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Effect of Atili Shell Ash on the Geotechnical Properties of Lateritic Soil

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ABSTRACT

The use of agricultural waste materials as soil stabilizers continues to attract attention for its economic and environmental benefits. This study investigated the effect of Atili shell ash (ASA) -- an agro-waste pozzolan derived from the shells of Canarium schweinfurthii (African elemi) -- on the index, gradation and compaction properties of a lateritic soil, with a view to its use as a sustainable, low-cost stabilizer. Lateritic soil obtained from Shika, Zaria, Kaduna State, Nigeria, was treated with 0, 4, 8, 12 and 16% ASA by dry weight of soil. The natural soil classified as A-7-6 (GI = 12) under AASHTO and CL under USCS, with 64.00% fines, a liquid limit of 47.00%, a plastic limit of 27.30%, a plasticity index of 19.70%, and a specific gravity of 2.61. Oxide analysis showed ASA to be a silica-rich pozzolan (57.2% SiO_2, with SiO_2 + Al_2O_3 + Fe_2O_3 exceeding 70%) and only marginally calcareous (1.78% CaO), indicating a slower, silica-driven pozzolanic mechanism rather than the rapid calcium-based cation exchange typical of lime- or cement-type stabilizers. Incorporation of ASA progressively coarsened the soil gradation, with the fines fraction falling from 3.15% to 1.14% under British Standard Light (BSL) compaction and from about 2.40% to 1.21% under West African Standard (WAS) compaction over the 0-16% ASA range. The specific gravity decreased slightly from 2.61 to 2.58 at 16% ASA. The liquid limit rose from 44.50% to a peak of 48.02% at 12% ASA before falling to 46.54% at 16% ASA, while the plastic limit fell from 25.00% to a minimum of 22.14% at 4% ASA. The plasticity index increased to a maximum of 25.54% at 8% ASA before reducing to 23.40% at 16% ASA. Maximum dry density decreased consistently with ASA content, from 1.60 to 1.55-1.57 Mg/m³ (BSL), 1.68 to 1.63-1.64 Mg/m³ (WAS), and 1.73 to 1.68-1.69 Mg/m³ (BSH), while optimum moisture content increased correspondingly, from 16.60% to 17.77% (BSL), 15.70% to 16.45% (WAS), and 14.64% to 15.41% (BSH). These results show that ASA modifies lateritic soil primarily through particle flocculation, aggregation and progressive pozzolanic bonding rather than densification, and indicate that 4-8% ASA offers the most favourable balance of improved gradation and consistency without excessive loss of compacted density, supporting its potential as an effective, sustainable and economical soil-stabilizing material for low-volume road and embankment applications.

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INTRODUCTION

The use of industrial and agricultural by-products as soil-stabilizing agents has attracted considerable interest among geotechnical researchers because of the environmental and economic benefits they offer over conventional stabilizers such as cement and lime. Materials including fly ash, red mud, waste wood ash and cement kiln dust have been widely investigated for improving the engineering behaviour of problematic soils, with encouraging results (Gupta et al., 2024). Such waste-derived materials have been reported to reduce the swelling and shrinkage potential of expansive, dispersive and soft clay soils while enhancing strength, dry unit weight and workability, demonstrating their effectiveness as sustainable alternatives to conventional stabilization (Almuaythir et al., 2025).

Lateritic soil is a naturally occurring tropical residual soil, typically porous, vesicular and largely unstratified, and rich in iron and aluminium oxides that impart its characteristic reddish-brown colour. Because of its widespread availability and generally favourable engineering characteristics, lateritic soil is extensively used in road works, embankments and building foundations across tropical regions, including much of Nigeria. Some lateritic soils, however, exhibit high porosity, variable strength and inadequate compaction characteristics that necessitate stabilization before they can be reliably used in construction (Gupta et al., 2024).

Atili shell ash (ASA), an agricultural by-product obtained from the controlled combustion of the shells of Canarium schweinfurthii -- known locally in northern Nigeria as 'Atili' -- has recently emerged as a promising eco-friendly stabilizing material. Its utilization provides a practical outlet for an otherwise discarded agricultural residue while offering a low-cost alternative for improving soil properties (Olukotun et al., 2019). Prior work on the parent material has established that calcined Canarium schweinfurthii shell ash is a silica-rich, Class C-type pozzolan, with combined SiO_2, Al_2O_3 and Fe_2O_3 oxides exceeding 50% of its composition (Olukotun et al., 2019), a chemistry broadly similar to that reported for other agro-waste shell ashes used in soil and concrete stabilization (Almuaythir et al., 2025).

The incorporation of ASA into lateritic soil is expected to modify its particle size distribution, consistency limits, specific gravity and compaction characteristics through pozzolanic reaction and particle flocculation, mechanisms that, because ASA is silica- rather than calcium-dominant, are expected to develop more gradually than the rapid cation-exchange response typical of lime- or cement-kiln-dust-type stabilizers. Compared with conventional stabilizers, which are associated with high production costs and significant carbon dioxide emissions (International Energy Agency, 2023), ASA represents a more sustainable and environmentally friendly option, particularly relevant in developing countries such as Nigeria, where inexpensive, locally sourced stabilizing materials can meaningfully advance sustainable geotechnical practice.

While the stabilizing potential of several agro-waste shell ashes -- including eggshell, clamshell, cockle shell and oyster shell ash -- has been documented in recent literature (Almuaythir et al., 2025), the effect of Atili shell ash specifically on the geotechnical index and compaction properties of tropical lateritic soil has received little attention. This study therefore examined the particle size distribution, Atterberg limits, specific gravity and compaction characteristics of a lateritic soil treated with 0-16% ASA, with the aim of establishing the dosage range at which ASA most favourably modifies these properties for potential use in road subgrade, embankment and low-volume construction applications.

MATERIALS AND METHODS

Materials

Lateritic soil

The lateritic soil used in this study was collected as disturbed samples from a lateritic deposit at Shika, Zaria, Kaduna State, Nigeria (latitude 11°15'N, longitude 7°45'E), from a depth of approximately 1.5 m below the ground surface to minimize the influence of organic matter and surface contamination. The samples were transported to the Civil Engineering Soil

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Laboratory, Nigerian Defence Academy, Kaduna, where they were air-dried, pulverized and sieved prior to testing. The natural soil is light brown, fine-grained, dominated by kaolinite clay mineral, and classifies as CL (Unified Soil Classification System) or A-7-6 (GI = 12) under AASHTO.

Water

Potable water used for the natural moisture content, specific gravity, Atterberg limit and compaction tests was obtained from the Soil Laboratory of the Department of Civil Engineering, Nigerian Defence Academy, Kaduna.

Atili Shell Ash (ASA)

Atili shells were collected from the Crossing area of Kachia Local Government Area, Kaduna State, Nigeria. The shells were thoroughly cleaned and calcined at 700-800°C to produce Atili shell ash, which was cooled, pulverized and sieved through a 0.075 mm (No. 200) sieve to obtain a uniform particle size for stabilization. Oxide analysis of the ASA (Table 1) shows a silica-dominated composition (57.2% SiO_2), with combined SiO_2, Al_2O_3 and Fe_2O_3 oxides of about 74%, comparable to the Class C pozzolan chemistry reported for calcined Canarium schweinfurthii shell ash used in cement replacement studies (Olukotun et al., 2019). Its CaO content (1.78%) is markedly lower than that of calcium-rich stabilizers such as cement kiln dust or hydrated lime, indicating that ASA is expected to act principally as a silica-supplying pozzolan that reacts with free lime already present in the soil system, rather than as an immediate source of exchangeable calcium.

Table 1: Oxide composition of Atili shell ash

Oxide	Atili shell ash, ASA (%)
SiO_2	57.21
Al_2O_3	11.75
Fe_2O_3	5.01
CaO	1.78
MgO	11.39
MnO	0.58
Na_2O	0.013
K_2O	1.03
P_2O_5	0.23
Loss on ignition (LOI)	10.13

Natural Moisture Content

The natural moisture content of the soil was determined in accordance with BS 1377 (1990) Part 2. Three clean, pre-weighed containers (mass M_1) were filled with freshly collected, loosely crumbled soil and weighed (mass M_2), oven-dried at 105-110°C for 24 hours, and re-weighed (mass M_3). Moisture content was computed as:

$$w\ (\%) = [(M_2 - M_3) / (M_3 - M_1)] \times 100 \qquad (1)$$

and the reported value was the average of the three determinations.

Particle Size Distribution

Particle size analysis was carried out in accordance with BS 1377 (1990) Part 2 by dry sieving of 200 g samples of the natural and ASA-treated soils, prepared at the optimum moisture content corresponding to each compactive effort (BSL, WAS and BSH), to evaluate the effect of ASA on soil gradation under each compaction condition.

Specific Gravity

Specific gravity was determined using the density-bottle method described in BS 1377 (1990) Test B for fine-grained soils. The empty density bottle and stopper were weighed (m_1), oven-dried soil was introduced and the assembly weighed (m_2), sufficient water was added to cover the soil and the mixture de-aired, after which the bottle was topped up with water and weighed (m_3); the bottle was then emptied, refilled with water alone, and weighed (m_4). Specific gravity was computed as:

$$Gs = (m_2 - m_1) / [(m_4 - m_1) - (m_3 - m_2)] \qquad (2)$$

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The same procedure was repeated for all ASA-treated soils.

Atterberg limits

Liquid limit, plastic limit and plasticity index were determined for the natural and ASA-treated soils in accordance with BS 1377 (1990) Part 2, using the Casagrande cup method for liquid limit and the thread-rolling method for plastic limit. Plasticity index was computed as the difference between liquid and plastic limit.

Compaction

Compaction tests were performed on the natural and ASA-treated soils in accordance with Head (1994), BS 1377 (1990) Part 4, the Nigerian General Specification (1997) and BS 1924 (1990), using three compactive efforts: British Standard Light (BSL) -- 27 blows of a 2.5 kg rammer falling 300 mm on each of 3 layers in a 1000 cm³ mould; West African Standard (WAS) -- 10 blows of a 4.5 kg rammer falling 450 mm on each of 5 layers; and British Standard Heavy (BSH) -- 27 blows of the 4.5 kg rammer on each of 5 layers. Maximum dry density (MDD) and optimum moisture content (OMC) were obtained from the peak of the dry density-moisture content relationship for each compactive effort, with bulk and dry densities computed as:

$$\rho_b = Ms / Vs \quad (3)$$

$$\rho_d = \rho_b / (1 + w) \quad (4)$$

where Ms is the mass of compacted soil, Vs is the volume of the mould, ρ_b is bulk density, ρ_d is dry density and w is the moulding water content expressed as a fraction.

RESULTS AND DISCUSSION

Properties of the Natural Lateritic Soil

The natural lateritic soil exhibited a high fines content, with 64.00% passing the BS No. 200 sieve, confirming that the soil is predominantly fine-grained. Its natural moisture content of 16.70% reflects a moderately moist condition typical of tropical lateritic soils. The Atterberg limits -- liquid limit 47.00%, plastic limit 27.30% and plasticity index 19.70% -- indicate moderate plasticity, and the soil classifies as CL (low-plasticity clay) under the Unified Soil Classification System and A-7-6 with a group index of 12 under AASHTO, confirming its clayey character. The specific gravity of 2.61 falls within the typical range for lateritic soils dominated by iron and aluminium oxides with minimal organic matter.

A slightly alkaline pH of 7.65 and a low cation exchange capacity of 0.56 meq/100 g, consistent with a kaolinite-dominated clay fraction, complete the natural-soil characterization. Compaction behaviour followed the expected pattern, with maximum dry density increasing (1.60, 1.68 and 1.73 Mg/m³ under BSL, WAS and BSH compaction respectively) and optimum moisture content decreasing (16.60%, 15.70% and 14.64%) with increasing compactive effort, reflecting more effective particle rearrangement and void reduction at higher compaction energy.

Table 2: Properties of the natural lateritic soil

Property	Quantity
Percentage passing BS No. 200 sieve (%)	64.00
Natural moisture content (%)	16.70
Liquid limit, LL (%)	47.00
Plastic limit, PL (%)	27.30
Plasticity index, PI (%)	19.70
Specific gravity	2.61
USCS classification	CL
AASHTO classification	A-7-6 (GI = 12)
pH	7.65
CEC (meq/100 g)	0.56
MDD - BSL / WAS / BSH (Mg/m³)	1.60 / 1.68 / 1.73
OMC - BSL / WAS / BSH (%)	16.60 / 15.70 / 14.64
Colour	Light brown
Dominant clay mineral	Kaolinite

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Effect of Atili Shell Ash on Particle Size Distribution

Using OMC of British Standard Light (BSL) compaction

The particle size distribution curves for the soil treated with 0, 4, 8, 12 and 16% ASA, prepared at the OMC corresponding to BSL compaction, are shown in Figure 1. A progressive reduction in the fines fraction was observed with increasing ASA content, from 3.15% in the untreated soil to 2.40%, 2.12%, 1.54% and 1.14% at 4, 8, 12 and 16% ASA respectively. This coarsening trend indicates that ASA promotes flocculation and agglomeration of the clay and silt fractions into larger aggregates, consistent with pozzolanic interaction between the ash and the soil particles. Once hydrated, ASA particles act as nucleation sites that draw fine particles together, and this effect intensifies as ASA content increases, progressively reducing the proportion of free fines within the soil matrix. Similar gradation improvements through particle aggregation have been reported for other agro-waste ashes used in soil stabilization (Almuaythir et al., 2025).

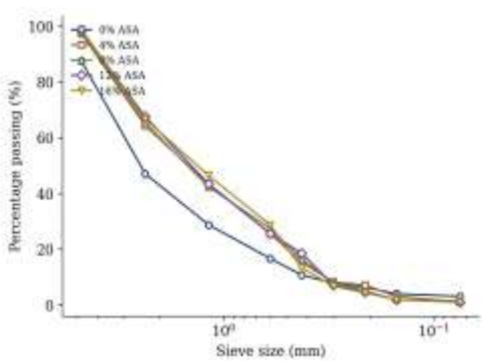

Fig. 1: Particle size distribution curves for soil treated with ASA (BSL compaction energy)

Using OMC of West African Standard (WAS) compaction

The corresponding particle size distribution curves under WAS compaction are presented in Figure 2. As under BSL compaction, the fines content decreased progressively with ASA addition, from approximately 2.40% in the untreated soil to about 1.21% at the highest ASA content, confirming that the aggregation mechanism observed under BSL compaction persists across compactive efforts. The slightly lower starting fines fraction relative to the BSL condition (2.40% versus 3.15%) reflects the influence of the higher compaction energy and correspondingly lower moulding water content associated with WAS compaction on the as-tested gradation.

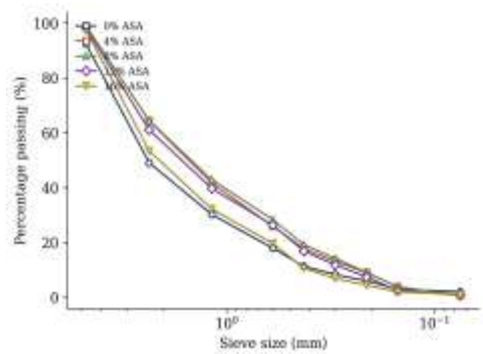

Fig. 2: Particle size distribution curves for soil treated with ASA (WAS compaction energy)

Using OMC of British Standard Heavy (BSH) compaction

Under BSH compaction (Figure 3), increasing ASA content again modified the soil gradation by promoting particle aggregation, with the clearest divergence among the curves occurring in the intermediate sieve range, around 1.18 mm and 600 µm, rather than at the fines end of the distribution. Changes in the coarse fraction were comparatively modest. The higher compactive energy associated with BSH compaction appears to enhance particle rearrangement during moulding, so that the effect of ASA addition is expressed more as a redistribution of the intermediate size fractions than as a further reduction of the already-low fines content at this compactive effort. This is consistent with the general pattern reported for pozzolanic agro-waste ashes, where higher compaction energy amplifies particle bonding and structural rearrangement (Almuaythir et al., 2025).

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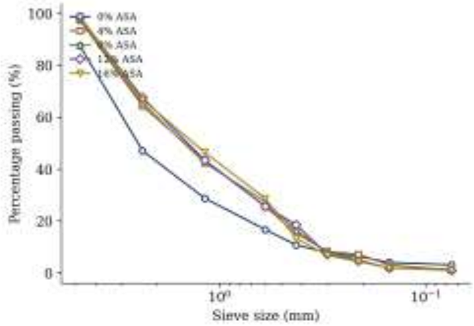

Fig. 3: Particle size distribution curves for soil treated with ASA (BSH compaction energy)

Atterberg limits

Liquid Limit

The variation of liquid limit with ASA content is shown in Figure 4. Liquid limit increased from 44.50% in the untreated soil to 47.12%, 47.68% and a peak of 48.02% at 4, 8 and 12% ASA respectively, before declining slightly to 46.54% at 16% ASA. This initial rise is consistent with the introduction of fine, water-absorbent ash particles into the soil matrix, which increases the overall surface area and water demand of the soil-ash blend before pozzolanic bonding becomes fully established. As ASA content increased further, calcium and other reactive ions released from the ash progressively promoted flocculation of the clay fraction, reducing the thickness of the diffuse double layer around clay particles and thereby lowering their affinity for water, which accounts for the modest decline in liquid limit beyond 12% ASA.

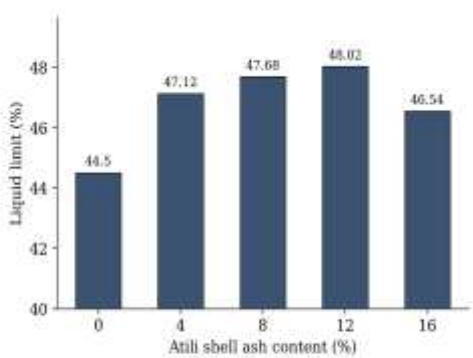

Fig. 4: Variation of liquid limit with ASA content

Plastic Limit

The plastic limit (Figure 5) decreased from 25.00% in the untreated soil to a minimum of 22.14% at 4% ASA, before rising slightly and stabilizing between 22.95% and 23.14% at 8-16% ASA. The initial reduction is attributable to early cation exchange and flocculation reactions, which lower the thickness of the adsorbed water layer surrounding clay particles so that less moisture is required for the soil to reach a plastic state. The subsequent slight recovery and stabilization of the plastic limit at higher ASA contents suggests that, once initial flocculation is complete, further ash addition contributes comparatively little additional change to the plastic-state water demand of the soil-ash mixture.

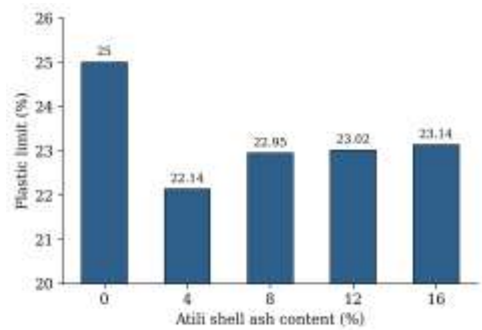

Fig. 5: Variation of plastic limit with ASA content

Plasticity Index

The plasticity index (Figure 6) followed a non-linear trend, rising from 19.50% in the untreated soil to a maximum of 25.54% at 8% ASA, before declining to 25.00% and 23.40% at 12% and 16% ASA respectively. Since plasticity index is the difference between liquid and plastic limit, this initial increase reflects the liquid limit rising faster than the plastic limit over the 0-8% ASA range; as ASA content increases further, more complete pozzolanic reaction and the associated formation of cementitious products act to suppress plasticity, producing the decline observed at 12-16% ASA.

This pattern -- an early increase in plasticity followed by a gradual reduction as stabilizer content rises -- has also been reported for other silica-rich agro-waste ashes, where the

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balance between early ion exchange and progressively developing pozzolanic bonding governs the net effect on soil consistency (Almuaythir et al., 2025).

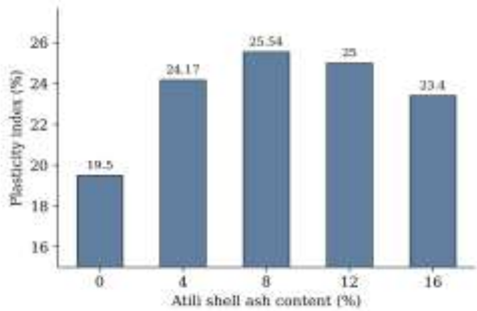

Fig. 6: Variation of plasticity index with ASA content

Specific Gravity

The specific gravity of the soil (Figure 7) decreased gradually and consistently with ASA content, from 2.61 in the untreated soil to 2.60, 2.59, 2.59 and 2.58 at 4, 8, 12 and 16% ASA respectively. This behaviour reflects the substitution of relatively dense soil mineral particles by the lighter, more porous and partially combusted particles that make up the ash, a mechanism consistent with that reported for other pozzolanic agricultural ashes used in soil stabilization (Gupta et al., 2024; Almuaythir et al., 2025). The magnitude of the reduction is modest, indicating that ASA modifies soil structure principally through particle flocculation, aggregation and cementitious bonding rather than through any significant change in the intrinsic density of the soil solids.

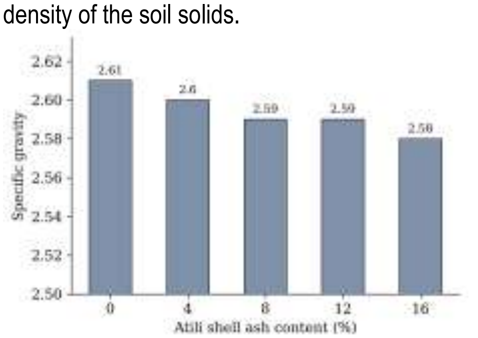

Fig. 7: Variation of specific gravity with ASA content

Compaction Characteristics

Maximum Dry Density

The variation of maximum dry density (MDD) with ASA content under the three compactive efforts is shown in Figure 8. A general decline in MDD was observed with increasing ASA content across all three compaction conditions: under BSL compaction, MDD fell from 1.60 Mg/m³ in the untreated soil to a minimum of 1.55 Mg/m³ at 12% ASA, before recovering slightly to 1.57 Mg/m³ at 16% ASA; under WAS compaction, MDD decreased from 1.68 to 1.63-1.64 Mg/m³ over the same range; and under BSH compaction, it declined from 1.73 to 1.68-1.69 Mg/m³. This reduction is consistent with the replacement of relatively dense soil mineral particles by lighter, more porous ash particles, which lowers the overall dry density of the soil-ash mixture even as gradation and consistency properties improve (Gupta et al., 2024). The modest recovery in MDD observed at the highest ASA content under BSL compaction may reflect improved particle interlocking and the onset of more substantial cementitious bonding at this lighter compactive effort, which partially offsets the density-reducing effect of the lighter ash particles.

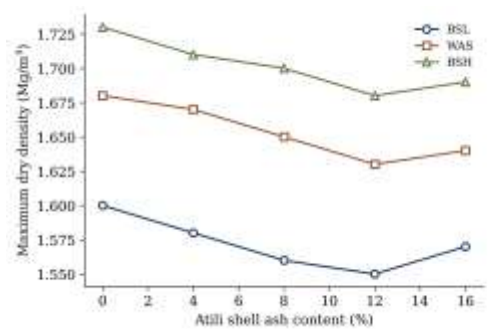

Fig. 8: Variation of maximum dry density with ASA content for BSL, WAS and BSH compactive efforts

Optimum Moisture Content

The corresponding optimum moisture content (OMC) results are shown in Figure 9. OMC increased with ASA content under all three compactive efforts, from 16.60% to 17.77% under BSL compaction, from 15.70% to 16.45% under

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WAS compaction, and from 14.64% to 15.41% under BSH compaction, in each case peaking before the highest ASA dosage and easing only slightly at 16% ASA. This increase in water demand is attributable primarily to the higher water absorption capacity of the porous, silica-rich ash particles relative to the soil solids they replace, together with the additional water consumed in early-stage pozzolanic reaction. The consistent, moderate rise in OMC across all three compactive efforts confirms that the influence of ASA on moisture demand is governed principally by the physical and pozzolanic character of the ash rather than by the compaction energy applied.

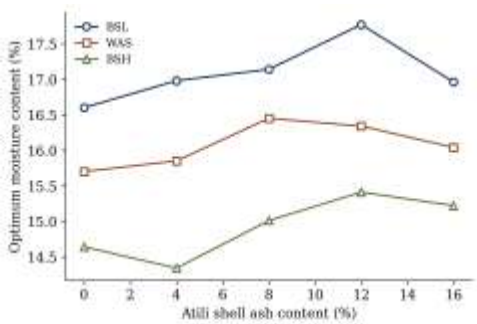

Fig. 9: Variation of optimum moisture content with ASA content for BSL, WAS and BSH compactive efforts

CONCLUSION

This study evaluated the effect of Atili shell ash (ASA), a silica-rich agro-waste pozzolan, on the particle size distribution, Atterberg limits, specific gravity and compaction characteristics of a lateritic soil from Shika, Zaria, Nigeria. The following conclusions are drawn:

1. The natural soil is a moderately plastic, fine-grained lateritic soil (CL/A-7-6, GI = 12) with 64.00% fines, a liquid limit of 47.00%, a plasticity index of 19.70% and a specific gravity of 2.61.
2. Oxide analysis showed ASA to be a silica-dominant pozzolan (57.2% SiO_2; $SiO_2 + Al_2O_3 + Fe_2O_3 \approx 74\%$) with a low CaO content (1.78%), indicating that it stabilizes the soil principally through a gradual, silica-driven pozzolanic mechanism rather than rapid calcium-based cation exchange.
3. ASA progressively coarsened the soil gradation under all three compactive efforts, reducing the fines fraction from 3.15% to 1.14% under BSL compaction and from about 2.40% to 1.21% under WAS compaction, with the effect under BSH compaction concentrated in the intermediate (1.18 mm-600 μm) sieve range.
4. Liquid limit increased from 44.50% to a peak of 48.02% at 12% ASA before declining to 46.54% at 16% ASA, while plastic limit fell from 25.00% to a minimum of 22.14% at 4% ASA; the plasticity index rose to a maximum of 25.54% at 8% ASA before reducing to 23.40% at 16% ASA.
5. Specific gravity decreased marginally and consistently, from 2.61 to 2.58 at 16% ASA, consistent with the replacement of denser soil minerals by lighter ash particles.
6. Maximum dry density decreased and optimum moisture content increased consistently with ASA content across all three compactive efforts, reflecting the lower specific gravity and higher water demand of the ash relative to the natural soil.
7. On balance, ASA contents in the range of 4-8% provided the most favourable combination of improved gradation and moderated consistency limits without excessive loss of compacted density, indicating this range as the most promising dosage for practical stabilization purposes.

These findings support the technical potential of Atili shell ash as a sustainable, low-cost stabilizing material for lateritic soils in road subgrade, embankment and other low-volume construction applications, and demonstrate a practical route for valorising an agricultural residue that would otherwise be discarded. Future work should extend this characterization to the strength

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(unconfined compressive strength, California bearing ratio) and durability behaviour of ASA-stabilized lateritic soil, and evaluate its performance under field curing and moisture-cycling conditions..

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