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INVESTIGATING THE POTENTIAL OF GROUNDNUT SHELL ASH AS A CEMENTITIOUS SUPPLEMENT IN ENHANCING THE ENGINEERING PROPERTIES OF LATERITIC SOIL

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ABSTRACT: *There has been a lot of global research on the economically effective use of wastes for engineering applications as a result of the need to lower the cost of waste disposal and the rising expense of soil stabilizers. This study investigates the performance of Groundnut Shell Ash (GSA) as a supplementary material to cement in the stabilization of lateritic soil, with the aim of enhancing its engineering properties for geotechnical applications. The experimental program involved the characterization of lateritic soil blended with varying GSA contents (0%–6%) and evaluation through geotechnical, chemical, mineralogical, and strength tests. Results reveal that the specific gravity of the soil decreased with increased GSA content due to the ash's lower density, although values at 2%–4% remained within acceptable limits. Plasticity characteristics were moderately affected; the plasticity index decreased significantly at 6% GSA, indicating reduced soil plasticity and improved workability. The California Bearing Ratio (CBR) test results showed a significant improvement in soil strength with GSA addition, with maximum CBR (48%) recorded at 4% GSA, exceeding the minimum standard of 30% for sub-base materials. Statistical analysis further confirmed a strong positive correlation (r = 0.997) between GSA content and CBR, validating GSA's efficacy in enhancing load-bearing capacity. The regression equation shows that at 0% GSA, the CBR value is reduced by 7.333% from the base intercept (41.33%), reflecting the unmodified lateritic soil's lower strength. As 2% GSA is added, the CBR slightly improves by 0.6667%, while at 4% GSA, the improvement becomes more significant with a 6.667% increase. This trend suggests that GSA has a positive effect on soil strength when used moderately, particularly at 4% replacement.*

KEYWORDS: Groundnut shell, Ash, Cementitious, Stabilizing, Laterite, Engineering properties.

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INTRODUCTION

The stabilization of lateritic soils has become an essential aspect of geotechnical engineering, particularly in regions where these soils are predominant and exhibit undesirable engineering properties such as high plasticity, low strength, and poor bearing capacity. Traditional soil stabilization methods commonly employ cement or lime as binding agents to improve the mechanical behavior and durability of problematic soils. However, the increasing environmental concerns associated with the production of ordinary Portland cement (OPC), including high energy consumption and significant CO_2 emissions, have spurred interest in alternative, more sustainable materials. In this context, the use of agro-industrial waste as supplementary cementitious materials (SCMs) has garnered significant attention in recent years. Among such wastes, groundnut shell ash (GSA) presents a promising option due to its rich silica content, which imparts pozzolanic properties when processed under appropriate conditions. Groundnut shells, often discarded as agricultural waste, are abundant in many tropical and subtropical regions, offering both an environmental disposal solution and a potential raw material for construction applications.

This study explores the potential of groundnut shell ash as a partial replacement for cement in the stabilization of lateritic soils. The primary objective is to assess the effect of GSA on the geotechnical properties of the soil, including Atterberg limits, compaction characteristics, unconfined compressive strength (UCS), and California Bearing Ratio (CBR). By investigating these parameters, the study aims to determine whether GSA can serve as a sustainable and cost-effective alternative to conventional stabilizers. The outcome of this research may contribute to the advancement of environmentally friendly soil stabilization practices, particularly in developing countries where the availability of conventional materials is limited and the need for sustainable infrastructure development is high. Furthermore, the utilization of groundnut shell ash aligns with broader goals of waste valorization and circular economy within the construction industry.

There has been a lot of global research on the economically effective use of wastes for engineering applications as a result of the need to lower the cost of waste disposal and the rising expense of soil stabilizers (Navaratnarajah *et al*., 2023).

Owing to the harmful impact these materials have on the environment and the health hazards they pose, the safe disposal of industrial and agricultural waste products demands immediate and cost-effective solutions (Sathiparan, 2022). Highway and structural engineers are faced with the issue of obtaining adequate material for civil engineering structures (Arrigoni, 2017; Sadeeq *et al*., 2014). To this end, continuous research has been carried out by individuals, firms and institutions on the ways to improve the engineering properties of soil. The most available soils do not have, in most cases, adequate engineering properties to really bear the expected loads, so improvisations have to be made to make these soils better (Navaratnarajah *et al*., 2023). This led to the concept called soil stabilization or modification, which is any treatment applied to a soil to improve its index properties, workability, and strength and to reduce its vulnerability to water (Thanushan, 2022).

The utilization of groundnut shells will promote waste management at little cost and reduce pollution by this waste. It can be used to improve soil stabilization in the ground because it is a good waterproofer, and its binding properties are adequate for stabilization (Sathiparan, 2022).

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And also, because of its being usually rich in calcium carbonate, which is a good binding agent and its other pozzolana with good stabilization properties, it can be used in a cement-based construction material to improve soil in the ground (Arrigoni*,* 2017; Salahudeen, 2014).

Navaratnarajah *et al. (2023)* investigated the properties of stabilized earth blocks using GSA as a cement substitute. The percentage by mass of the total binder in the stabilized earth block that has been replaced with GSA content is 0%, 10%, 20%, 30%, and 40%. The experiments on stabilized earth blocks investigate the physical, mechanical, and durability properties and thermal performance as well as cost-effectiveness and eco-benefit analysis. Results showed that, even though the strength of stabilized earth blocks decreases with GSA content, it improves the thermal performance, lowers the production cost and reduces the CO_2 emission and embodied energy.

Laterite Formation

Laterites are the results of severe and extensive long-term tropical rock weathering, which is deepened by increased precipitation and eminent temperatures (Gana & Okorie, 2019). Chemical weathering reduces during the dry seasons, at least beyond the inconsistent water table. Aqueous suspension of minerals continues when chemical stability is not attained, i.e., when the dissolved elements are removed in the water (Gana & Okorie, 2018). The chemical reactions are additionally well-ordered by the action of water, which is equivalent to that in spontaneously moving water but reduced within minor pores in the soil.

Factors Affecting Lateritic Soil Formation

Parent rock may perhaps be hard or it may be soft. Hard parent rock is generally impervious to weathering and can cause skeletal soils to be formed. Alternatively, comparatively soft rocks are effortlessly disintegrated into soil particles and the outcome is a greater rate of soil formation (Sandipan et al., 2015). The parent rock material is the rock material that disintegrates into rock particles and might affect the nature of the soil in relation to the fertility, mineral configuration, depth, colour and the ultimate soil profile (Sandipan et al., 2015). The parent rock arrangement may be categorized by connections or joints of weakness or may be just a block of massive rock.

Soil Stabilization

Soil Stabilization is the modification of soils to improve their physical properties. Stabilization can escalate the shear strength of a soil and/or regulate the shrink-swell properties of a soil, thus refining the load-bearing capacity of a subgrade to provide support for pavements and foundations (Mid-state, 2016). Soil stabilization can be employed on roadways, parking areas, site development projects, airports and numerous additional conditions in which subsoils are not appropriate for construction. Stabilization can be utilized in treating a wide variety of subgrade materials, ranging from expansive clays to granular materials.

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METHODS OF SOIL STABILIZATION

Soil stabilization can be accomplished using a variety of methods and techniques (Parracha, 2020). In terms of soil properties, these methods achieve more effective stabilization. Mechanical and additive (chemical stabilizers) techniques are the two most common ways to stabilize the soil. Groundnut shell ash (GSA), cement, lime (quick and hydrated lime), and fly ash are examples of chemical stabilizers. Bituminous stabilization, thermal stabilization, gravitational stabilization, and electrical stability are some of the other approaches. The application of mechanical energy to densify soil is known as mechanical stabilization or compaction.

Mechanical stabilization is the densification of soil by the application of mechanical energy. Densification occurs as air is expelled from soil voids without much change in water content (Adetoro *et al*., 2021). This method is particularly effective for cohesionless soils where compaction energy can cause particle rearrangement and particle interlocking. The technique may not be effective if these soils are subjected to significant moisture fluctuations. The efficacy of compaction may also diminish with an increase in the fine content (Arrigoni, 2017). This is because cohesion and inter-particle bonding interfere with particle rearrangement during compaction.

Laboratory testing indicates that GSA reacts with medium, moderately fine, and fine-grained soils to produce decreased plasticity, increased workability, and increased strength. Strength gain is primarily due to the chemical reactions that occur between the GSA and soil particles. These chemical reactions occur in two phases, with both immediate and long-term benefits (Victor, 2020). The first phase of the chemical reaction involves immediate changes in soil texture and soil properties caused by cation exchange. The free calcium of the GSA exchanges with the adsorbed cations of the clay mineral, resulting in a reduction in the size of the diffused water layer surrounding the clay particles (Victor, 2020).

This reduction in the diffused water layer allows the clay particles to come into closer contact with one another, causing flocculation/agglomeration of the clay particles, which transforms the clay into a more silt-like or sand-like material. Overall, the flocculation and agglomeration phase of GSA stabilization results in a soil that is more readily mixable, workable, and, ultimately, compactable (Victor, 2020). The second phase of the chemical reaction involves pozzolanic reactions within the lime-soil mixture, resulting in strength gain over time. When GSA is combined with clay soil, the pH of the pore water increases linearly (Victor, 2020). When the pH reaches 12.4, the silica and alumina from the clay become soluble and are released from the clay mineral. In turn, the released silica and alumina react with the calcium from the lime to form cement, which strengthens in a gradual process that continues for several years (Eades & Grim, 2012).

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Admixture

The compaction characteristics of the soils are improved by adding other materials known as admixtures. The most commonly used admixtures are lime, cement, and bitumen. The compaction test on the mix provides a relationship between the water content and dry density. The water content at which the maximum dry density (MDD) is attained is known as the optimum moisture content (OMC), provided by the relationship between dry density and moisture content on the test report.

Previous Work Done on Stabilization

The need to improve the strength and durability of lateritic soil in recent times has become imperative; this has geared researchers toward using stabilizing materials that can be sourced locally at a very low cost (Thanushan 2022; Bello *et al*., 2015). Groundnut shell ash is a by-product of the agricultural industry and has been found to possess promising properties for soil stabilization in civil engineering works. This natural material has been studied extensively due to its ability to bring about significant improvement in the engineering properties of soils, such as strength, bearing capacity, and permeability (Harshal *et al*., 2021). The soil stabilization process can be accomplished through the addition of groundnut shell ash to the soil, which can be done either as an admixture or by mixing with the soil. In cases where sourcing durable soil may prove economically unwise, the viable option is to stabilize the available soil to meet the specified requirements of construction (Mustapha, 2005; Thanushan, 2022).

Adetoro *et al*. (2021) concluded that the soil is lateritic in nature and belongs to the A-7-6 soil group. It is silt-clay, the soil of high plasticity. The treatment with the GSA content showed an increase in the coarse particles of the soil through cementation. There was also improvement in the mechanical strength of the soil as the CBR value (of 6% before treatment) increased to 18% after treatment. It is therefore recommended that it should be employed with other additives like cement for the formation of secondary cementitious compounds, which will be produced from the cement hydration. Krishna *et al*. (2015) concluded that groundnut shell ash could be considered an excellent ground improvement technique, particularly in engineering projects on unstable soils, where it can be used as a substitute for deep/raft foundations, saving energy and costs.

It was concluded that the increase in unconfined compression strength was determined to be 24.60%, 44.26%, and 59.01%, respectively, based on unconfined compressive strength tests on soil samples containing groundnut shell ash of 3%, 6%, and 9%. Moses and George (2015) studied the potential of stabilizing black cotton soil with groundnut shell ash for use in road construction. Black cotton soil is a highly expansive and highly plastic soil that is generally considered in civil engineering as an undesirable material due to its low strength. Groundnut shell ash was used as a stabilizing agent because it is abundant, cheap, and eco-friendly. To test this method of stabilization, laboratory experiments were conducted on the black cotton soil using varying percentages of groundnut shell ash. The unconfined compressive strength (UCS) and linear shrinkage test results showed that the black cotton soil could be significantly improved with groundnut shell ash, with the highest increase in UCS attributed to a 5% groundnut shell ash mixture. Additionally, a linear shrinkage test conducted on samples with a 0.8% lime dosage gave better results than with a 5% groundnut shell ash dosage. The results showed that groundnut shell

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ash can be a cost-effective, environmentally friendly, and effective alternative to conventional stabilization agents that can be used for black cotton soil in the construction of roads.

XRD Test

The effectiveness of GSA in these applications depends largely on its chemical and mineral composition, which can be accurately identified using XRD. The interpretation of XRD patterns is essential for quality control. Sharp, well-defined peaks in the XRD result indicate a crystalline structure, which is typical of stable, effective GSA.

MATERIALS AND METHODS

Material

The materials used for this study are; Laterite soil**,** Groundnut shell Ash (GSA) and Ordinary Portland cement.

Sample Collection

The laterite soil (Figure 1) used in this study was obtained from a site in Edo State. The pit was dug at a depth of 1 meter and the soil was collected in a disturbed state after the topsoil must have been removed. Proper inspection was carried out to ensure that it is free from deleterious materials.

Figure 1: Collection of Lateritic Material

Groundnut shell ash (GSA)

The groundnut shell was purchased from a market in Edo State. It was washed and liberated from any earth or contaminant. The shell obtained was dried outdoors for 72 hours. The ash was acquired by burning the shells in an enclosed area under normal temperature (Figure 2) and stored in a tight polythene bag to avoid any form of hydration. The ash obtained was passed through a British standard No. 200 (0.0075 m) sieve and the fine material passing the sieve was obtained.

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Figure 2: Groundnut Shell

Mixing proportion

The laterite soil (LS) sample was stabilized with cement and groundnut shell ash at different percentages, i.e., 0%, 2%, 4%, 4%,6% and 8% by dry weight of the natural soil.

Steel

Laboratory Tests and Methods

The techniques and procedures used for tests in this study were in accordance with British Standard International Codes (BS) and American Society for Testing and Materials (ASTM). Preliminary tests include natural moisture content, specific gravity, bulk density, particle size analysis and Atterberg's limit. The compaction characteristics and the strength properties (measured in terms of California Bearing Ratio) were carried out on the blend of soil samples with the stabilizing materials at different percentages by dry weight of the natural soil.

Moisture Content Test

The test was carried out on the natural soil sample to determine the amount of water in the soil as per BS 1377-2 (1990).

$$Moisture\ Content(\%) = \frac{weight\ of\ water}{weight\ of\ dry\ soil} \times 100 \quad (1)$$

Specific Gravity

The test was carried out on the soil sample in their natural state as per BS 1377-2 (1990) to determine the stability of the soil sample using Equation 2.

$$Specific\ Gravity = \frac{Ws}{Ws+W2-W3} \quad (2)$$

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Bulk Density

Bulk density is the weight of soil for a given volume. It provides data for how densely the soil particles are packed within a given volume. This influences factors such as water holding capacity, permeability and soil strength. The bulk density of soil depends greatly on the mineral makeup of soil and the degree of compaction. The test will be carried out as per BS 1377-2 (1990) to determine the bulk density and compaction characteristics of soils.

Particle Size Distribution Test

The grain size analysis test (Plate 3.2a) was carried out on the unstabilized soil to determine the distribution of different grain sizes contained within a soil as per BS 1377-2 (1990). This was used to classify the soil.

Strength Characteristics

The strength characteristics were measured in terms of the California Bearing Ratio (CBR), an in-situ test ordinarily used to gauge the strength of a soil layer by looking at the penetration resistance of the soil to that of a standard material. The CBR tests were directed at the OMC of the soil, soil-cement or soil-GSA as determined from the compaction test.

Atterberg Limit Test

The standard test technique for liquid limit, plastic limit, and plasticity index of soils was carried out by ASTM D 4318 (2010) on the soil samples in their natural state. The limits were used for soil identification, classification and strength correlations. This was used to determine the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of fine-grained cohesive soils, the water contents corresponding to the transition from one state to another, which are liquid, plastic and the different types of silt and clay.

Compaction Characteristics

A compaction test of soil was carried out using Proctor's test to understand compaction characteristics of soils with change in moisture content. Compaction of soil is the optimal moisture content at which a given soil type becomes most dense. The compaction test was done in accordance with the standard of ASTM D698 on soil samples and the stabilized sample at the varying percentages to obtain essential information about the soil's compaction characteristics.

Statistical Analysis

The statistical analysis was done using Minitab. The data were inputted in the worksheet. Then the stat icon was selected, then the ANOVA icon and one-way. GSA was selected as a factor, while CBR was selected as a response. Thereafter, the result was obtained in the store file.

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RESULTS AND DISCUSSIONS

Specific Gravity of the Laterite with 2%, 4% and 6% of Groundnut Shell Ash (GSA)

Specific gravity is a key indicator of the density of soil solids relative to water, and it plays an important role in determining the soil's engineering behavior. In this study, specific gravity tests were conducted on lateritic soil samples treated with varying percentages of groundnut shell ash (GSA). Specifically 2%, 4%, and 6% by dry weight of soil to evaluate how GSA influences the physical properties of the soil. From these values (Table 1,2 and 3), a gradual decrease in specific gravity is observed as the percentage of GSA increases. This trend can be explained by the lightweight nature of groundnut shell ash compared to the mineral constituents of lateritic soil. GSA, being an agricultural waste ash, contains silica and other oxides but has a lower relative density than natural soil particles, which typically include iron oxides, aluminum oxides, and silicate minerals. As GSA content increases, it partially replaces heavier soil solids, resulting in a reduced overall specific gravity.

According to BS 1377 (1990), typical specific gravity values for lateritic soils range from 2.60 to 2.80, depending on mineral composition. The control soil (0% GSA), while not stated here, can be assumed to fall within this standard range. However, the recorded values at 2.54 and 2.53 for 2% and 4% GSA are slightly below the lower bound of this range, and the value of 2.42 at 6% GSA is significantly lower. This deviation indicates that GSA has a noticeable diluting effect on the density of the soil solids, especially at higher proportions. The decline at 6% is particularly steep and suggests that excessive GSA addition may affect the compactness and weight-bearing capacity of the stabilized soil, though further strength tests (such as CBR or UCS) would be required to confirm this.

The findings align with those reported by Amu *et al*. (2011), who observed that the specific gravity of lateritic soil decreased progressively when stabilized with agricultural ashes such as rice husk ash (RHA) and bagasse ash. Similarly, Edeh and Nwankwo (2018) found that incorporating palm kernel shell ash into lateritic soil led to a reduction in specific gravity due to the ash's lower density. In the context of groundnut shell ash, Onyelowe *et al*. (2020) reported that GSA-treated soils exhibited a slight but consistent drop in specific gravity, which they attributed to the lightweight siliceous nature of the ash and its amorphous microstructure. This supports the results obtained in your study, where increased GSA content corresponded to decreased specific gravity.

Table 1: Average Specific Gravity of Laterite +2% GSA

Sample		Specific Gravity
	1	2.55
	2	2.53
average		**2.54**

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Table 2: Average Specific Gravity of Laterite +4% GSA

Sample	Specific Gravity
1	2.55
2	2.50
average	**2.53**

Table 3: Average Specific Gravity of Laterite +6% GSA

Sample	Specific Gravity
1	2.34
2	2.49
average	**2.42**

The observed decrease in specific gravity with increasing GSA content indicates that GSA contributes lighter particles into the soil matrix. While this may be beneficial in reducing the unit weight of soil for lightweight fill applications, it also suggests caution in using high percentages of GSA for load-bearing structures without proper strength verification. The optimal range for GSA replacement may lie between 2% and 4%, where specific gravity remains close to acceptable limits and the integrity of the soil is likely retained. A further increase to 6% GSA shows a sharp drop (to 2.42), which may adversely affect other properties like compaction, strength, and durability. Therefore, while GSA proves promising as a partial stabilizing agent, its percentage in the soil-cement matrix must be carefully controlled to maintain essential geotechnical standards.

Sieve Analysis Result

This data was used to plot the particle size distribution curve on a semi-logarithmic graph (Figure 4.1), from which key diameters were obtained: D10 = 0.25 mm, D30 = 0.50 mm, and D60 = 1.50 mm. Using these values, the Coefficient of Uniformity (Cu) and Coefficient of Curvature (Cc) were calculated to classify the soil according to the Unified Soil Classification System (USCS).

The Cu, which is the ratio of D60 to D10, was found to be 6.00, indicating a wide range of particle sizes, an attribute generally associated with better compaction and shear strength.

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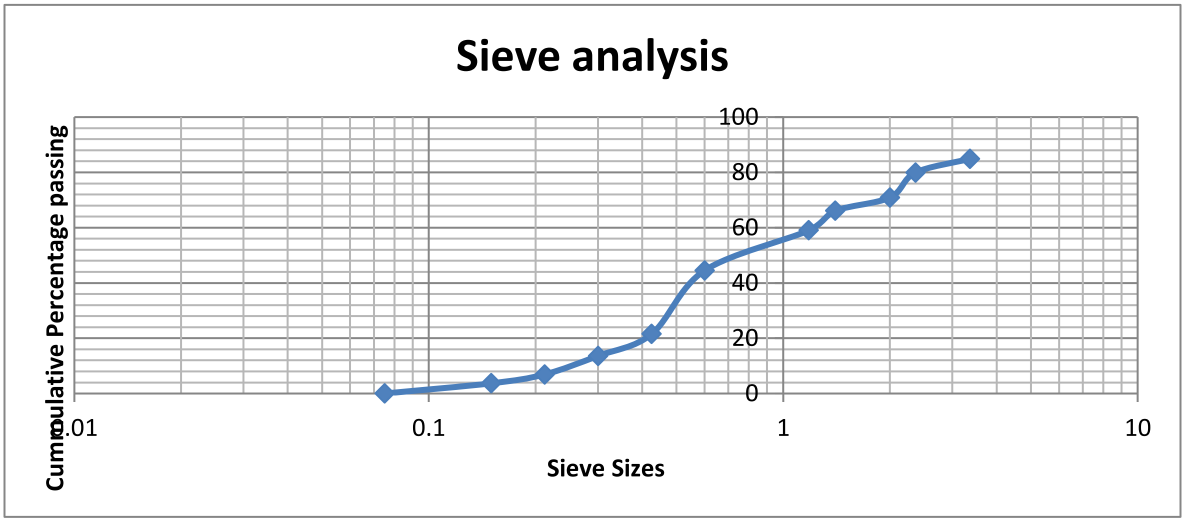
Figure 3: Sieve Analysis Result



However, the Cc, which evaluates the balance of intermediate particles using the formula , was computed as 0.67. This value is below the acceptable range of 1 to 3, which suggests a gap in intermediate particle sizes, leading to potential issues in gradation. In comparison with USCS standards, a well-graded sand is expected to have a Cu greater than 6 and a Cc between 1 and 3. While the soil in this test met the minimum requirement for Cu, the Cc value fell short, meaning that the soil cannot be classified as well-graded. Instead, it is better described as a poorly graded sand (SP). Such soils typically exhibit lower stability, higher permeability, and a tendency to settle under load unless properly compacted or modified. This gradation can negatively affect its performance in applications like subgrade, base courses, and embankment fill. The sieve analysis revealed that the soil sample has a relatively wide particle size distribution but a deficiency in intermediate particles, making it poorly graded. Although it may still be usable in construction, especially where high permeability is desired, it would require improvement or stabilization for structural applications where strength and stability are critical.

Atterberg Test Result

The Atterberg limits (Figure 4), which include the liquid limit (LL), plastic limit (PL), and plasticity index (PI), are essential indicators of the consistency and plastic behavior of fine-grained soils. In this study, Atterberg limits tests were carried out to evaluate the influence of groundnut shell ash (GSA) on the plasticity characteristics of lateritic soil, a common construction material in tropical regions. From the results, it is evident that the liquid limit values remain relatively stable, hovering around 27% across all GSA replacement levels. This indicates that the addition of GSA up to 6% does not significantly alter the water content required for the soil to transition from a plastic to a liquid state. However, slight fluctuations observed may be due to variations in the ash's fineness or pozzolanic reaction, especially as it interacts with clay minerals in the lateritic soil.

The plastic limit values show more variation, ranging from 17.46% to 18.95%. Notably, at 4% GSA, the plastic limit dropped slightly to 17.46%, which corresponds to the highest plasticity index (PI) of 9.68%. This suggests that at this level, the soil is relatively more plastic, perhaps due

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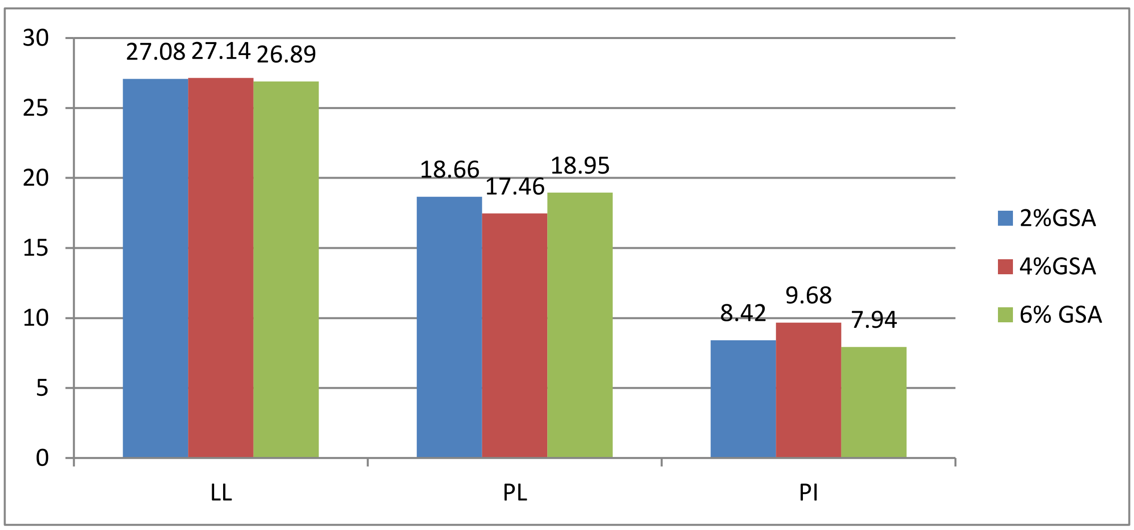
to incomplete binding reactions between the ash and the soil particles. On the other hand, the lowest plasticity index (7.94%) was recorded at 6% GSA, indicating a reduction in soil plasticity.

This behavior can be attributed to the filler effect and partial cementitious reaction of GSA, which reduces the moisture sensitivity and cohesion among clay particles. According to ASTM D4318 and the Unified Soil Classification System (USCS), a plasticity index between 7% and 17% places the soil in the low to medium plasticity range, which is generally favorable for engineering works, especially subgrade and subbase layers. In this study, all PI values fall within this range, showing that the treated soils maintain acceptable workability and do not pose serious shrink-swell problems. Comparatively, Amu *et al*. (2012) noted a similar trend when lateritic soil was treated with rice husk ash and cement, observing that the plasticity index initially increased at lower replacement levels due to unreacted ash particles but decreased at higher levels due to pozzolanic reactions and the filler effect. Similarly, Onyelowe *et al*. (2019) found that the addition of agricultural waste ashes like GSA and bamboo leaf ash reduced the PI of expansive soils, leading to improved dimensional stability.

Figure 4: Atterberg Test Result



The observed changes in Atterberg limits reveal important insights into the behavior of lateritic soil stabilized with GSA. The liquid limit remains stable, indicating that the soil's overall water affinity is not significantly affected by moderate GSA inclusion. The plastic limit fluctuates but tends to increase at higher GSA content, likely due to reduced clay activity. The plasticity index decreases at 6% GSA, implying improved soil behavior in terms of reduced plasticity and enhanced stability. This reduction in plasticity index is desirable for civil engineering applications, as it suggests that the soil is less susceptible to deformation under load and will exhibit less shrink-swell behavior during moisture changes. Therefore, 6% GSA appears optimal in terms of reducing soil plasticity without compromising workability.

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CBR Test Results

The study investigates the effect of incorporating Groundnut Shell Ash (GSA) as a partial supplement for cement in the stabilization of lateritic soil by evaluating California Bearing Ratio (CBR) values at different depths (top and bottom) and penetration levels (2.5 mm and 5 mm). The CBR is a critical parameter used to assess the strength and load-bearing capacity of subgrade soil materials for pavement and road construction. For the untreated soil (Figure 3), the CBR at 2.5 mm penetration was 14.4 mm (top) and 29.5 mm (bottom), while at 5 mm penetration, it was 21.5 mm (top) and 34 mm (bottom). These results reflect relatively low bearing capacity, which is typical of natural lateritic soil without stabilization. The values fall below the minimum required CBR of 30% for subbase materials as per the Federal Ministry of Works and Housing (FMWH, Nigeria) and AASHTO standards, which often recommend a minimum of 30–80% depending on the pavement layer function (subgrade, subbase, base). With 2% GSA added, a noticeable improvement in CBR values was observed. At 2.5 mm penetration, values increased to 18.5 mm (top) and 31.8 mm (bottom), and at 5 mm, to 24 mm (top) and 42 mm (bottom). This increase in strength can be attributed to pozzolanic reactions between the silica in GSA and calcium hydroxide from the cement, leading to the formation of additional calcium silicate hydrate (C-S-H) gel, which enhances the soil matrix. The bottom CBR value at 5 mm (42 mm) now meets the minimum requirement for subbase applications.

This result is consistent with findings by Osinubi and Eberemu (2006) and Amu *et al*. (2011), who reported that partial replacement of cement with agro-waste ash (e.g., rice husk ash and groundnut shell ash) in lateritic soil improved strength characteristics due to the pozzolanic reactivity of the ash. The sample with 4% GSA showed the highest improvement. CBR values at 2.5 mm increased to 21.2 mm (top) and 37.9 mm (bottom), while at 5 mm, the values were 28.5 mm (top) and 48 mm (bottom).

This enhancement suggests that the optimal percentage of GSA may lie between 2–4%, beyond which additional GSA may not necessarily lead to further significant improvements due to potential dilution of cementing content or unreacted ash. Compared to standards, the bottom 5 mm CBR value of 48 mm is very promising and exceeds the minimum thresholds for both subgrade and subbase material specifications.

Figure 3: CBR Result

These findings align with research conducted by Ettu *et al.* (2013), who concluded that agricultural ashes can enhance the mechanical properties of weak soils when added within optimal limits. Moreover, Nnochiri *et al.* (2020) also observed that groundnut shell ash addition in stabilized lateritic soil improved CBR values significantly up to 4–6% replacement levels.

The statistical analysis carried out on the study (Figure 4.5 and Table A4 in the Appendix) revealed a strong relationship between the percentage of GSA added and the resulting California Bearing Ratio (CBR), which is a key indicator of soil strength for pavement design. The regression equation developed from the experimental data is **CBR = 34.333 + 3.500 % GSA.**

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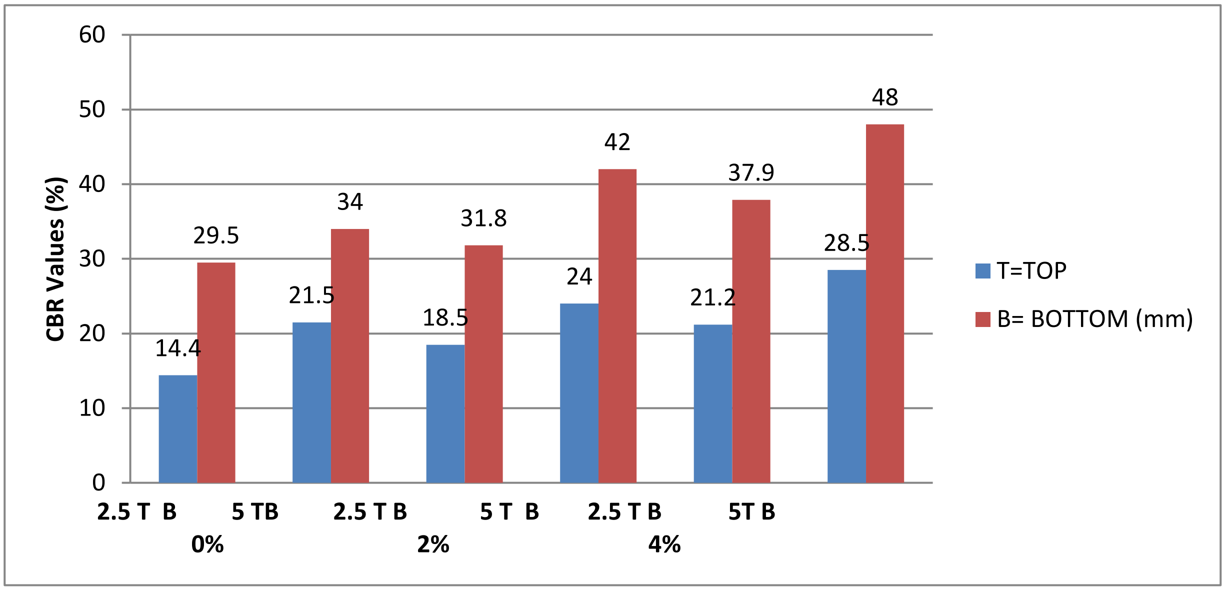
This equation shows that at 0% GSA, the CBR value is reduced by 7.333% from the base intercept (41.33%), reflecting the unmodified lateritic soil's lower strength. As 2% GSA is added, the CBR slightly improves by 0.6667%, while at 4% GSA, the improvement becomes more significant with a 6.667% increase. This trend suggests that GSA has a positive effect on soil strength when used moderately, particularly at 4% replacement. The result supports the idea that GSA can act as a pozzolanic material, contributing to the cementitious reactions that enhance soil stability and load-bearing capacity.



XRF for 4% addition

The X-ray diffraction (XRD) analysis of 4% groundnut shell ash (GSA) used for soil stabilization provides key insights into the crystalline phases present in the ash, which are crucial for evaluating its pozzolanic and stabilizing potential. The XRF pattern shows that the dominant crystal structure corresponds to a hexagonal crystal system, with a space group P 32121, and the following lattice parameters: a = 4.913 Å, b = 4.913 Å, c = 5.405 Å, α = 90°, β = 90°, and γ = 120°. These parameters are indicative of quartz-like or silica-based structures, which are common in plant-based ashes due to the presence of amorphous to semi-crystalline silica formed during thermal processing. The hexagonal symmetry and specific space group (P 32121) suggest a well-defined crystal structure with relatively low internal strain, supporting stable interaction in soil matrices. The observed crystalline phase could be a polymorph of silica, such as α-quartz or tridymite, depending on firing conditions and temperatures during the ash preparation.

The Reference Intensity Ratio (RIR) = 3.15 is a comparative value used to estimate the amount of crystalline phase in a mixture. An RIR value of 3.15 implies a moderate to high relative intensity, which reflects a substantial crystalline component in the ash. This is beneficial for stabilization

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purposes, as crystalline silica can provide a skeleton that improves mechanical interlock and long-term stability in soil.

Table 4: XRF 4% of GSA

Crystallographic parameters	
Crystal system:	Hexagonal
Space group:	P 31 2 1
Space group number:	152
a (Å):	4.9130
b (Å):	4.9130
c (Å):	5.4050
Alpha (°):	90.0000
Beta (°):	90.0000
Gamma (°):	120.0000
Calculated density (g/cm^3):	2.65
Volume of cell (10^6 pm^3):	112.98
RIR:	3.15

The analysis showed an average crystallite size of 12.33 nm, which is within the nano-range; this confirms that the ash contains nanocrystalline silica. Nanocrystalline particles enhance the surface area and reactivity of the ash, promoting better bonding with soil particles and improving the pozzolanic reaction when combined with soil moisture and calcium ions (e.g., from lime or cement additives). The XRD analysis of 4% groundnut shell ash reveals that the ash is crystalline with a hexagonal crystal system and lattice parameters indicative of silica-based phases. The space group P 32121 and RIR value of 3.15 confirm a significant proportion of crystalline materials. The crystallite size of approximately 12.33 nm places it in the nanocrystalline range, which is highly beneficial for reactivity and strength development.

CONCLUSION

The specific gravity of lateritic soil decreases with increasing groundnut shell ash (GSA) content due to the ash's lower density. While 2%–4% GSA remains within or near standard limits, 6% causes a significant drop, potentially affecting soil strength. The CBR values improved progressively with the addition of Groundnut Shell Ash (GSA), with the highest strength recorded at 4% GSA. The bottom CBR value at 5 mm penetration reached 48%, exceeding the 30% minimum standard for subbase materials, indicating enhanced load-bearing capacity due to pozzolanic reactions. The statistical analysis shows that Groundnut Shell Ash (GSA) enhances the strength of lateritic soil, with the highest improvement in CBR observed at 4% GSA replacement. The strong positive correlation (r = 0.997) between GSA content and CBR confirms its

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effectiveness, making GSA a viable supplement for cement in soil stabilization. XRD and elemental analyses reveal that 2% and 6% GSA contain significant reactive oxides (SiO_2, Al_2O_3, CaO) with low quartz content, indicating good pozzolanic potential. The 4% GSA sample shows high carbon content and low oxide levels, reducing its effectiveness as a stabilizer. The untreated soil (0% GSA) is rich in organic matter and lacks reactive minerals, making it unsuitable for engineering applications. The XRF analysis shows that 4% GSA contains a silica-based crystalline phase with hexagonal symmetry (space group P 32121), an RIR of 3.15, and a nano-crystalline size of 12.33 nm. These properties indicate good structural stability and high pozzolanic reactivity.

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