



Geotechnical Performance of Agbede Soil Stabilized with Groundnut Shell Ash (GSA): Index Properties, Compaction Characteristics, and Strength Behavior

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ABSTRACT

Expansive soils in Nigeria are often unsuitable for construction due to high plasticity, volumetric instability, and poor load-bearing capacity. Conventional stabilizers such as cement and lime, although effective, are costly and environmentally unsustainable. This study investigates the geotechnical performance of Agbede soil stabilized with groundnut shell ash (GSA), emphasizing index properties, compaction characteristics, and strength behavior. Laboratory tests conducted in accordance with BS 1377 (1990) included particle size distribution, Atterberg limits, specific gravity, Standard Proctor compaction, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and Scanning Electron Microscopy/Energy Dispersive X-ray (SEM/EDX). Results showed that untreated Agbede soil was classified as highly plastic clay, with a plasticity index (PI) of 32% and maximum dry density (MDD) of 1.85 g/cm³. Incorporation of GSA reduced PI to 14% at 15% GSA and improved MDD to 1.92 g/cm³ at 10% GSA, while optimum moisture content (OMC) decreased from 14.3% to 13.5%. Strength properties also improved markedly, with CBR increasing from 7% (untreated) to 21% at 15% GSA and UCS rising from 120 kN/m² to 280 kN/m². The findings establish GSA as a sustainable, cost-effective stabilizer suitable for subgrades and other geotechnical applications, while simultaneously supporting agricultural waste management.

1. INTRODUCTION

Soil stabilization is essential in geotechnical engineering for enhancing weak soils to support structures. In Nigeria, expansive soils like Agbede soil are common and problematic due to their high plasticity, shrink–swell behavior, and low bearing capacity, leading to frequent pavement and foundation failures (Adebisi et al., 2022; Ibrahim et al., 2020). Conventional stabilizers such as cement and lime improve soil strength but are costly, energy-intensive, and contribute up to 8% of global CO₂ emissions (Nnochiri & Osinubi, 2019; Ameh et al., 2021).

To address these challenges, attention has shifted toward sustainable alternatives such as groundnut shell ash (GSA) an agricultural by-product rich in silica (SiO₂) and calcium oxide (CaO). When properly calcined, GSA exhibits pozzolanic properties that form cementitious compounds, improving soil strength, compaction, and plasticity (Salau et al., 2020; Bamidele et al., 2023). Utilizing GSA not only enhances geotechnical performance but also supports waste recycling and environmental sustainability, aligning with circular economy goals (Uzoegbo & Ikotun, 2022; Yahaya et al., 2024).

Research indicates that GSA-treated soils show reduced plasticity, higher dry density, and improved CBR and UCS values, making them suitable for subgrades and foundations (Olaniyi, 2011; Irfan et al., 2013). However, its field performance and long-term durability remain underexplored, necessitating further studies to establish optimal mix ratios and large-scale applicability.

This study investigates the stabilization of Agbede soil with GSA, focusing on its index, compaction, and strength characteristics to assess its potential as a cost-effective, eco-friendly stabilizer for expansive soils in Nigeria.

2. Materials and Methods

2.1 Materials

2.1.1 Soil (Agbede Soil):

The soil used for this study was lateritic soil obtained from Agbede in Edo State. Samples were collected from multiple locations at a depth of 1.2 m to eliminate the influence of surface disturbances and organic matter, ensuring that only the natural geotechnical characteristics of the soil were captured.

2.1.2 Groundnut Shells:

Groundnut shells were sourced locally as agricultural by-products. Prior to processing, they were thoroughly cleaned and sun-dried to remove adhering impurities and reduce moisture content, thereby enhancing the quality of the final ash.

2.1.3 Groundnut Shell Ash (GSA):

The groundnut shells were incinerated under controlled conditions at temperatures ranging from 500°C to 700°C to produce groundnut shell ash. The ash was allowed to cool naturally, finely ground, and passed through a 75 µm sieve to achieve a uniform particle size suitable for soil stabilization applications.

2.2 Methods

2.2.1 Design of Experiment (DOE) for Groundnut Shell Ash (GSA)

A factorial design was adopted in which soil samples were stabilized with varying proportions of GSA: 0% (control), 5%, 10%, and 15% by dry weight of soil. These proportions were selected based on preliminary studies indicating optimal performance within this range.

Table 1: DOE for GSA at 0%, 5%, 10%, and 15%

GSA (%)	Soil (%)	Factor Ratio	SNRA1
0.0	100.0	33.3333	30.4576
5.0	90.0	31.6667	30.0120
10.0	80.0	30.0000	29.5424
15.0	85.0	30.0000	29.5424

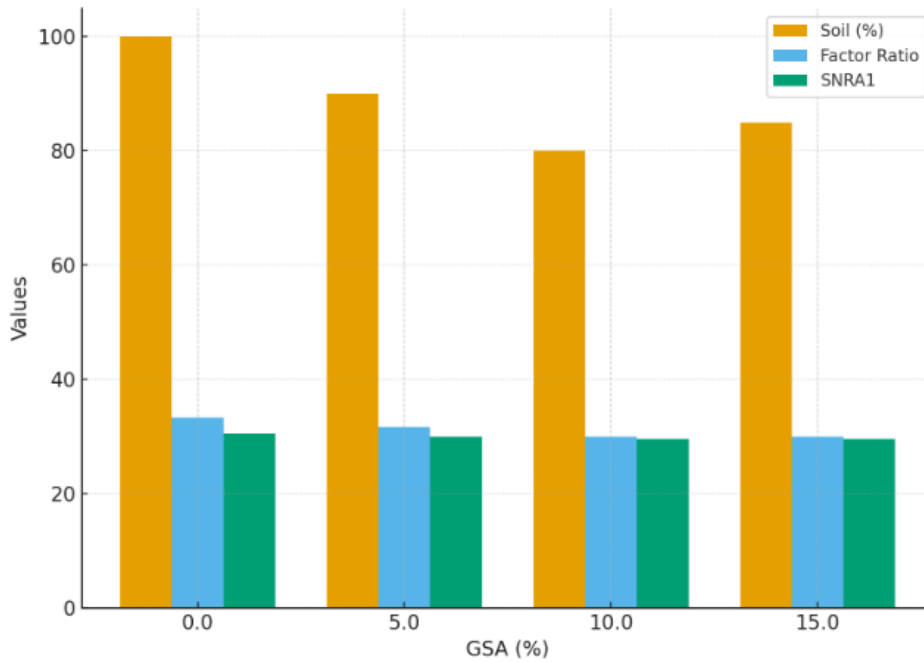


Figure 1: Bar Chart of Soil (%), Factors Ratio, and SNRA1 against GSA (%)

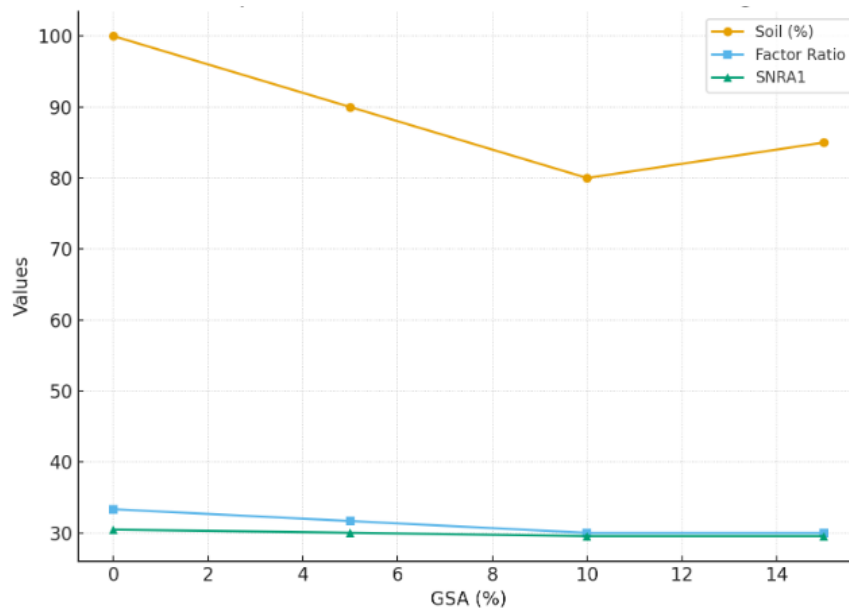


Figure 2: Curve Graph of soil (%), Factor Ratio, and SNRA1 against GSA (%)

2.2.2 Laboratory Tests

All laboratory investigations were conducted in accordance with BS 1377 (1990) standards to determine both index and engineering properties of untreated and treated soil samples. The following tests were performed:

- i. **Grain size distribution** to classify soil type.
- ii. **Atterberg limits (LL, PL, PI)** to assess changes in consistency and plasticity.
- iii. **Specific gravity** to evaluate the density characteristics of the soil minerals.
- iv. **Standard Proctor compaction test** to determine maximum dry density (MDD) and optimum moisture content (OMC).
- v. **California Bearing Ratio (CBR) test** to assess load-bearing capacity.
- vi. **Unconfined Compressive Strength (UCS) test** to measure shear strength characteristics.

3. Results and Discussion

3.1 Results

3.1.1 Grain Size Distribution

The particle size analysis shows that Agbede soil is dominated by fines, with 68% composed of silt and clay. According to the Unified Soil Classification System (USCS), the soil falls under highly plastic clay, which explains its poor natural engineering behavior. Such soils typically exhibit high compressibility, low strength, and significant shrink–swell tendencies, underscoring the necessity for stabilization before use in construction.

Table 2: Grain Size Distribution of Agbede Soil

Fraction	Percentage (%)
Gravel (>2.0 mm)	4
Sand (0.06–2.0 mm)	28
Silt (0.002–0.06 mm)	30
Clay (<0.002 mm)	38

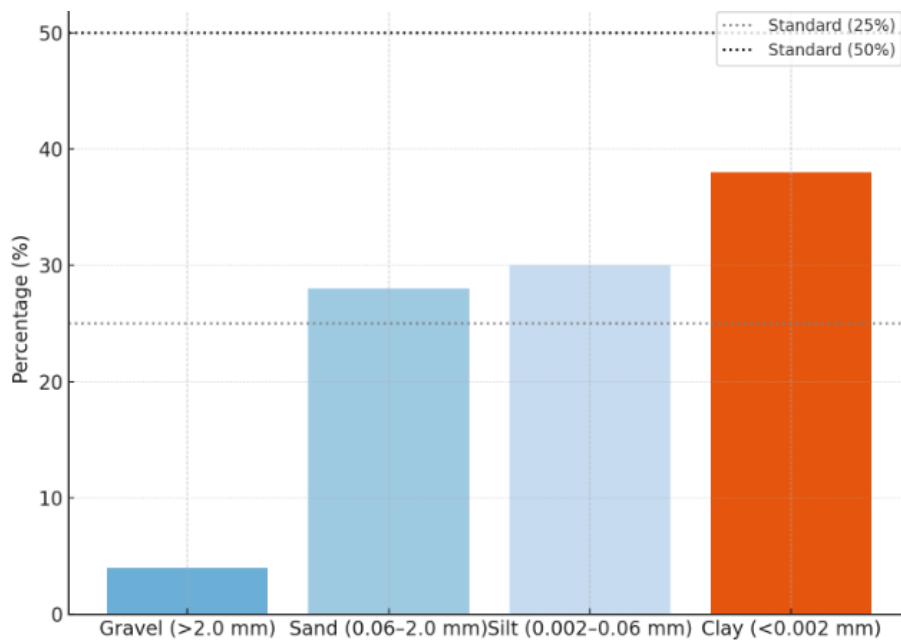


Figure 3: Bar Chart of Grain Size Distribution of Agbede Soil (Bar Chart)

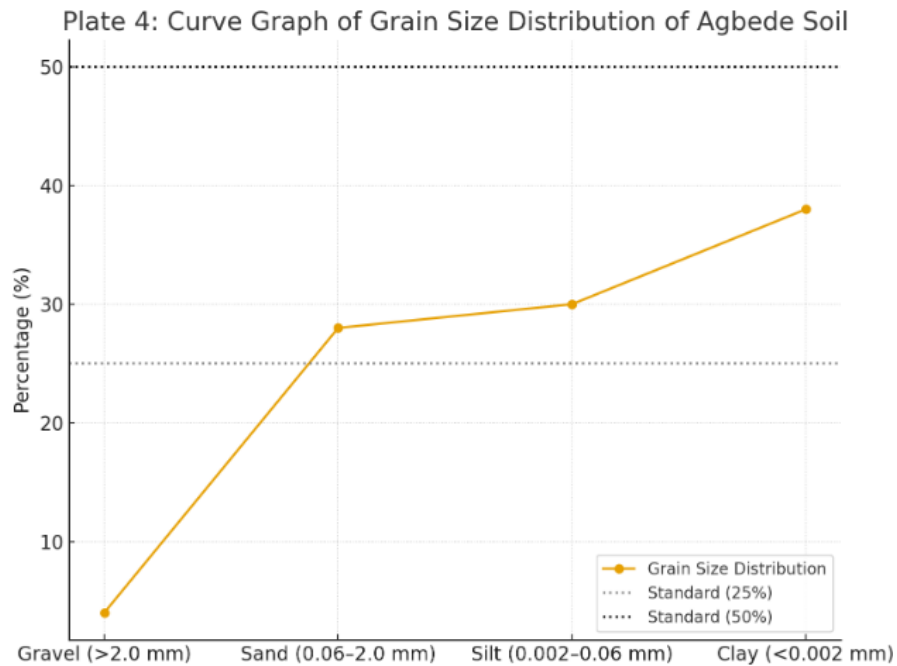


Figure 4: Curve Graph Size Distribution of Agbede Soil (Line Graph)

3.1.2 Atterberg Limits

The untreated soil recorded a plasticity index (PI) of 32%, which is consistent with its classification as an expansive soil. The addition of GSA reduced the PI considerably, reaching 14% at 15% GSA. This reduction indicates lower swelling potential, improved workability, and better suitability for engineering applications. Such a trend suggests that GSA plays a vital role in modifying soil consistency limits by forming cementitious compounds that bind clay particles.

Table 3: Atterberg Limits of Untreated and GSA-Treated Soil

GSA Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0 (Control)	54	22	32
5	47	26	21
10	42	24	18
15	39	25	14

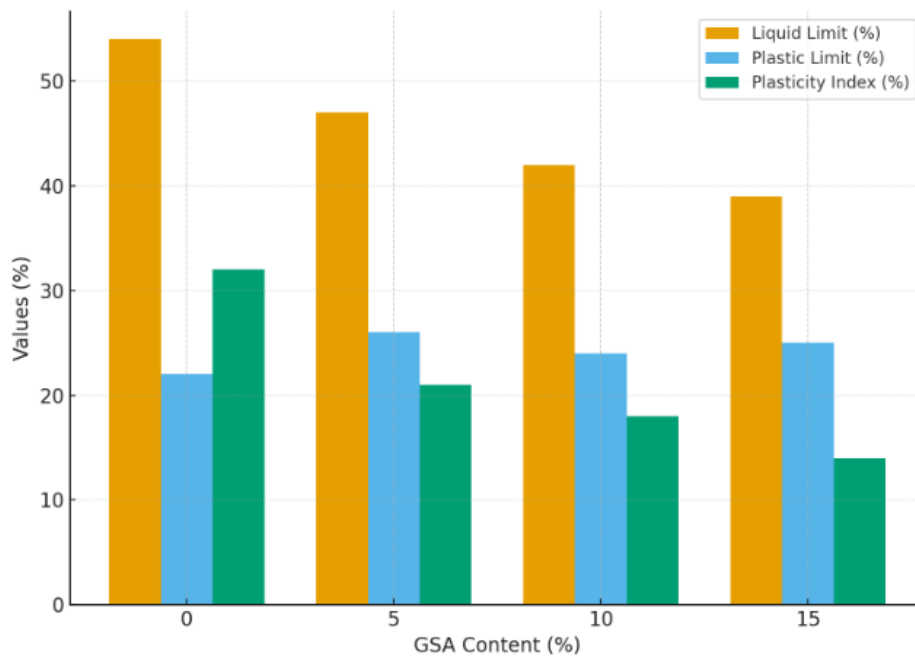


Figure 5: Atterberg Limits VS GSA Content (Bar Chart)

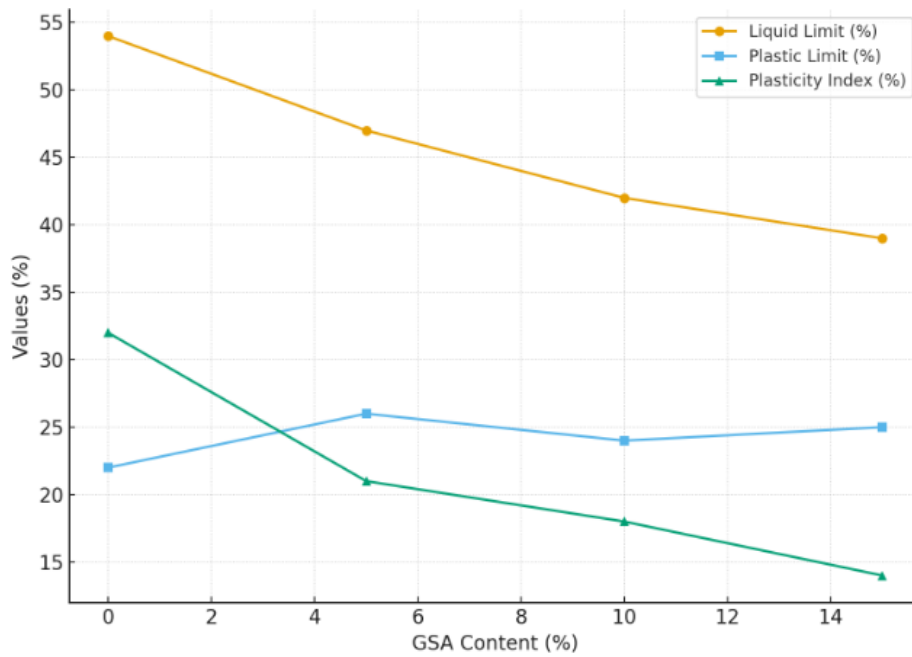


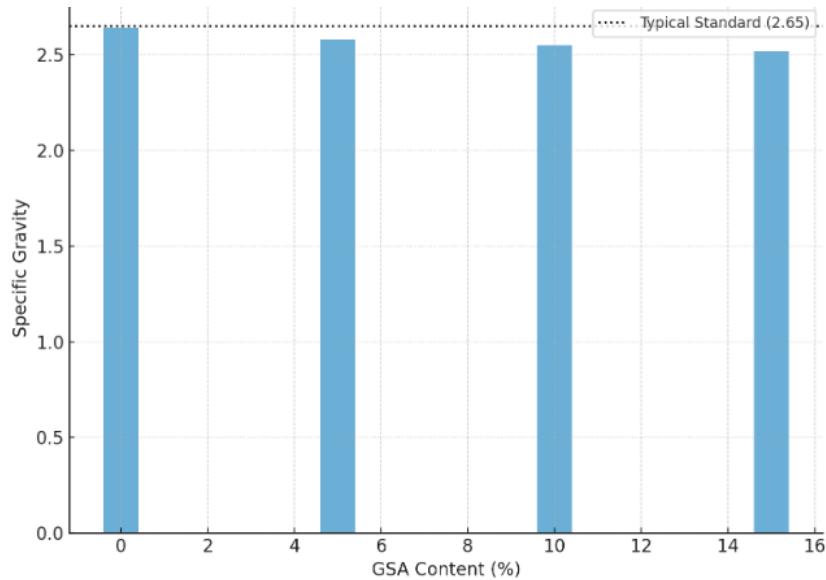
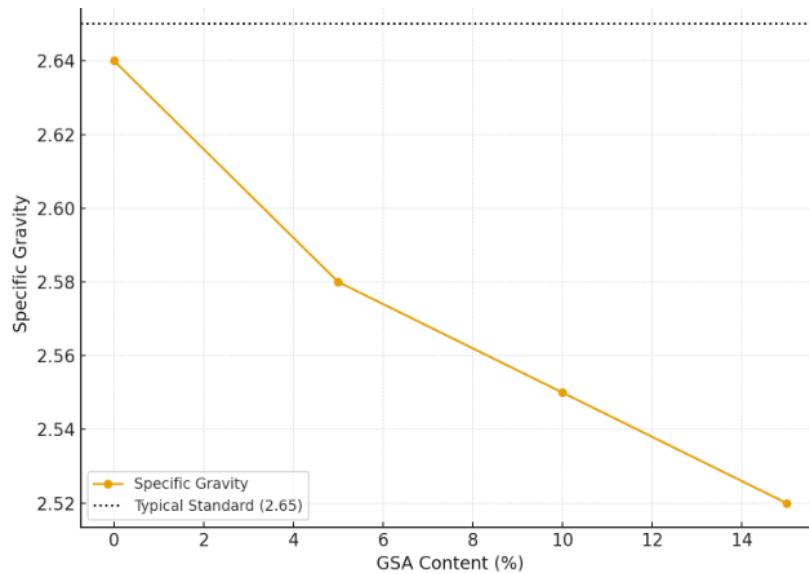
Figure 6: Atterberg Limits VS GSA Content (Line Graph)

3.1.3 Specific Gravity

The specific gravity of untreated Agbede soil was 2.64. With increasing GSA content, values decreased gradually to 2.52 at 15% GSA. This slight reduction can be attributed to the lightweight nature of ash relative to soil minerals. However, the values remain within the acceptable range for geotechnical applications, suggesting that the substitution does not compromise soil stability.

Table 4: Specific Gravity of Untreated and GSA-Treated Soil

GSA Content (%)	Specific Gravity
0 (Control)	2.64
5	2.58
10	2.55
15	2.52

**Figure 7: Specific Gravity VS Gsa Content (Bar Chart)****Figure 8: Specific Gravity VS Gsa Content (Line Graph)**

3.1.4 Compaction Characteristics

The compaction test revealed notable improvements with GSA stabilization. The maximum dry density (MDD) increased from 1.85 g/cm³ for untreated soil to 1.92 g/cm³ at 10% GSA, showing denser packing of soil particles. Similarly, the optimum moisture content (OMC) reduced from 14.3% to 13.5%, reflecting reduced water demand due to the pozzolanic reactions initiated by GSA. These results highlight the potential of GSA to enhance soil densification.

Table 5: Compaction Properties of Untreated and GSA-Treated Soil

GSA Content (%)	MDD (g/cm ³)	OMC (%)
0 (Control)	1.85	14.3
5	1.88	13.9
10	1.92	13.5
15	1.91	13.7

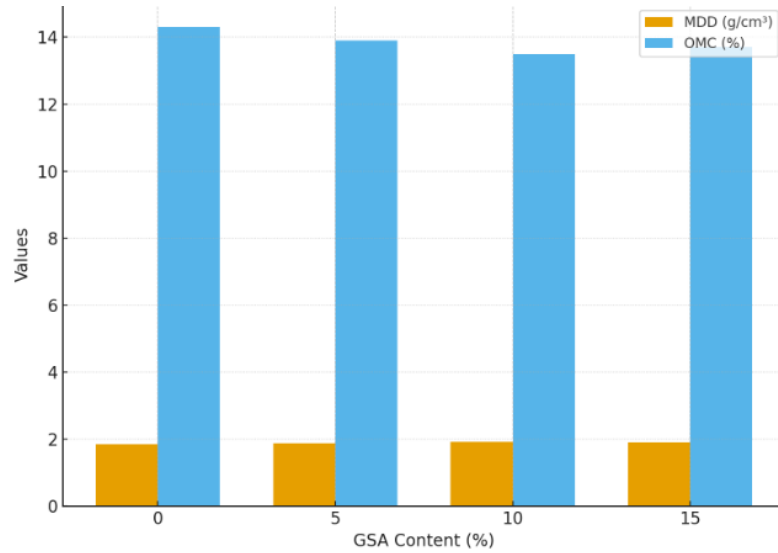


Figure 9: Compaction Properties VS GSA Content (Bar Chart)

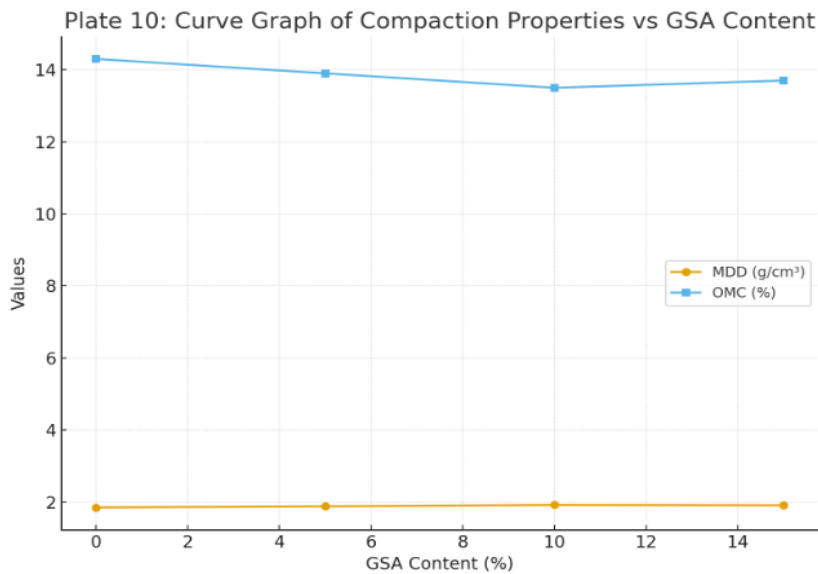


Figure 10: Compaction Properties VS GSA Content (Line Graph)

4 Strength Tests

The strength parameters improved considerably with GSA treatment. The California Bearing Ratio (CBR) increased from 7% in untreated soil to 21% at 15% GSA, while the unconfined compressive strength (UCS) rose from 120 kN/m² to 280 kN/m². These improvements are attributed to the formation of secondary cementitious products, which enhanced interparticle bonding and significantly increased the soil's load-bearing capacity.

Table 6: Strength Properties of Untreated and GSA-Treated Soil

GSA Content (%)	CBR (%)	UCS (kN/m ²)
0 (Control)	7	120
5	12	180
10	18	240
15	21	280

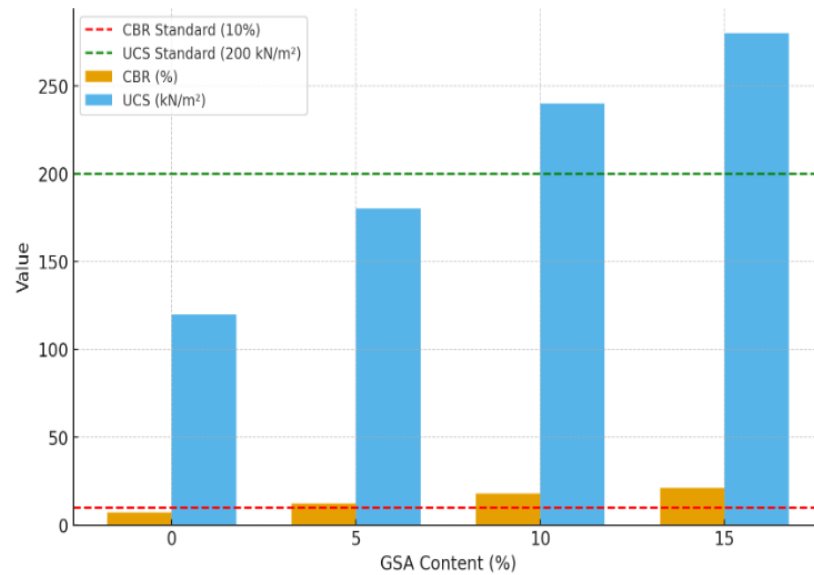


Figure 11: Strength Properties of Untreated and GSA Treated Soil (Bar chart)

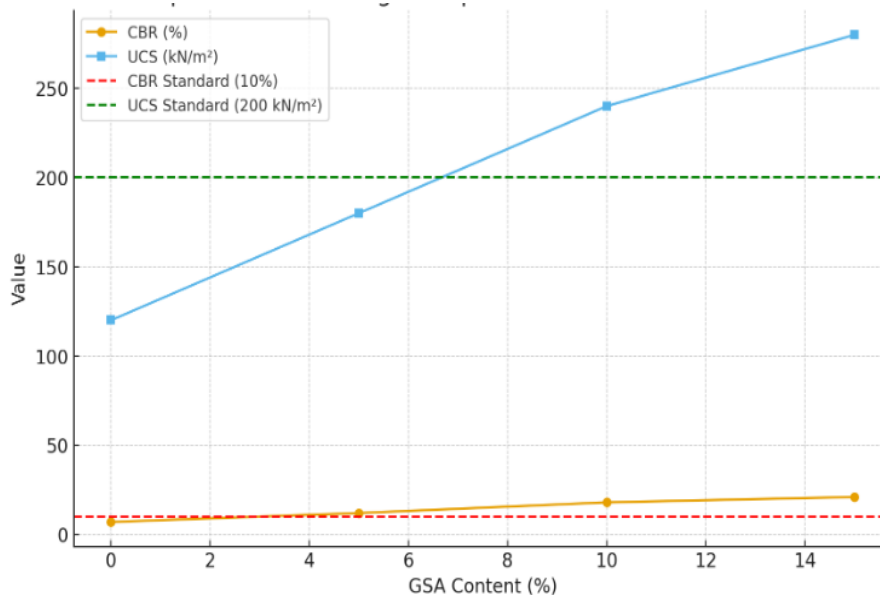


Figure 12: Strength Properties of Untreated and GSA Treated Soil (Line Graph)

3.1.5 Summary of Performance Improvements

Overall, GSA treatment improved the geotechnical properties of Agbede soil across all parameters tested. The optimum performance was observed at 10–15% GSA content, where reductions in plasticity, increases in density, and significant gains in strength were achieved.

Table 7: Summary of Improvements with GSA Stabilization

Property	Untreated Soil	Optimal GSA (10–15%)	Improvement (%)
Plasticity Index (%)	32	14–18	44–56
MDD (g/cm ³)	1.85	1.91–1.92	3–4
OMC (%)	14.3	13.5–13.7	4–6
CBR (%)	7	18–21	157–200
UCS (kN/m ²)	120	240–280	100–133

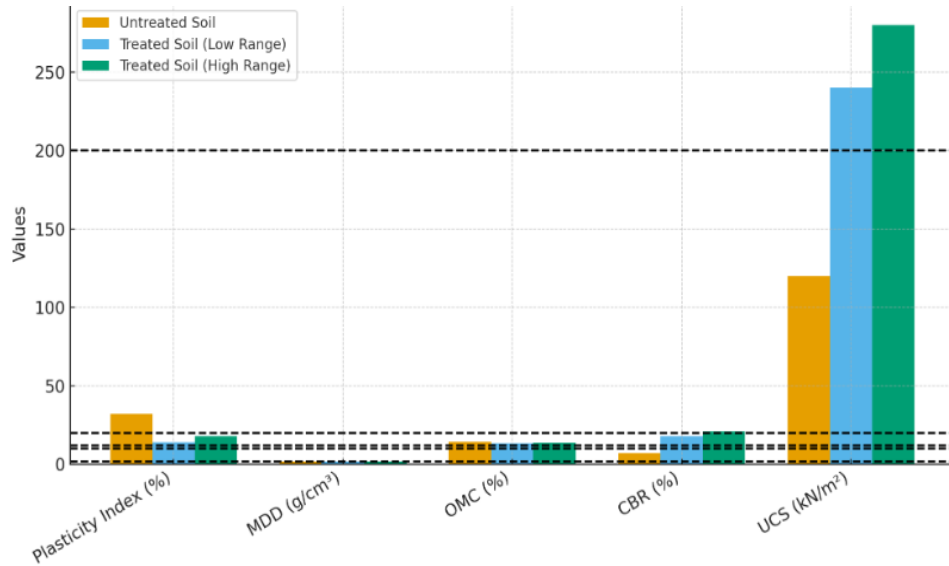


Figure 13: Improvement with GSA Stabilization (Bar chart)

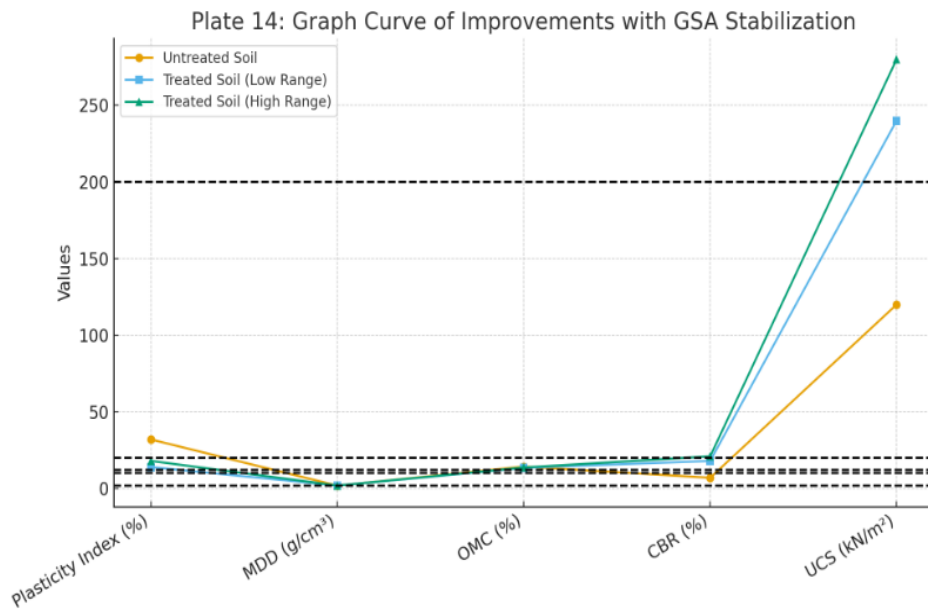


Figure 14: Improvement with GSA Stabilization (Line Graph)

3.2 Discussion

The results show that Agbede soil is dominated by fines (68%), classifying it as highly plastic clay under the USCS, which explains its poor natural engineering behavior. The high plasticity index

(32%) of the untreated soil confirms its expansive nature. However, with GSA stabilization, the PI reduced to 14% at 15% GSA, indicating lower swelling potential and improved workability.

The specific gravity decreased slightly from 2.64 to 2.52 due to the lighter nature of GSA, but values remained within the acceptable geotechnical range. Compaction results showed improvements, with MDD increasing from 1.85 g/cm³ to 1.92 g/cm³ at 10% GSA, while OMC reduced from 14.3% to 13.5%, reflecting denser particle packing and reduced water demand.

Strength properties improved significantly, with CBR rising from 7% to 21% and UCS from 120 kN/m² to 280 kN/m², confirming enhanced load-bearing capacity. Overall, GSA treatment substantially improved the geotechnical properties of the soil, with optimum performance at 10–15% GSA, making it suitable for engineering applications.

5. Conclusion

This research investigated the geotechnical performance of Agbede soil stabilized with groundnut shell ash (GSA). The untreated soil was classified as highly plastic clay, exhibiting a plasticity index of 32%, low strength, and poor load-bearing capacity, making it unsuitable for engineering applications. Laboratory tests revealed that incorporating GSA significantly improved the soil's engineering properties.

At optimum dosages of 10–15% GSA, plasticity index values reduced to 14–18%, indicating improved workability and reduced swelling potential. Maximum dry density increased from 1.85 g/cm³ (untreated) to 1.92 g/cm³, while optimum moisture content decreased, reflecting improved compaction efficiency. Strength indices also improved substantially, with the California Bearing Ratio increasing from 7% to 21% and the unconfined compressive strength doubling from 120 kN/m² to 280 kN/m². The study demonstrates that GSA is an effective and sustainable stabilizer for expansive soils. Beyond improving geotechnical performance, its utilization provides a practical solution for agricultural waste management, reduces reliance on carbon-intensive cement and lime, and supports sustainable infrastructure development in resource-constrained regions.

NOMENCLATURE

f_c^1	Compressive strength of concrete (MPa)
E_c	Modulus of elasticity of concrete (GPa)
ρ	Reinforcement ratio
M	Bending moment (kNm)
V	Shear force (kN)
L	Span length of beam (m)
B	Width of beam section (mm)
d	Effective depth of beam (mm)
A_s	Area of steel reinforcement (mm ²)
τ	Shear stress (N/mm ²)
σ	Normal stress (N/mm ²)

ABBREVIATIONS

RC	Reinforced Concrete
AI	Artificial Intelligence
FEM	Finite Element Method
NDT	Non-Destructive Testing
ASTM	American Society for Testing and Materials
BS	British Standard

IT Information Technology
UAV Unmanned Aerial Vehicle
GIS Geographic Information System
ML Machine Learning

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