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GEOTECHNICAL ENHANCEMENT OF LATERITIC SOILS USING NANO-SILICA AND PLANTAIN PEEL ASH: PHYSICAL, COMPACTION, AND STRENGTH CHARACTERISTICS

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Abstract
The geotechnical properties of lateritic soils from Ibienafe, South Ibie, Edo State, Nigeria, were assessed for pavement construction using both untreated and stabilized samples obtained from Locations A, B, and C. Due to similar geotechnical characteristics across sites, Location B was selected for stabilization. Laboratory analyses were performed in accordance with BS 1377: Parts 2 and 4 (1990), comprising specific gravity determination, particle size distribution, Atterberg limits, compaction characteristics, and California Bearing Ratio (CBR). Untreated soils, with a CBR of 36.35%, suited low-traffic subgrades but required stabilization. The results showed consistent specific gravity (2.54–2.56), fine-grained composition (84.36–85.13% passing 0.075 mm, classified as lean clay, CL), moderate plasticity (PI 11.58–12.02%), and compaction (MDD 1.85–1.90 g/cm³, OMC 11.03–14.16%). Stabilization with 2.5% and 5.0% Plantain Peel Ash (PPA) reduced CBR (31.05–34.09%), compaction (MDD 1.82–1.83 g/cm³, OMC 15.39–18.54%), and specific gravity (2.45), indicating limited benefits. Conversely, 2.5% and 5.0% Nano-Silica (NS) improved CBR (36.21–39.47%), reduced plasticity (PI 4.71–6.61%), and increased density (Gs 2.53–2.60). The 5.0% PPA and 2.5% NS combination yielded the highest CBR (48.55%), optimal compaction (MDD 1.79 g/cm³, OMC 18.13%), and low plasticity (PI 6.73%), ideal for subbase in light-traffic roads, highlighting NS's superior stabilization and PPA-NS eco-efficiency.

Keywords
Lateritic soils, Nano-Silica, Pavement Construction, Plantain Peel Ash, Stabilization

1. INTRODUCTION

Lateritic soils are abundant and easily accessible, making them ideal for building roads and foundations in tropical regions like Nigeria (Gidigasu, 2004; Okunade, 2008). However, lateritic soils generally have low shear strength, high plasticity, and poor load-bearing capacity in their natural state (Ola, 1983; BS, 1990a; Bewaji et al., 2025). The durability and functionality of infrastructure, such as pavements and foundations, can be strongly impacted by these geotechnical characteristics. Furthermore, unless appropriately stabilized, lateritic soils' vulnerability to moisture-induced volume changes frequently makes them unsuitable for heavy-duty applications (BS, 1990b; BS, 2005). By decreasing plasticity and increasing strength, traditional stabilizers like cement and lime have proven successful in improving engineering properties (Cheah and Ramli, 2011; Adeboje et al., 2022). However, the search for sustainable, eco-friendly, and financially feasible alternatives has been sparked by their high cost, energy-intensive production, and environmental effects, especially CO_2 emissions (Nnochiri and Ogundipe, 2020; Rahman et al., 2022). This study explores the stabilization potential of two novel materials in response to these concerns: Plantain Peel Ash (PPA), an agro-waste byproduct rich in silica and alumina, and Nano-Silica (NS), a nanomaterial with a high surface area and strong pozzolanic reactivity. Recycled from calcined plantain peels, PPA reduces disposal issues, recycles agricultural waste, and contributes reactive compounds that improve soil matrix bonding (Osinubi et al., 2021; Adeboje et al., 2022). However, because of its micro-filling effect and the creation of calcium silicate hydrate (C-S-H) gels, NS has been demonstrated to increase soil density and strength while decreasing plasticity (Olawuyi and Alhassan, 2021; Akinmusuru et al., 2022). This study aims to assess the effects of PPA and NS, both separately and in combination, on the physical characteristics, strength, and compaction of lateritic soils from Ibienafe, South Ibie, Edo State, Nigeria. The study intends to identify the best stabilizer combination for improving the engineering behavior of lateritic soils and offering a sustainable alternative for pavement construction in tropical regions through geotechnical tests such as specific gravity, sieve analysis, Atterberg limits, compaction, and California Bearing Ratio (CBR).

The pozzolanic qualities of plantain peel ash (PPA), an agro-waste byproduct high in silica and alumina, have drawn attention because they help stabilize soil by creating cementitious compounds. According to studies, PPA is a feasible environmentally friendly stabilizer because it lowers the plasticity index and increases the compressive strength of lateritic soils when used in part as a substitute for cement (Osinubi et al., 2021). The formation of calcium silicate hydrates (C-S-H) that enhance particle bonding is the reason why researchers discovered that PPA increases the California Bearing Ratio (CBR) of lateritic soils, with the best results occurring at a PPA content of 4–6% (Adeboje et al., 2022).

A nanomaterial with a large surface area and high reactivity, nano-silica (NS), has demonstrated great promise for stabilizing soil. By filling in gaps and encouraging cementitious reactions, its pozzolanic nature and fine particle size increase soil strength and decrease plasticity. Studies claim that adding NS in small amounts (1–3%) considerably raises the lateritic soils' Maximum Dry Density (MDD) and CBR while lowering their Optimum Moisture Content (OMC) (Olawuyi and Alhassan, 2021). This is because NS can speed up pozzolanic reactions and improve particle packing. Similarly, researchers found that NS improves workability and stability under a range of moisture conditions by reducing the lateritic soils' plasticity index by as much as 40% ((Akinmusuru et al., 2022).

Although less research has been done, there may be synergistic effects when agro-waste and nanomaterials are combined. By utilizing the pozzolanic qualities of both materials, the blend maximizes soil stabilization, according to investigations into the combined use of agricultural waste ash and nanomaterials (Bello et al., 2021). According to the study, these combinations are appropriate for sustainable pavement construction because they can produce higher CBR values and less plasticity than single stabilizers. Researchers also highlighted the effectiveness of the Taguchi Design of Experiment in determining the best mix ratios for lateritic soil improvement, minimizing experimental trials, and optimizing stabilizer proportions (Rahman et al., 2022).

There are still issues with scaling up the use of PPA and NS in spite of these developments. The practical application of nanomaterials may be limited by their high cost and the variability in the chemical composition of agro-waste ash (Nnochiri and Ogundipe, 2020). To make sure these stabilizers are practical for large-scale projects, more research is also needed to determine their long-term durability and environmental effects (Adeboje et al., 2022). However, combining PPA and NS provides a sustainable way to enhance lateritic soils' geotechnical qualities, supporting international initiatives to lessen the environmental impact of building.

2. MATERIALS AND METHOD

In order to prevent contamination from organic matter, roots, or surface debris, soil samples were taken from Ibienafe, Edo State, Nigeria, at a depth of roughly 1.2 meters below the natural ground surface. The material was guaranteed to be representative of the lateritic subsurface layer, which is frequently utilized in the area for geotechnical applications, thanks to this sampling depth. The location was chosen because it was easily accessible, had a lot of lateritic deposits, and was pertinent to nearby building projects. Before being calcined, plantain peels were gathered, thoroughly cleaned to get rid of contaminants, and allowed to air dry. The open burning method was used for the calcination. The starting temperature was 43 °C, and the temperature of the burning fire peaked at about 1010 °C. The peels were burned directly throughout the procedure until they turned entirely to ash.

The calcined material's temperature was recorded at 668 °C right after burning and was then left to cool gradually in the surrounding air. The temperature decreased gradually over the following cooling times: 20 minutes (498 °C), 40 minutes (425 °C), 60 minutes (339 °C), 80 minutes (296 °C), 100 minutes (283 °C), and 120 minutes (206 °C). It took around 24 hours for it to completely cool and turn into ash.

To obtain the Plantain Peel Ash (PPA) used in the soil stabilization study, the resultant ash was then gathered, ground into a fine powder, and sieved through a 75 μm sieve. A certified chemical supplier in Lagos provided the finely powdered nano-silica. As air drying is preferred over oven drying to prevent changes in clay minerals, the collected soil samples were allowed to air dry at room temperature in order to maintain the soil's natural particle structure and chemical composition (Osinubi et al., 2021). To ensure uniform particle size and break down aggregates, the dried soil was manually ground. The material was made to meet the particle size requirements for laboratory tests, especially compaction and Atterberg limits tests, which concentrate on the fine fraction of the soil, by passing the ground sample through a 2 mm sieve to remove coarse fragments. To find the mix proportions, a trial-and-error approach was used. Six compositions were made by altering the ratios of plantain peel ash (PPA) and nano-silica (NS), along with a control sample devoid of stabilizers. As shown in Table 1, the chosen ratios were intended to capture the effects of PPA and NS on the soil properties, both separately and in combination.

Table 1: Mix Proportions of Plantain Peel Ash (PPA) and Nano-Silica (NS) Used for Soil Stabilization

Mix ID	PPA (%)	NS (%)	Description
Control	0	0	Untreated soil
Mix 1	2.5	0	PPA only
Mix 2	5.0	0	PPA only
Mix 3	0	2.5	NS only
Mix 4	5.0	2.5	PPA + NS
Mix 5	0	5.0	NS only

To guarantee uniform geotechnical characterization, all laboratory tests were carried out in compliance with BS EN soil testing standards and BS 1377: Part 2–4 (1990) (BS, 1990a, b). To reduce experimental error and improve the reliability of the results, the following tests were conducted on the prepared soil samples, each in triplicate. All laboratory equipment was calibrated in compliance with BS EN ISO/IEC 17025 standards to guarantee measurement accuracy (BS, 2005). The tests that followed were then conducted: The mass of soil solids divided by the mass of an equivalent volume of water is known as specific gravity, and it affects compaction and strength behavior. To determine the soil's particle size distribution and classify it using the Unified Soil Classification System (USCS), sieve analysis was carried out. To measure soil plasticity and its behavior under different moisture conditions, Atterberg limits (liquid limit, plastic limit, and plasticity index) were established. The optimum moisture content (OMC) and maximum dry density (MDD), which are essential for effective compaction, were determined using the Standard Proctor Compaction Test. Finally, the strength of the soil for possible use in base layers and pavement subgrades was assessed using the California Bearing Ratio (CBR) test, a crucial prerequisite for road construction applications.

3. RESULTS AND DISCUSSION

3.1 Specific Gravity

As the ratio of the unit weight of soil solids to that of water, specific gravity (Gs) is a basic geotechnical property that represents the density and mineral composition of the soil and affects compaction, strength, and void ratio (BS, 1990a). Gs normally falls between 2.50 and 2.80 for lateritic and clayey soils; lower values imply organic matter, while higher values show the presence of heavy minerals like iron oxides (Gidigasu, 2004; Okunade, 2008). Lateritic soils from Ibienafe, Edo State, Nigeria, both treated and untreated, were investigated in this study. Location B was specifically chosen as a representative site among the three. For Locations A, B, and C, the untreated soils showed Gs values of 2.56, 2.54, and 2.55, respectively. These values are all within the anticipated range of 2.50 to 2.80. According to these findings, the mineralogy is uniform, contains a moderate amount of iron oxide, and has very little organic matter. The use of Location B as the reference soil for stabilization studies is supported by the consistency across locations (Ola, 1983; Bewaji et al., 2025). Table 2 displays the different trends that the treated samples displayed.

Table 2: Specific Gravity Values for Untreated and Treated Soil

Sample	Stabilizer	Specific Gravity (Gs)	Design Recommendation
Untreated (A)	None	2.56	Suitable for stabilization
Untreated (B)	None	2.54	Suitable for stabilization, representative
Untreated (C)	None	2.55	Suitable for stabilization
Sample 1	2.5% PPA	2.45	Reduced density, needs activation
Sample 2	5.0% PPA	2.45	Limited benefit, needs activation
Sample 3	2.5% NS	2.53	Maintains density, good for subgrade
Sample 4	5.0% PPA + 2.5% NS	2.45	PPA-dominated, needs activation

Sample 5	5.0% NS	2.60	Best density, ideal for structural use

Treated Soil (Location B):

i. **Sample 1 (2.5% PPA)**: Because of the lightweight PPA particles (such as unburned carbon), which reduce density, the Gs of 2.45 is lower than the untreated value of 2.54 (Adewuyi and Adegoke, 2008).

ii. **Sample 2 (5.0% PPA)**: Gs remained at 2.45, showing no improvement, which agrees with findings that higher agro-ash contents without activation give limited benefit (Elinwa and Ejeh, 2004).

iii. **Sample 3 (2.5% NS)**: Gs of 2.53, close to untreated soil, indicates NS maintained density while improving reactivity, as noted by researchers (Olawuyi and Alhassan, 2021).

iv. **Sample 4 (5.0% PPA + 2.5% NS)**: The low Gs of 2.45 suggests PPA dominated the blend, similar to findings on agro-ash–nanomaterial mixes (Bello et al., 2021).

v. **Sample 5 (5.0% NS)**: The highest Gs of 2.60 reflects NS densification through C-S-H gel formation, aligning with studies (Akinmusuru et al., 2022).

Design Implications: Compaction energy, void ratio, and unit weight are all impacted by Gs. Reduced density and the possibility of a lower Maximum Dry Density (MDD) are indicated by lower Gs in PPA-treated samples (1, 2, 4), necessitating cement or lime for pozzolanic activation. Greater matrix densification is indicated by higher Gs in NS-treated samples (3,5), which enhances strength and pavement application suitability.

3.2 Sieve Analysis

Sieve analysis, carried out in accordance with BS 1377: Part 2 (1990), establishes the soils' particle size distribution, which is essential for evaluating their strength, drainage, and construction suitability (BS, 1990a). In order to help with soil classification (such as USCS) and behavior prediction under load and moisture conditions, the test entails passing soil through sieves of decreasing sizes and calculating the percentage passing. While well-graded soils provide better compaction and stability, fine-grained soils (>50% passing 0.075 mm sieve) usually have low permeability and high-volume change potential, necessitating stabilization for pavement use (Gidigasu, 2004; Adeboje et al., 2022). Untreated lateritic soils from Locations A, B, and C in Ibienafe, Edo State, Nigeria, were examined in this study.

Table 3: Sieve Analysis Values for Untreated

Location	% Passing (0.075 mm)	USCS Classification	Design Recommendation
Location A	85.09	CL – Lean Clay	Fine-grained, needs stabilization
Location B	85.13	CL – Lean Clay	Fine-grained, needs stabilization
Location C	84.36	CL – Lean Clay	Fine-grained, needs stabilization

Location A: As shown in Table 3, the soil was classified as fine-grained (silt/clay) based on sieve analysis, which showed 100% passing for sieves ≥5.00 mm and 85.09% passing the 0.075 mm sieve. Poor particle interlocking and compaction are suggested by the steady decline in passing percentage, which denotes uniform grading (Gidigasu, 2004). This soil is not suitable for pavement subgrade without stabilization due to its high fine content, which suggests poor drainage, low shear strength, and susceptibility to volume changes (TRRL Road Note 31, 1977).

Location B: In a similar vein, 85.13% of samples passed the 0.075 mm sieve, confirming fine-grained classification (lean clay, CL), while 100% passed sieves ≥5.00 mm. Limited particle size variation is indicated by the uniform grading pattern, which results in poor compaction and structural stability under load. The high fine content of the soil indicates low CBR and moisture sensitivity, necessitating chemical stabilization for pavement applications (Adeboje et al., 2022).

Location C: According to the results, the soil was classified as fine-grained (lean clay, CL) with 100% passing the sieves ≥5.00 mm and 84.36% passing the 0.075 mm sieve. Uniform grading with inadequate compaction and interlocking characteristics is reflected in the steady, progressive decline in the passing percentage. Stabilization is required to improve strength and durability because this soil is prone to deformation and swelling/shrinkage under traffic loads (TRRL Road Note 31, 1977).

Engineering Significance: More than 84% of the fine-grained soils in all three sites pass through the 0.075 mm sieve, suggesting low permeability, inadequate drainage, and a high potential for volume change. These soils cannot be used directly in pavement subgrades or sub-bases without stabilization because uniform grading reduces compaction efficiency and load-bearing capacity (TRRL Road Note 31, 1977; Gidigasu, 2004; Adeboje et al., 2022). For dependable road construction, chemical treatments are necessary to increase CBR, strength, and moisture resistance.

3.3 Atterberg Limit

According to BS 1377: Part 2 (1990), the Atterberg limits which include Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI = LL - PL) are essential for evaluating the workability, volume change potential, and plasticity of fine-grained soils (BS, 1990a). Compaction, strength, and appropriateness for pavement subgrades are all influenced by these characteristics. Better stability and less swelling/shrinkage are indicated by lower PI values, which are desirable in pavement design according to AASHTO and USCS standards (Seed et al., 1962; TRRL Road Note 31, 1977; Adeboje et al., 2022). In this study, lateritic soils from Ibienafe, Edo State, Nigeria, were examined in both untreated and stabilized conditions, with a focus on treated samples from Location B (Table 4).

Untreated Soil: The untreated soils from Locations A, B, and C were classified as CL (Lean Clay) with low to medium plasticity based on their Atterberg limits, which showed LL of 23.00–24.00%, PL of 10.98–12.42%, and PI of 11.58–12.02% (Table 4). According to AASHTO and USCS standards, soils within this PI range exhibit moderate workability but are prone to volume change under moisture fluctuations, making stabilization necessary for improved pavement performance (TRRL Road Note 31, 1977; Adeboje et al., 2022). Similar PI values and the associated need for stabilization of lateritic soils were also reported by researchers (BS, 2005; Osinubi et al., 2021). Stabilization testing on Location B is supported by the consistent PI across locations, which indicates uniform mineralogy.

Table 4: Atterberg Limits of Untreated and Treated Soil

Sample	Stabilizer	LL (%)	PL (%)	PI (%)	USCS Classification	Design Recommendation
Untreated (A)	None	23.00	10.98	12.02	CL – Lean Clay	Subgrade, needs stabilization
Untreated (B)	None	24.00	12.42	11.58	CL – Lean Clay	Subgrade, needs stabilization
Untreated (C)	None	23.00	11.13	11.87	CL – Lean Clay	Subgrade, needs stabilization
Sample 1	2.5% PPA	24.01	17.12	6.89	CL – Lean Clay	Improved stability, subgrade use
Sample 2	5.0% PPA	23.71	16.38	7.33	CL – Lean Clay	Limited benefit, subgrade use
Sample 3	2.5% NS	17.08	12.37	4.71	CL – Lean Clay	Best stability, ideal for subgrade
Sample 4	5.0% PPA + 2.5% NS	16.11	9.38	6.73	CL – Lean Clay	High stability, eco-efficient subgrade
Sample 5	0.0% PPA, 5.0% NS	21.00	14.39	6.61	CL – Lean Clay	Good stability, subgrade use

Treated Soil (Location B):

i. **Sample 1 (2.5% PPA)**: LL = 24.01%, PL = 17.12%, PI = 6.89%. PPA reduced PI from 11.58% (untreated) by binding water and clay particles, which improved stability. Similar PI reduction effects of agro-ash were reported by researchers (Seed et al., 1962; Bello et al., 2021).

ii. **Sample 2 (5.0% PPA)**: LL = 23.71%, PL = 16.38%, PI = 7.33%. A higher PPA dosage showed limited further PI reduction, likely due to unreactive filler effects. This aligns with findings that excess agro-ash without activators contributes little to additional plasticity reduction (Elinwa and Ejeh, 2004).

iii. **Sample 3 (2.5% NS)**: LL = 17.08%, PL = 12.37%, PI = 4.71%. NS achieved the lowest PI, enhancing stability through micropore filling and strong surface interactions. Comparable outcomes were reported by researchers (Olawuyi and Alhassan, 2021).

iv. **Sample 4 (5.0% PPA + 2.5% NS)**: LL = 16.11%, PL = 9.38%, PI = 6.73%. The combination leveraged NS's water regulation and PPA's pozzolanic reactivity, resulting in reduced plasticity. Researchers similarly observed that agro-ash and nanomaterial blends synergistically improve soil plasticity and workability (Bello et al., 2021).

v. **Sample 5 (5.0% NS)**: LL = 21.00%, PL = 14.39%, PI = 6.61%. A higher NS dosage maintained low PI but was less effective than Sample 3 due to potential particle agglomeration. Researchers also noted that excessive NS can reduce dispersion efficiency, lowering its effectiveness (Akinmusuru et al., 2022).

Engineering Significance: According to TRRL Road Note 31 (1977), pavement subgrade suitability is indicated by a lower PI (<10%). Samples 3, 4, and 5 demonstrated the highest stability, while all treated samples had PIs below 10%. The most successful samples were Sample 3 (2.5% NS) and Sample 4 (combined stabilizers), which improved workability and compaction energy efficiency while lowering volume instability.

3.4 Compaction

Compaction testing (Table 5), carried out in accordance with BS 1377: Part 4 (1990), assesses the soils' Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), which are crucial for figuring out the pavement design's strength, permeability, and resistance to deformation (BS, 1990b). Utilizing Plantain Peel Ash (PPA) and Nano-Silica (NS) as stabilizers, this study evaluated both untreated and treated lateritic soils from Ibienafe, Edo State, Nigeria, with a focus on Location B for treated samples

Table 5: Compaction Test Results (OMC and MDD)

Sample	Stabilizer	OMC (%)	MDD (g/cm³)	Design Recommendation
Untreated (A)	None	11.03	1.90	Suitable for subgrade; needs stabilization
Untreated (B)	None	14.16	1.85	Suitable for subgrade; needs stabilization
Untreated (C)	None	12.38	1.88	Suitable for subgrade; needs stabilization
Sample 1	2.5% PPA	15.39	1.83	Marginal benefit, subgrade use
Sample 2	5.0% PPA	18.54	1.82	Poor compaction, avoid use
Sample 3	2.5% NS	14.56	1.80	Good for subgrade, efficient water use
Sample 4	5.0% PPA + 2.5% NS	18.13	1.79	Best strength despite lower MDD
Sample 5	5.0% NS	16.25	1.78	Subgrade use, challenging compaction

Untreated Soil: For untreated soils from Locations A, B, and C, compaction results revealed OMC values of 11.03–14.16% and MDD values of 1.85–1.90 g/cm³. Location B had the lowest MDD (1.85 g/cm³) at the highest OMC (14.16%), indicating a higher clay content or plasticity, while Location A had the highest MDD (1.90 g/cm³) at the lowest OMC (11.03%). Although these MDD values (>1.80 g/cm³) are appropriate for subgrade applications, moderate CBR and plasticity indices show that stabilization is required to improve load-bearing capacity and moisture resistance.

Treated Soil (Location B):

i. **Sample 1 (2.5% PPA)**: MDD = 1.83 g/cm³, OMC = 15.39%. Slightly worse than untreated soil (1.85 g/cm³, 14.16%), due to lightweight, water-absorbing PPA particles. Similar findings were reported by researchers where agro-ash increased OMC while reducing density (Osinubi et al., 2021).

ii. **Sample 2 (5.0% PPA)**: MDD decreased to 1.82 g/cm³ with a high OMC of 18.54%, showing reduced compaction efficiency due to excessive fines and voids, consistent with studies (Adewuyi and Adegoke,2008)

iii. **Sample 3 (2.5% NS)**: MDD = 1.80 g/cm³, OMC = 14.56%. Values close to untreated soil, showing NS improved water use efficiency with minimal density loss. Researchers also reported that NS improves compaction by filling micropores (Olawuyi and Alhassan, 2021).

iv. **Sample 4 (5.0% PPA + 2.5% NS)**: MDD = 1.79 g/cm³, OMC = 18.13%. Increased water demand due to PPA and NS activity. Despite lower MDD, superior CBR (48.55%) suggests stronger bonding. Researchers likewise found that ash–nano blends enhance strength despite reduced density (Bello et al., 2021)

v. **Sample 5 (5.0% NS)**: MDD = 1.78 g/cm³, OMC = 16.25%. Reduced density likely from NS agglomeration, which hinders uniform compaction. Researchers noted similar agglomeration challenges at higher NS dosages (Akinmusuru et al., 2022).

Engineering Significance: Lower OMC makes field compaction easier, while MDD is correlated with bearing capacity and settlement resistance. For subgrade use, all treated samples maintained an MDD above 1.78 g/cm³. Despite having a slightly lower MDD, Sample 4 offers the best mechanical performance because of synergistic PPA-NS bonding, while Samples 1 and 3 have good compaction properties (high MDD, moderate OMC). Because of their low density or high water demand, samples 2 and 5 are less effective.

3.5 California Bearing Ratio (CBR)

In order to determine the thickness of the pavement layer in flexible pavement design, the California Bearing Ratio (CBR) test assesses the soils' resistance to penetration under a standardized plunger force (Table 6). The CBR value is determined by taking the higher of the 2.5 mm or 5.0 mm penetration results, as per BS 1377: Part 4 (1990) (BS, 1990b). AASHTO and TRRL Road Note 31 (1977) state that CBR values categorize soils as follows: 80% (excellent, base course) [20]. Plantain Peel Ash (PPA) and Nano-Silica (NS) were used as stabilizers in this study to evaluate untreated and stabilized lateritic soils from Ibienafe, Edo State, Nigeria. The results were compiled for five samples.

Table 6: California Bearing Ratio (CBR)

Sample	Stabilizer	CBR (%)	Use Class	Design Recommendation
Untreated	None	36.35	Subgrade (low traffic)	Suitable for low-traffic roads; needs drainage
Sample 1	2.5% PPA	34.09	Subgrade (low traffic)	Not economical, low gain
Sample 2	5.0% PPA	31.05	Barely subgrade	Avoid use, performance decline
Sample 3	2.5% NS	36.21	Subgrade (light-med)	Good low-dose option
Sample 4	5.0% PPA + 2.5% NS	48.55	Subbase (light traffic)	Best performance, eco-efficient
Sample 5	5.0% NS	39.47	Subgrade/light subbase	Robust for moisture-sensitive areas

Untreated Soil (Control): With a CBR of 36.35% (5.0 mm), the untreated soil demonstrated a moderate strength appropriate for subgrade use in low-traffic roads (such as estate streets, <1000 ESALs). The soil's performance is attributed to its low plasticity, kaolinite and quartz content, and natural compaction; however, without stabilization, it remains prone to moisture-induced weakening. For long-term durability, thicker pavement layers or improved drainage are required (Ola,1983; Gidadisu, 2004;Osinubi et al, 2021).

Sample 1 (2.5% PPA): This sample's CBR of 34.09% (2.5 mm) was barely better than the control's (36.35%). Due to its high carbon content (8.63%) and limited pozzolanic activity, the low PPA dosage was unable to produce sufficient cementitious compounds such as calcium silicate hydrate (C–S–H), thereby functioning more as a filler than as a stabilizer (Elinwa and Ejeh, 2004; Adewuyi and Adegoke, 2008; Osinubi et al, 2021). Although it has no mechanical or financial advantages, it is still appropriate for low-traffic subgrade.

Sample 2 (5.0% PPA): Compared to the control, this sample's CBR of 31.05% (5.0 mm) showed decreased strength. Overuse of PPA increased porosity and decreased compaction efficiency by introducing non-reactive fines, which disrupt soil particle packing and reduce density (Elinwa and Ejeh, 2004; Adewuyi and Adegoke, 2008; Bello et al., 2021). The high carbon residue (5.75%) prevented bonding in the absence of cement or lime activation, rendering this mix unsuitable for pavement applications.

Sample 3 (2.5% NS): Through matrix densification and early C–S–H formation, this sample achieved a CBR of 36.21% (2.5 mm), which was comparable to the untreated control. Similar improvements in CBR due to pozzolanic reaction and matrix densification have been reported by researchers(Osinubi, 1998; Olawuyi and Alhassan, 2021; Akinmusuru et al., 2022). Nano-silica can be used to improve subgrades in areas that are sensitive to moisture because its high surface area enhances particle packing and moisture control (Yadav and Tiwari, 2019; Olawuyi and Alhassan, 2021; Akinmusuru et al., 2022). For light to medium-traffic roads, it provides an affordable substitute for lime.

Sample 4 (5.0% PPA + 2.5% NS): With a CBR of 48.55% (5.0 mm), this sample outperformed the control by 33%. A dense, cohesive matrix with C–S–H bonds was created by the combined action of nano-silica's rapid pozzolanic activity and the silica/alumina contribution from plantain peel ash (Bello et al., 2021; Olawuyi and Alhassan, 2021;Akinmusuru et al., 2022). By using agro-waste and nanomaterials, eco-efficient design is promoted while dependency on cement is reduced, making the stabilized soil suitable for use in subbase layers of light-traffic roads (up to 5000 ESALs) (Ghavami et al., 2019; Yadav and Tiwari, 2019; Bello et al., 2021)

Sample 5 (5.0% NS): The micro-filling and pozzolanic effects of nano-silica enabled this sample to outperform the control by 8.6%, achieving a CBR of 39.47% (2.5 mm). This improvement in density and cohesiveness makes it suitable for light subbase or premium subgrade applications, particularly in moisture-prone areas (Yadav and Tiwari, 2019; Olawuyi and Alhassan, 2021). However, it does not provide the long-term strength gain exhibited by the hybrid mix in Sample 4, where synergistic stabilization effects were observed (Bello et a., 2021).

4. CONCLUSION

The following conclusions can be made from the research:

i. Specific gravity (2.54–2.56), fine-grained composition (84.36–85.13% passing 0.075 mm sieve, classified as lean clay, CL), moderate plasticity (PI 11.58–12.02%), and compaction characteristics (MDD 1.85–1.90 g/cm³, OMC 11.03–14.16%) were among the consistent geotechnical properties of the untreated soils from Locations A, B, and C. Their CBR values ranged from 35.80% to 36.35%, indicating suitability for low-traffic subgrades but showing the need for stabilization to meet TRRL Road Note 31 standards for durability and load-bearing capacity (TRRL Road Note 31, 1977). Owing to this homogeneity among the three locations, Location B was selected for stabilization tests to ensure representative results.

ii. PPA-only stabilization (2.5% and 5.0%) decreased specific gravity (2.45), compaction efficiency (MDD 1.82–1.83 g/cm³, OMC 15.39–18.54%), and CBR (31.05–34.09%), suggesting that the lightweight, unreactive ash particles only partially improved the situation and that more cement or lime was required for pozzolanic activation.

iii. On the other hand, NS (2.5% and 5.0%) improved CBR (36.21–39.47%), decreased plasticity (PI 4.71–6.61%), and increased density (Gs 2.53–2.60). It also showed superior stabilization through micro-filling and dense C-S-H gel formation, which made it appropriate for subgrade and light subbase applications.

iv. With the highest CBR (48.55%), effective compaction (MDD 1.79 g/cm³, OMC 18.13%), and low plasticity (PI 6.73%), the combination of 5.0% PPA and 2.5% NS proved to be ideal for subbase in light-traffic roads.

v. These results demonstrate NS's potential as a very powerful stabilizer and the eco-efficiency of using NS in conjunction with PPA to improve soil performance and repurpose agro-waste.

vi. In addition to meeting pavement design specifications, the combined stabilizer provides a sustainable and affordable substitute for conventional cement and lime.

In order to validate these laboratory results for large-scale road construction in tropical regions, future studies should concentrate on long-term durability, cost scalability, and field implementation.

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