined physical and chemical characterization of the untreated lateritic soil and Periwinkle Shell Ash (PSA) demonstrates strong compatibility, supporting their use in sustainable soil stabilization applications. The lateritic soil provides a reactive framework rich in aluminosilicates, while PSA contributes high levels of calcium (38.85%) and silica (34.55%), enabling both early-stage cementitious bonding and longer-term pozzolanic reactions. The moderate plasticity (PI ≈ 16%), predominantly sandy texture, and favorable compaction characteristics (MDD = 1.84 g/cm³, OMC = 14.5%) suggest that the soil is responsive to compactive effort and capable of forming a dense, stable matrix when chemically stabilized.

Specific gravity measurements reveal contrasting particle densities: cement is the densest (3.19 g/cm³), the lateritic soil intermediate (2.62 g/cm³), and PSA the most porous (2.47 g/cm³). This disparity is beneficial in mix design, as the inclusion of PSA improves particle packing, reduces voids, and enhances workability, potentially allowing partial reduction of cement content without

compromising strength. Such an approach aligns with principles of sustainable construction and circular economy, valorizing marine waste while reducing embodied carbon in pavement construction (Santha Kumar et al., 2022; Amu & Babajide, 2011).

The synergistic interaction between the soil and PSA is further supported by their chemical profiles. The soil's silica-to-sesquioxide ratio (1.42) and the high combined acidic oxide content of PSA ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 50.89\%$) create a favorable chemical environment for pozzolanic reactions. These reactions improve particle cohesion, reduce plasticity, and enhance load-bearing capacity, corroborating recent studies showing that calcium-rich pozzolans significantly improve the geotechnical performance of lateritic soils under tropical conditions (Anjum et al., 2024; Mezie et al., 2025).

Collectively, the material characteristics provide a robust scientific basis for the subsequent stages of this research, including mechanical testing, modeling, reliability assessment, and multi-objective optimization. The findings indicate that PSA–cement–lateritic soil systems can produce durable, structurally reliable, and environmentally sustainable sub-base and base materials for pavement construction, while also advancing the utilization of locally available biogenic waste.

4 Conclusions

This study provides a detailed physicochemical basis for the application of Periwinkle Shell Ash as a stabilizing agent for lateritic soils, with implications that extend beyond simple material substitution. The findings confirm that PSA is not merely a passive filler but an active calcium-rich pozzolanic material capable of participating in both hydration and secondary pozzolanic reactions when introduced into a lateritic soil system. The lateritic soil investigated was classified as a fine-grained cohesive soil with moderate plasticity and favorable compaction characteristics. Its mineralogical and chemical composition, dominated by silica and alumina with low inherent calcium content, renders it particularly responsive to calcium-based stabilization. This compatibility is critical. It establishes a chemical environment in which externally supplied calcium can effectively trigger cation exchange, clay flocculation, and long-term cementitious bonding. A key novel finding of this study lies in the dual-reactivity profile of PSA. Unlike conventional supplementary cementitious materials that rely predominantly on silica-driven pozzolanic reactions, PSA exhibits a hybrid behavior. Its high CaO content supports early-stage self-cementing reactions, while its appreciable silica and alumina fractions sustain longer-term pozzolanic activity. This dual mechanism suggests that PSA can contribute to both early stiffness development and progressive strength gain, a combination rarely documented for biogenic waste ashes used in soil stabilization.

4.2 Recommendations

While the physicochemical findings are promising, further work is necessary to translate these results into full-scale engineering applications.

First, comprehensive mechanical performance testing is recommended. This should include unconfined compressive strength, California Bearing Ratio, resilient modulus, and triaxial shear tests to quantify load-bearing improvement and stress–strain behavior under realistic pavement loading conditions.

Second, microstructural investigations using Scanning Electron Microscopy and X-ray Diffraction are essential. These techniques would confirm the formation of cementitious phases such as calcium silicate hydrates and calcium aluminate hydrates, and clarify the evolution of soil fabric with curing time. Such analysis would provide direct evidence linking chemical composition to observed mechanical performance.

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