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E-mail: editor@iaeme.com, iaemedu@gmail.com Website: www.iaeme.com Mobile: +91-9884798314

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GEOTECHNICAL CHARACTERIZATION AND SUITABILITY OF WEAK SOILS FOR SUSTAINABLE STABILIZATION IN RUKPOKWU, RIVERS STATE, NIGERIA

Smile Daniel George[1], Nurudeen Ahmed Onomhoale[2*], Temple C. Nwofo[3], Chiedozie Francis Ikebude[4], Finjite Dorathy Olali[5]

[1, 3, 4]Centre for Geotechnical & Coastal Engineering Research, Department of Civil Engineering, Faculty of Engineering, University of Port Harcourt, Rivers State, Nigeria.
[2]Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia.
[5]Centre for Petroleum Geosciences (CPG), University of Port Harcourt, Rivers State, Nigeria.
[2, 5]Geoscience and Environment (G&E), Petrous Eco Geosolutions, Port Harcourt, Rivers State, Nigeria.

***Corresponding Author: Nurudeen Ahmed Onomhoale**

ABSTRACT

Weak, moisture-sensitive soils in deltaic environments present major constraints to safe and durable infrastructure. This study provides a comprehensive geotechnical characterization of natural (untreated) soil from Rukpokwu, Obio/Akpor LGA, Rivers State, Nigeria, to assess its engineering suitability and establish a baseline for potential improvement. Representative samples were collected from the subgrade horizon (≈1.0 m) and tested in the laboratory according to BS 1377 procedures for Natural Moisture Content (NMC), Specific Gravity (Gs), Particle Size Distribution (PSD), Atterberg Limits (Liquid Limit [LL], Plastic Limit [PL], and Plasticity Index [PI]), and Standard Proctor Compaction to determine Maximum Dry Density (MDD) and Optimum

Moisture Content (OMC), as well as California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS). Results show a mean natural moisture content of ~18.0%, specific gravity between 2.63 and 2.70, and a predominantly fine-grained matrix dominated by silt and clay. Index tests returned LL ≈ 38%, PL ≈ 17%, and PI ≈ 21%, classifying the soil as a highly plastic clay with significant shrink–swell potential. Compaction tests yielded an MDD of approximately 1.72 g/cm³ at an OMC of about 14.2%. Strength indicators were poor, with a CBR of roughly 3.99% and a UCS of about 433 kPa. Collectively, these findings demonstrate that the natural soil is moisture-sensitive, highly plastic, poorly graded, and of low bearing capacity, unsuitable for direct use as pavement subgrade, shallow foundation support, embankment fill, or backfill without treatment. The study concludes that stabilization is necessary and highlights the potential of sustainable pozzolanic additives from agricultural waste as viable options for improving the soil's engineering performance.

Keywords: Geotechnical characterization, Plastic clay soil, Soil engineering properties, Bearing capacity assessment, Sustainable soil stabilization, Rukpokwu, Niger Delta

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1. Introduction

Weak and moisture-sensitive soils constitute one of the most persistent challenges in geotechnical engineering, particularly within tropical and deltaic environments where high rainfall, shallow groundwater, and fine-grained sedimentary formations dominate (Ahmed et al., 2024a; Reijers 2011). These soils typically exhibit undesirable engineering characteristics such as low shear strength, high compressibility, poor bearing capacity, elevated natural moisture content, and significant shrink–swell potential (De Albuquerque, et al., 2021; Lee et al., 2023). Such behaviors directly influence the performance and durability of foundations, embankments, and pavement structures. In many parts of Nigeria, especially the Niger Delta region, these problems are widespread due to the predominance of young, unconsolidated, and water-sensitive clay and silt deposits (Amajor, 1989; Etu-Efeotor & Akpokodje, 1990).

The engineering challenges posed by these soils have long necessitated various forms of soil treatment and stabilization. Traditional stabilizers such as cement and lime have been widely used because of their ability to enhance soil strength, reduce plasticity, and improve load-bearing performance (Abdi et al., 2021; Chuo & Tsai, 2021). However, growing environmental concerns and the high carbon footprint associated with cement production, combined with the rising costs of industrial stabilizers, have motivated the search for more sustainable and cost-effective alternatives (Mallela et al., 2004). This shift aligns with modern sustainability principles and global engineering efforts aimed at reducing emissions, maximizing resource recovery, and extending infrastructure life cycles (Ma et al., 2022). Before selecting any stabilization strategy, whether conventional or innovative, it is essential to conduct a comprehensive geotechnical characterization of the natural soil. Soil characterization provides insights into essential properties such as particle size distribution, consistency limits, compaction behavior, bearing resistance, and unconfined strength (Javdanian & Lee, 2019). These parameters inform foundational engineering decisions regarding suitability, material behavior under load, moisture susceptibility, and expected performance in the field (Jiang et al., 2019; Iravanian et al., 2022). Without such baseline understanding, stabilization measures may be ineffective, uneconomical, or even detrimental to long-term structural integrity.

Rukpokwu, located within Obio/Akpor Local Government Area of Rivers State, is emblematic of the geotechnical limitations common to the Niger Delta. The area is characterized by silty clay and clayey sand deposits, high groundwater levels, poor drainage, and intense rainfall, factors that collectively exacerbate soil instability (Omange et al., 1988; Omange & Aitsebaomo, 1989). The region has witnessed rapid urbanization, with growing residential, commercial, and roadway development. Unfortunately, these engineering activities are frequently hindered by subgrade failure, foundation settlement, pavement rutting, and slope instability, all of which are symptomatic of weak natural soils (Nwankwoala & Warmate, 2014; Oghenero, Akpokodje, & Tse, 2014). These challenges underscore the pressing need for detailed assessment and improvement of local soils to ensure safe, durable, and sustainable infrastructure (Onomhoale et al., 2025a). Despite the recognized geotechnical difficulties of the Niger Delta, there remains limited locality-specific data for Rukpokwu, particularly regarding the mechanical behavior of its natural soils before stabilization (Afolayan et al., 2019). Most existing studies focus on broader regional soil behavior or emphasize the performance of stabilized soils without providing adequate baseline characterization. This creates a notable gap in understanding natural engineering properties of soils in Rukpokwu and their suitability for construction projects without modification.

This study addresses this critical gap by conducting a comprehensive geotechnical characterization of the natural soil in Rukpokwu using standard laboratory procedures in accordance with BS 1377 (BSI, 2016). Key parameters evaluated include natural moisture content, specific gravity, grain size distribution, consistency limits, linear shrinkage, compaction characteristics, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). By establishing a detailed baseline of the soil's engineering properties, the study not only determines its limitations but also provides foundational data for selecting appropriate and sustainable stabilization strategies in subsequent phases of research. Ultimately, the findings of this study contribute to improved geotechnical design practice in the Niger Delta, support sustainable infrastructure development, and enable more effective application of environmentally friendly soil stabilization technologies.

2. Study Area

Rukpokwu is a rapidly expanding peri-urban settlement situated within the Obio/Akpor Local Government Area of Rivers State, in the eastern Niger Delta region of Nigeria (Opu-Ogulaya, 1973; Ngulube, 2011). The locality lies geographically between latitudes 4°50′N and 5°10′N and longitudes 6°55′E and 7°10′E (Fig. 1), placing it within one of the most dynamic geomorphic and hydrological environments in West Africa (Ahmed et al., 2024b). The Niger Delta is well documented as a zone dominated by young, unconsolidated sediments that exhibit significant geotechnical challenges, including low shear strength, high compressibility, and moisture susceptibility (Reijers, 2011; Omange et al., 1988). These characteristics make Rukpokwu a critical area for geotechnical evaluation, particularly in relation to sustainable stabilization and infrastructure development.

2.1 Climate and Hydrological Conditions

Rukpokwu experiences a humid equatorial climate characterized by a long rainy season from March to October and a short dry season between November and February. The region records an annual rainfall ranging between 2,000 and 2,500 mm, aligning with observations for the wider Niger Delta climate system, where high precipitation intensity and frequency contribute to extremely wet soil conditions (Onomhoale, 2025b). Relative humidity remains consistently high, often exceeding 85%, while temperatures typically fluctuate from 25°C to 32°C, creating conditions that promote elevated natural moisture content in near-surface soils (Adejuwon, 2012). Hydrologically, the area is influenced by a shallow groundwater regime, which is common throughout the coastal alluvial terrains of the Niger Delta (Abam & Fubara, 2022). Groundwater levels often rise to near-surface elevations during the rainy season, leading to prolonged soil saturation and significant reductions in soil strength. Seasonal variations in moisture lead to repeated wetting and drying cycles, which are known to enhance shrink–swell activity in clayey soils and accelerate deterioration of pavement and foundation performance (Akpoborie & Ovuru, 2021). These climatic and hydrological dynamics play a central role in defining the engineering behavior of Rukpokwu soils.

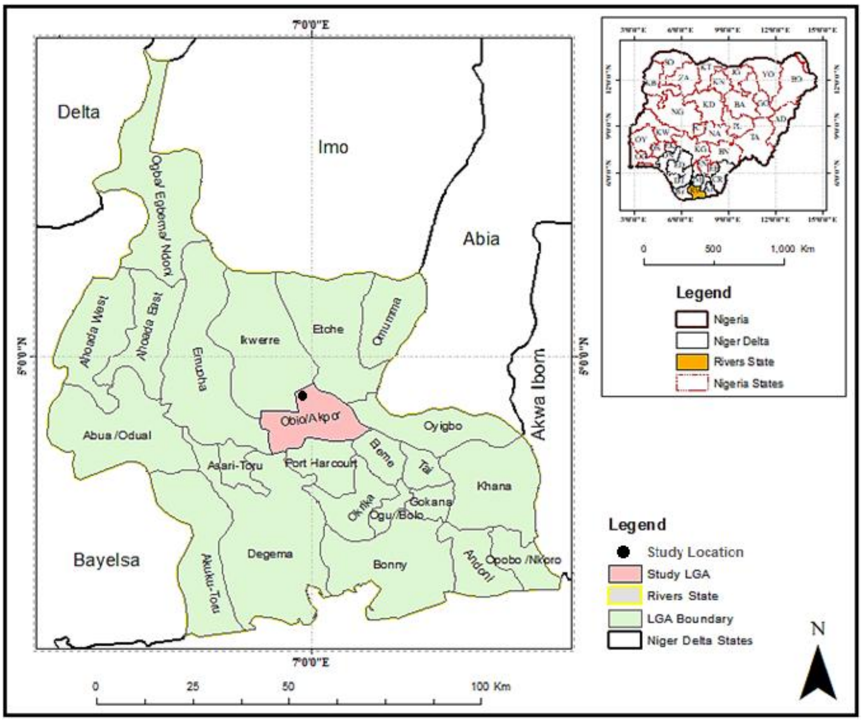

Fig. 1: Map showing Nigeria, Rivers State, Study LGA and Study Location (Source: Digitized by Author)

2.2 Topography and Drainage Characteristics

The topography of Rukpokwu is predominantly flat to gently undulating, with elevations ranging from approximately 10 to 15 meters above sea level. This low-relief landscape is typical of the Niger Delta floodplain environment, where sediment accumulation, shallow gradients, and poor natural drainage converge to produce persistent waterlogging (Njoku et al., 2020). Numerous depressional areas within the terrain act as seasonal retention basins, enhancing infiltration and inhibiting runoff. Drainage challenges are further compounded by inadequate urban drainage infrastructure, leading to localized flooding during high-intensity storms (Musa et al., 2014; Abam & Fubara, 2022). Waterlogging significantly alters the geotechnical performance of fine-grained soils by decreasing their apparent cohesion, increasing plasticity, and reducing shear strength, conditions widely associated with settlement instability and pavement failure in the Niger Delta (Nwankwoala & Warmate, 2014). Thus, the drainage setting is not only a defining environmental attribute but also a major contributor to the engineering problems encountered in Rukpokwu.

2.3 Geological and Soil Characteristics

Geologically, Rukpokwu is underlain by Quaternary sediments composed of coastal plain sands, silty clays, clayey sands, and localized lateritic soils (Reijers, 2011). These deposits represent the uppermost units of the Niger Delta stratigraphic sequence, which is characterized by weakly consolidated, fine-grained, and moisture-sensitive materials (Etu-Efeotor & Akpokodje, 1990). The silty clay soils found across much of the study area exhibit medium to high plasticity, poor drainage, and pronounced shrink–swell behavior (Oghenero et al., 2014). Such soils undergo significant volume changes during seasonal moisture fluctuations, leading to cracking, settlement, and loss of bearing capacity, conditions that have been documented extensively in tropical clay environments and Nigerian subgrade studies (Omange et al., 1988). Clayey sands present in some locations provide marginally better drainage and shear strength, but they still fall below desirable thresholds for subgrade applications without modification. Lateritic soils, while stronger due to their ferruginous composition, can soften considerably when subjected to prolonged wetting, a common event in Rukpokwu due to its climate and hydrology (Abam & Fubara, 2022). The geological composition of the area provides inherent limitations for construction activities, underpinning the necessity for stabilization efforts.

2.4 Engineering Context and Construction Challenges

The increasing rate of urbanization in Rukpokwu has amplified the demand for reliable and stable ground conditions to support buildings, transportation networks, and drainage infrastructure. However, the predominance of weak fine-grained soils has contributed to recurrent foundation settlement, pavement deformation, embankment failure, and erosion-related instability (Omange & Aitsebaomo, 1989). These geotechnical deficiencies often necessitate costly remediation measures and can critically affect the longevity and structural integrity of civil engineering works (Ahmed et al., 2024a). Studies conducted in similar Niger Delta environments highlight that the combination of high rainfall, low-lying terrain, high groundwater levels, and expansive clayey soils produces a suite of engineering challenges not easily addressed through conventional construction methods (Nwankwoala & Warmate, 2014; Oghenero et al., 2014). This complex interplay of geologic, climatic, and hydrologic factors forms the foundation for characterizing the natural soil in Rukpokwu and identifying sustainable strategies for improvement.

3. Materials and Methods

3.1 Research Design

This study employed an experimental laboratory research design to characterize the physical and geotechnical behavior of the natural, untreated soil collected from Rukpokwu, Rivers State. This design was considered appropriate because laboratory experimentation allows direct measurement of soil consistency, strength, compaction behavior, and bearing resistance under controlled conditions. Following the principles of standardized soil testing, all procedures adhered strictly to the British Standards for Soil Testing (BS 1377:2016) to ensure methodological integrity, accuracy, and reproducibility (BSI, 2016). The research design focused on determining index properties (moisture content, specific gravity, particle size distribution, Atterberg limits, linear shrinkage) and engineering strength characteristics (compaction behavior, California Bearing Ratio, and Unconfined Compressive Strength). All tests were performed in triplicate to strengthen statistical confidence and minimize the effects of sample variability (ASTM, 2017).

3.2 Sample Collection

Soil samples were obtained from a representative location within Rukpokwu at 1.0 m depth, corresponding to the typical subgrade horizon in road and foundation engineering. This depth was selected to avoid the influence of organic-rich topsoil and to capture the natural engineering properties of the soil profile most commonly subjected to structural loading. Disturbed samples were collected for classification tests, including moisture content, Atterberg limits, particle size distribution, shrinkage, and compaction (ASTM, 2017). These samples were extracted using hand augers and small excavation tools. Where soil consistency permitted, undisturbed samples were collected using thin-walled Shelby tubes specifically for Unconfined Compressive Strength (UCS) testing. Immediately after retrieval, each sample was placed in airtight polyethylene bags, labeled with location, depth, date, and sample identification code, and transported promptly to the geotechnical laboratory to preserve moisture content and structural integrity (IAEA, 2006). This procedure ensured the accuracy of laboratory test results by maintaining the natural condition of the soil.

3.3 Laboratory Testing

A full suite of geotechnical tests was performed on the untreated soil to determine its baseline physical and engineering characteristics. All laboratory tests followed the procedures outlined in BS 1377 (BSI, 2016). The tests conducted were:

- Natural Moisture Content
- Specific Gravity
- Particle Size Distribution (Sieve + Hydrometer Analysis)
- Atterberg Limits (Liquid Limit, Plastic Limit, Plasticity Index)
- Linear Shrinkage
- Standard Proctor Compaction Test
- California Bearing Ratio (CBR)
- Unconfined Compressive Strength (UCS)

Table 1 is presented below to summarize all laboratory tests performed in this study along with their corresponding standards and engineering purpose.

Table 1: Summary of Laboratory Tests Conducted

Test	Parameter Measured	Standard	Purpose
Natural Moisture Content	Water content (%)	BS 1377-2	Soil consistency & classification
Specific Gravity	Gs of soil solids	BS 1377-2	Compaction & strength calculations
Particle Size Distribution	Grain size gradation	BS 1377-2	Soil classification
Atterberg Limits	LL, PL, PI	BS 1377-2	Plasticity & engineering behavior
Linear Shrinkage	Shrinkage (%)	BS 1377-2	Volume change potential
Standard Proctor Test	OMC, MDD	BS 1377-4	Compaction suitability
California Bearing Ratio	CBR (%)	BS 1377-5	Bearing capacity
UCS	Axial compressive strength	BS 1377-5	Cohesive soil strength

3.3.1 Natural Moisture Content

The natural moisture content represents the percentage of water in the soil at the time of sampling. It provides insight into soil workability and strength behavior (Ahmed et al., 2024a). Before applying the formula used to determine moisture content, it is important to define the three primary mass values measured during testing: Where, m_1 = mass of empty container, m_2 = mass of container + wet soil sample, and m_3 = mass of container + dried soil after oven-drying. Using these masses, the natural moisture content was calculated using Equation (1), which expresses moisture content as the ratio of the mass of water lost during drying to the mass of oven-dried soil solids.

$$\mathbf{w} = \frac{\mathbf{m_2 - m_3}}{\mathbf{m_3 - m_1}} \mathbf{X\,100} \qquad (1)$$

3.3.2 Specific Gravity

Specific gravity (Gs) determines the ratio of the density of soil solids to the density of water (ASTM, 2017). Before presenting the governing equation, it is essential to describe the masses involved in the density bottle method: Where, m_1 = empty bottle, m_2 = bottle + dry soil, m_3 = bottle + soil + water, and m_4 = bottle + water only. To compute specific gravity, Equation (2) accounts for the displaced water volume caused by soil addition.

$$\mathbf{Gs} = \frac{\mathbf{m_2 - m_1}}{(\mathbf{m_4 - m_1}) - (\mathbf{m_3 - m_2})} \qquad (2)$$

3.3.3 Particle Size Distribution

Particle size analysis combined wet sieving and hydrometer testing following BS 1377 (BSI, 2016). Soil was soaked for 24 hours, washed through a No. 200 sieve (75 µm), oven-dried, and dry-sieved. The <75 µm fraction was dispersed using sodium hexametaphosphate and analyzed by hydrometer to obtain percent fines and a complete gradation curve. Wet sieving removed coarse fractions, while hydrometer analysis quantified sedimentation behavior in suspension (Stokes' law). These results were used to classify the soil according to geotechnical classification systems and compared against Nigerian subgrade studies (Okeniyi et al., 2022).

3.3.4 Atterberg Limits

Liquid limit (LL) was measured using the Casagrande cup and plotted on semi-logarithmic paper to determine the moisture content corresponding to 25 blows, while the plastic limit (PL) was obtained through thread rolling until crumbling occurred at approximately 3 mm in diameter (BSI, 2016). The Atterberg limits classify soil consistency across varying moisture states and provide essential insight into its potential for deformation, swelling, and shrinkage (ASTM, 2017). Tests conducted included:

- **Liquid Limit (LL)** determined using the Casagrande apparatus
- **Plastic Limit (PL)** measured using the thread-rolling method
- **Plasticity Index (PI)** calculated as PI = LL – PL

Together, these parameters quantify the soil's plasticity and moisture sensitivity, both of which are critical for predicting engineering performance. High values of LL and PI typically indicate the presence of active clay minerals capable of absorbing significant amounts of water, resulting in substantial volume changes under wetting and drying conditions. This behaviour directly influences shear strength, compressibility, and overall stability.

3.3.5 Standard Proctor Compaction Test

Standard Proctor tests (BS 1377-4) used a 100 mm diameter mould and 2.5 kg rammer (25 blows per layer, three layers). Soil passing 4.75 mm was mixed at incremental water contents (2% steps), compacted, and bulk densities measured. The Standard Proctor Test determined the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) (BSI, 2016). To introduce the compaction equations properly; Bulk density (ρ) is computed first, using mould mass values: Where, M_1 = mass of empty mould + base, and M_2 = mass of mould + compacted soil. Bulk density was calculated using Equation (3):

$$\mathrm{p} = \frac{M_2 - M_1}{Volume\ of\ mould} \tag{3}$$

After determining moisture content (w), dry density (ρd) was obtained using Equation (4):

$$\mathrm{p}_d = \frac{\mathrm{p}}{1+w} \tag{4}$$

3.3.6 California Bearing Ratio (CBR) Test

Conducted per BS 1377-5. Soil passing 2 mm sieve was compacted in the CBR mould in three layers (56 blows per layer), conditioned (soaked for soaked CBR where applicable), and penetrated with the standard plunger. CBR (%) was calculated as the ratio of applied penetration force to standard force (1370 kg at 2.5 mm or 2055 kg at 5 mm) × 100 (BSI, 2016). Applied force was obtained from proving-ring readings and instrument calibration. The readings were recorded and plotted and the CBR calculated using Equation (5).

$$\mathbf{CBR} = \frac{\textbf{Applied force}}{\textbf{standard value}}\ \mathbf{X\ 100\%} \tag{5}$$

The applied load was calculated using plunger readings and calibration values, as shown in Equation (6):

$$\textbf{Applied force} = \frac{\textbf{plunger reading x proving ring factor}}{\mathbf{1000}} \tag{6}$$

Where; the standard value = 1370Kg for 2.5mm penetration and 2055Kg for 5mm penetration.

3.3.7 Unconfined Compressive Strength (UCS)

Per BS 1377-5, cylindrical specimens (where undisturbed samples were available) were tested at a constant axial strain rate until failure. Peak axial stress (corrected for changing cross-sectional area) was recorded as UCS (BSI, 2016). When undisturbed samples were not available, remolded specimens compacted at OMC and target dry density were used and results interpreted with caution.

4. Results and Discussion

The laboratory investigation produced a comprehensive dataset describing the physical and geotechnical behaviour of the natural (unstabilized) soil from Rukpokwu. The results reported below establish the baseline characteristics required to judge the soil's suitability for construction and to justify the need for stabilization.

4.1 Natural Moisture Content

The natural moisture content of the soil was determined using three replicate samples, with values ranging from 17.90% to 18.10%, and an average of 18.02%. This moisture level is characteristic of fine-grained, cohesive soils typical of humid tropical environments, where clay soils retain significant moisture due to their high surface area and capillary suction (Akpoborie & Ovuru, 2021; Ahmed et al., 2024a). A natural moisture content around 18% suggests that the soil is moderately wet relative to its likely plastic limit. Such moisture levels influence both the soil's shear strength and its compaction response, often resulting in reduced bearing capacity and increased compressibility (Okeniyi et al., 2022; Abija et al., 2025). The low variability among the three tests also reflects uniformity in the soil profile at the sampling depth and reliability in sample handling. The measured moisture content supports field observations of soft, plastic soil conditions in Rukpokwu and aligns with typical values reported for clayey soils within the Niger Delta region (Ehibor et al., 2022). This moisture condition indicates that the soil is prone to large deformation under load and requires modification for engineering applications. The detailed mass measurements and computed moisture contents for each replicate are summarized in Table 2.

Table 2. Natural Moisture Content

S/N	Test Sample No. Observations	1	2	3
1	Mass of container alone(m1)	39.67	39.58	39.93

2	Mass of container + wet soil (m2)	132.52	132.03	132.02
3	Mass of container + oven dry soil (m3)	118.29	117.88	118.04
5	m3-m1	78.62	78.3	78.11
6	m2-m3	14.23	14.15	13.98
7	Applying Equation (3.1), w	18.10	18.07	17.90

4.2 Specific Gravity

The specific gravity values obtained for the untreated soil samples ranged from 2.63 to 2.70, with an average of 2.66. This falls within the normal range for inorganic clay minerals (2.60–2.80), indicating that the soil is predominantly composed of aluminosilicate minerals typically found in tropical clay deposits (Onomhoale et al., 2025b). Specific gravity is an important index parameter because it influences compaction characteristics and volumetric relationships. The value obtained here suggests that the soil has a moderately dense mineral structure consistent with kaolinitic or mixed-layer clays commonly recorded in the Niger Delta (Okeniyi et al., 2022; Ahmed et al., 2024a). A Gs of 2.66 is neither excessively high nor low, implying that the soil is not unusually organic or ferruginous. Given this typical mineral density, any challenges associated with the soil's engineering performance are not due to unusual mineral composition but result from its plasticity, fine-grained nature, and moisture sensitivity. Table 3 presents the raw mass readings and computed Gs values for each trial.

Table 3. Specific Gravity Test

S/N	Test no Observations	1	2	3
1	Mass of density bottle alone(m1)	27.65	27.55	27.50
2	Mass of density bottle + oven dry soil (m2)	53.06	53.49	53.50
3	Mass of density bottle + oven dry soil + distilled water (m3)	96.17	96.68	96.27
4	Mass of density bottle + distilled water (m4)	80.36	80.36	80.17
5	m3-m2	43.11	43.19	42.77
6	m4-m1	52.71	52.81	52.67
7	(m4-m1)-(m3-m2)	9.60	9.62	9.9
8	m2-m1	25.41	25.94	26
9	Applying Equation (3.2), Gs	2.65	2.70	2.63

The measured Gs supports the PSD and Atterberg-limit results in indicating a predominantly inorganic, fine-grained soil that derives its weakness from texture and moisture rather than unusual mineral density (Okeniyi et al., 2022).

4.3 Particle Size Distribution

The particle size distribution curve demonstrates that the soil contains a predominantly fine-grained matrix, with the majority of particles passing the 0.075 mm sieve. This classification confirms that the soil is dominated by silt and clay fractions, typical of alluvial and residual soils in the Niger Delta basin (Abija et al., 2025). Such fine-grained soils typically exhibit low permeability, high water retention, poor drainage characteristics, and a pronounced susceptibility to consolidation settlement (Akpoborie & Ovuru, 2021). These inherent properties significantly limit the soil's natural engineering performance and contribute to the challenges associated with its use in structural or transportation infrastructure without modification. Figure 2 is the PSD curve and highlights the percentage of fines (<0.075 mm).

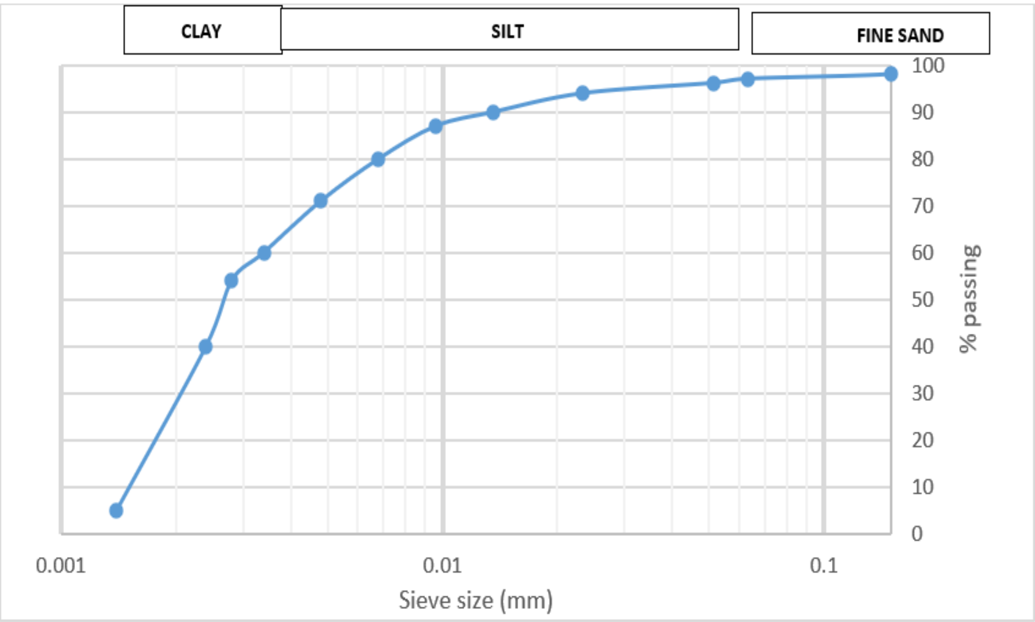

Figure 2. Particle Size Distribution (Gradation) Curve for Untreated Soils

These characteristics collectively reduce soil strength and increase deformation potential under loading, making such soils unsuitable for pavement and foundation applications without treatment. The PSD curve also shows a narrow gradation, indicating poor soil structure and inadequate particle interlocking, an important factor contributing to low CBR and UCS values. According to Howard (1986), soils with more than 50% fines behave as cohesive soils, and their engineering suitability depends heavily on their Atterberg limits. The PSD result confirms that the soil is fine-grained, poorly graded, highly plastic, and moisture susceptible, supporting the need for stabilization. The PSD curve's narrow gradation and dominance of fines explain the observed high plasticity, low CBR and reduced compaction efficiency. Poor particle interlocking, typical of such soils, contributes to low shear resistance and high compressibility under load (Okeniyi et al., 2022).

4.4 Atterberg Limits

The liquid limit (LL), plastic limit (PL), and plasticity index (PI) results were approximately 38.21%, 17.36%, and 20.85%, respectively. These values place the soil within the high plasticity (CH) classification according to the Unified Soil Classification System (ASTM, 2017). A PI above 20% indicates substantial clay activity and strong moisture dependence. High-plasticity soils tend to swell upon wetting and shrink significantly during drying, leading to differential settlement and structural distress in lightly loaded foundations (Abija et al., 2025). These values align with thresholds reported by Akpoborie and Ovuru (2021) for highly compressible Nigerian clays and indicate that the soil possesses low shear strength, high compressibility, poor workability, and a pronounced tendency to undergo shrink–swell behaviour. Together, these characteristics further underscore the soil's unsuitability for engineering applications without appropriate modification or stabilization. Such soils are considered problematic for engineering use and require modification to reduce plasticity and improve strength (Okeniyi et al., 2022). The Atterberg limits therefore reinforce the soil's classification as a weak, moisture-sensitive clay. Table 4 and 5 summarizes the LL and PL test data used to compute PI, and Figure 3 shows the liquid-limit determination plot.

Table 4: Liquid Limit (LL) Results

	Liquid Limit (%)		
Container No.	1	2	3
No. of Blows	36	24	12
Wet sample + Container (mt+mc)	234	237	235
Dry sample + Container (md+mc)	183	184	182
Water (mw= mt- md)	51	53	53
Container, mC	46	45	47
Dry soil, md	137	139	135
Moisture Content,w=(mw/md)*100	37.23	38.13	39.26

Table 5: Plastic Limit (PL) Results

Container No.	1	2	3
Wet sample + Container (mt+mc)	72	74	71
Dry sample + Container (md+mc)	67.5	69.2	66.7
Water (mw= mt- md)	4.5	4.8	4.3
Container, mC	42	41	42
Dry soil, Wd	25.5	28.2	24.7
Moisture Content,w=(mw/md)*100	17.65	17.02	17.41

The high LL and PI corroborate the clayey classification from PSD. Such index properties predict swelling and shrinkage tendencies that are detrimental to shallow foundations and pavement subgrades. Practical implications include excessive post-construction settlement and potential for heave, necessitating stabilization or removal/replacement in engineering works (De Albuquerque et al., 2021).

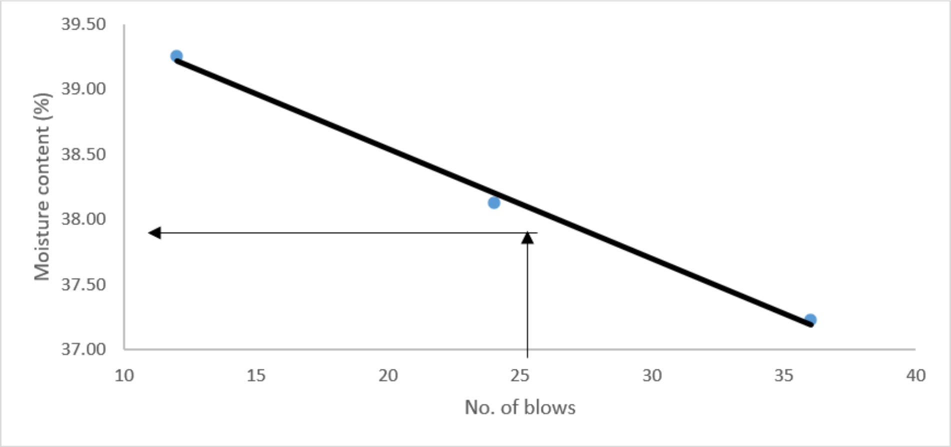

Figure 3: Liquid Limit Determination for Untreated Soils

4.6 Standard Proctor Compaction Characteristics

he compaction curve for the soil indicates a Maximum Dry Density (MDD) of approximately 1.72 g/cm³ and an Optimum Moisture Content (OMC) of about 14.2%, values that fall within the typical range for fine-grained lateritic clays reported in Nigerian geotechnical studies (Okon et al., 2022). The combination of a relatively low MDD and a moderate OMC reflects the soil's high fines content, elevated plasticity, and substantial water absorption capacity. These characteristics collectively contribute to reduced compaction efficiency and increased sensitivity to moisture fluctuations, emphasizing the soil's poor performance under standard compactive effort (Omotoso et al., 2012). Due to these characteristics, compaction in the field would be highly sensitive to moisture fluctuations. Even slight increases in moisture content above the OMC could significantly reduce dry density and strength, complicating construction operations and compromising long-term performance (Abija et al., 2025). The compaction results confirm that the soil in its natural state is unsuitable as a load-bearing subgrade without stabilization. Figure 4 displays the compaction curve with MDD and OMC annotated.

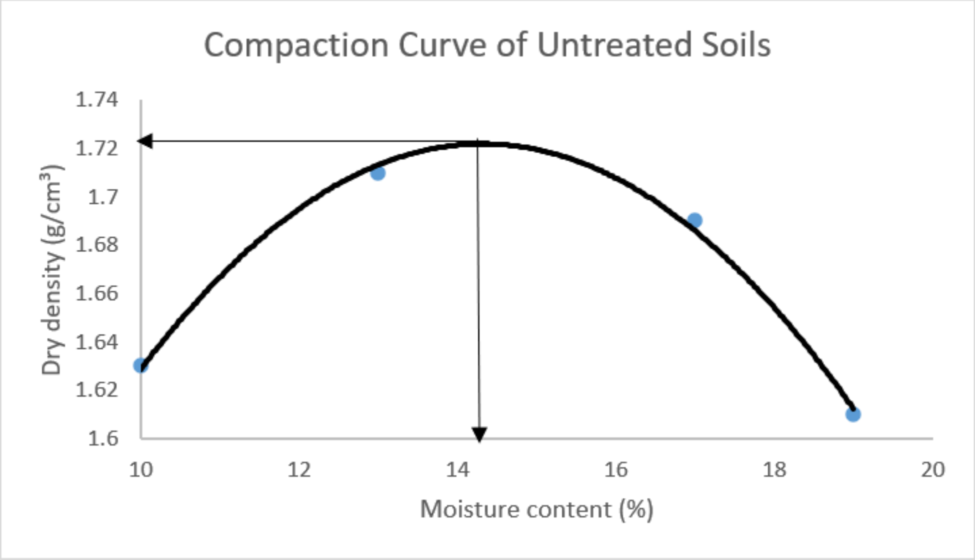

Figure 4: Compaction Curve (Dry density vs Moisture Content) for Untreated Soils

The comparatively low MDD and moderate OMC reflect the high fine content and plasticity of the soil; such soils achieve lower peak densities under standard compactive energy than coarse, granular materials. Field compaction will therefore be sensitive to moisture control, if moisture increases beyond OMC, dry density and strength can decline markedly, leading to poor subgrade performance (Okeniyi et al., 2022).

4.7 California Bearing Ratio (CBR)

The CBR value of the untreated soil was determined to be approximately 3.99%, a value significantly below the minimum requirement for subgrade soils, which typically ranges between 5% and 10% depending on design specifications (Ehibor et al., 2022). Soils with CBR values below 5% are commonly classified as very poor subgrade materials. A CBR of 3.99% therefore indicates poor resistance to penetration, a high susceptibility to rutting under traffic loads, and a very low load-bearing capacity, all of which reinforce the conclusion that the soil is unsuitable for pavement or other load-bearing applications in its natural state (Irokwe et al., 2022). This performance is expected given the soil's high plasticity, high moisture content, and fine-grained structure. Low CBR values are commonly reported for clayey Niger Delta soils and form the basis for using stabilizers in road construction (Okeniyi et al., 2022). The result here further demonstrates that the soil cannot support pavement layers or structural foundations without improvement. The penetration loads and computed CBR values with the corresponding load–penetration curve is plotted and presented in Table 5.

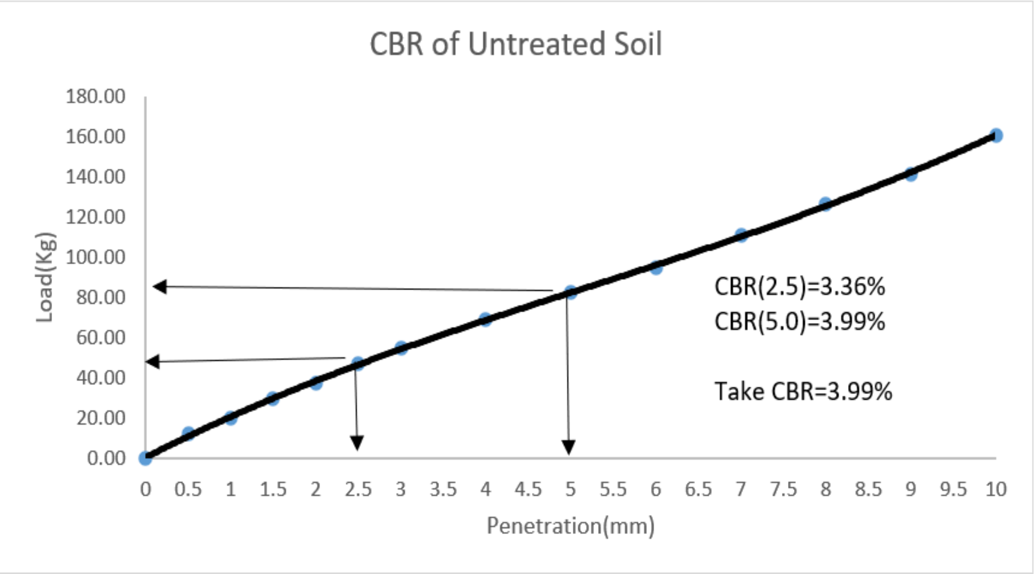

Figure 5: Load Penetration Curve (CBR Determination) for Untreated Soils

A CBR of 3.99% classifies the soil as a very poor subgrade, unsuitable for pavement sub-bases or bases without improvement (ASTM, 2017). Low CBR values stem from high plasticity, high moisture content, and lack of granular interlock. This quantifies the need for stabilization or subgrade replacement in road construction designs for the area.

4.8 Unconfined Compressive Strength (UCS)

The UCS test yielded a peak compressive stress of approximately 433 kPa, which falls within the expected range for weak to moderately strong clay soils (200–500 kPa), as noted by ASTM (2017). The corresponding stress–strain curve demonstrates an initial linear elastic response, followed by a gradual transition into a plastic deformation phase before failure occurs at relatively low axial stress levels (Okeniyi et al., 2022). A UCS value of 433 kPa therefore confirms that the soil possesses low shear strength, exhibits high deformability under load, and has a limited capacity to withstand compressive stresses, characteristics that further underscore its unsuitability for structural applications in its natural state (Akpoborie & Ovuru, 2021). The interpretation of UCS and its use as a performance indicator follows established practice. These findings are consistent with earlier results from the Atterberg limits and CBR tests, reinforcing the soil's classification as a weak clay unsuitable for structural applications in its natural state. Omange et al. (1988) similarly reported UCS values around 400–450 kPa for untreated lateritic clays prior to stabilization, underscoring that the soil has minimal natural strength and requires modification. The full load–displacement data are given in Table 6 and the stress–strain curve is plotted in Figure 6.

Table 6: UCS Result for Untreated Soils

Compression, Δl (mm)	Strain, ε = Δl/l0	Force, F (N)	Corrected Area (mm2), A= A0/1-ε	Compressive Stress(kPa), σ1= 1000F/A
0	0.00000	0	2642	0
0.042	0.00036	44	2643	17
0.107	0.00092	109	2644	41
0.215	0.00185	181	2647	68
0.325	0.00280	235	2649	89
0.403	0.00347	267	2651	101
0.513	0.00442	294	2654	111
0.626	0.00540	347	2656	131
0.703	0.00606	385	2658	145
0.787	0.00678	412	2660	155
0.834	0.00719	433	2661	163

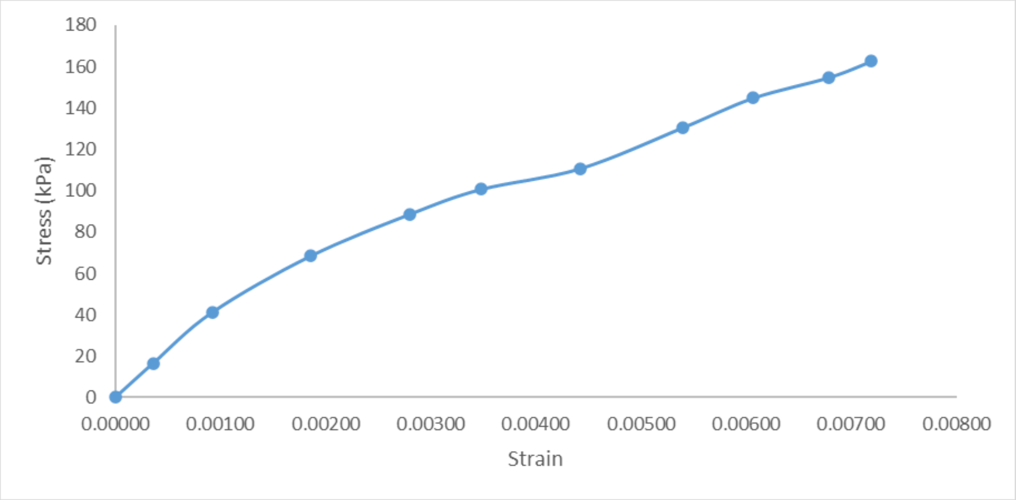

Figure 6: Stress-Strain Curve for Untreated Soils

The UCS result corroborates other indicators of limited natural strength (CBR, Atterberg limits). Although 433 kPa lies within reported ranges for unstabilized clays, it is insufficient for many structural applications without modification or deeper foundations (Iravanian et al., 2022). The stress–strain curve's shape, linear elastic behavior followed by plastic deformation, indicates limited ductility and strength mobilization under axial loading, warning against reliance on the natural soil for shallow load-bearing structures (Nwankwoala & Warmate, 2014). The combined laboratory data, natural moisture content (~18%), specific gravity (~2.66), predominance of fines in the PSD, high Atterberg limits (PI ≈ 20.85%), MDD ≈ 1.72 g/cm³ at OMC ≈ 14.2%, low CBR (~3.99%), and UCS ≈ 433 kPa, collectively indicate that the natural soil in Rukpokwu is fine-grained, highly plastic, moisture-sensitive, and of low engineering strength. These characteristics render the soil unsuitable for direct use in pavement subgrades, shallow foundations, or load-bearing embankments without improvement, stabilization or replacement (Okeniyi et al., 2022). The combination of high fines, elevated LL/PI, and low MDD under standard compaction underscores the vulnerability of the soil to moisture variations and mechanical loading. The results provide a baseline for planning stabilization strategies and for the subsequent comparative studies of soil improvement techniques.

5. Engineering Suitability Evaluation

The engineering evaluation of the natural soil from Rukpokwu was based on a synthesis of its physical, index, compaction, and strength properties. Taken together, the results indicate that the soil exhibits the characteristic behaviour of weak, fine-grained clay soils prevalent in the Niger Delta, which are known for their instability under varying moisture and loading conditions (Omotoso et al., 2012). The parameters measured, including natural moisture content, specific gravity, particle size distribution, Atterberg limits, compaction characteristics, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS), provide a comprehensive appraisal of its engineering performance (Irokwe et al., 2022).

First, the high natural moisture content (~18%) reflects the soil's strong affinity for water, consistent with cohesive soils whose hydrophilic clay minerals retain moisture and cause volume changes. This moisture sensitivity decreases shear strength and increases settlement potential under load (Okon et al., 2020). Second, the specific gravity (~2.66) aligns with typical inorganic clays, suggesting that the soil's poor engineering performance is not mineralogically driven but primarily due to its fine texture and plasticity (Azam et al., 2013). The particle size distribution confirms that the soil is dominated by fines, with a large proportion passing the 0.075 mm sieve, indicative of a silt–clay matrix with low permeability and high compressibility (Okeniyi et al., 2022). This directly correlates with the results from the Atterberg limit tests, where the Plasticity Index (~20.85%) positions the soil in the high-plasticity (CH) category. High-plasticity soils typically undergo significant shrink–swell cycles, posing challenges to structural integrity, particularly in lightly loaded systems such as pavements and shallow foundations (Abija, 2025).

Compaction test results further reinforce these deficiencies. The Maximum Dry Density (MDD ≈ 1.72 g/cm³) and Optimum Moisture Content (OMC ≈ 14.2%) suggest a soil that compacts poorly and requires tight moisture control to achieve adequate field performance (Hejazi et al., 2012). Such soils tend to lose density rapidly when moisture deviates even slightly from the optimal range, complicating construction operations (Ahmed et al., 2024a).

Structurally, the soil displays inadequate strength. The CBR value (~3.99%) places it significantly below accepted subgrade standards (ASTM, 2017), classifying it as a very poor load-bearing material. The UCS (~433 kPa), while within the range for weak clays, is insufficient for supporting sustained compressive stresses typically encountered in geotechnical systems. These combined strength indicators confirm that the natural soil cannot safely accommodate traffic loads, foundation stresses, or embankment pressures without modification (Niyomukiza et al., 2021). Overall, the engineering assessment demonstrates that the natural soil from Rukpokwu is unsuitable for subgrade, embankment, or foundation applications in its untreated state. Table 7 summarizes the engineering behaviour of the soil.

Table 7: Summary of Soil Engineering Behaviour and Implications.

Property	Implication for Engineering Use
High Plasticity Index (≈20%)	Predicts high shrink–swell potential; unstable for subgrades and pavements
High fines content	Promotes poor drainage and high compressibility
High natural moisture content	Increased deformation risk; low shear strength
Low CBR (~3.99%)	Unsuitable for traffic loading; poor pavement support
Low UCS (~433 kPa)	Weak load-bearing capacity; unsuitable for foundations
Moderate OMC and low MDD	Difficult moisture control; poor compaction behaviour

These findings lead to the clear conclusion that the soil is not appropriate for direct use in road pavement layers, shallow foundations, embankment construction, or backfilling operations (Akpoborie & Ovuru, 2021). Its high plasticity, moisture sensitivity, low bearing capacity, and weak compressive strength collectively increase the likelihood of excessive settlement, shrink–swell behaviour, loss of density, and premature structural failure when subjected to loading or environmental fluctuations (Gidebo et al., 2023). Given these engineering deficiencies, the natural soil cannot safely or reliably support infrastructural systems in its untreated state, making stabilization an essential requirement for any sustainable construction application in the area.

6. Sustainable Soil Stabilization Approaches

Given the significant geotechnical deficiencies identified in the natural soil from Rukpokwu, stabilization becomes an essential intervention to its engineering performance. Stabilization alters the physical and chemical properties of soil to improve its strength, reduce plasticity, limit moisture susceptibility, and enhance bearing capacity (Hejazi et al., 2012). Conventional stabilizers such as cement and lime have historically been effective (Mo et al., 2016); however, their production contributes substantially to global carbon emissions, and increasing costs have raised concerns regarding economic and environmental sustainability (Aamir et al., 2019; Alqaisi et al., 202). This has accelerated the search for alternative, low-carbon stabilizers that can deliver comparable engineering improvements.

Agricultural waste-based pozzolanic materials, including sawdust ash (SDA), rice husk ash (RHA), and palm kernel shell ash (PKSA), have gained prominence as viable, sustainable soil stabilizers (Afolayan et al., 2019; Biswas et al., 2021). These ashes contain high proportions of amorphous silica and alumina, which react with calcium-containing minerals in the soil to form cementitious bonds that improve soil strength and reduce plasticity (Almuaythir et al., 2024; Manaviparast et al., 2025). By repurposing agricultural waste that would otherwise contribute to environmental degradation, such stabilizers support circular economy principles while reducing dependency on carbon-intensive materials (Arjmandi et al., 2015; Butt et al., 2016).

For the weak clay soil characteristic of Rukpokwu, these pozzolanic waste ashes offer several documented benefits. First, they reduce plasticity by decreasing the proportion of active clay minerals through pozzolanic reactions, thereby diminishing the soil's susceptibility to shrink–swell behaviour (Alqaisi et al., 2020; Benhaoua et al., 2020). Second, the formation of additional cementitious compounds enhances both unconfined compressive strength (UCS) and California Bearing Ratio (CBR), increasing the soil's load-bearing capacity to meet engineering requirements (Afolayan et al., 2019; Barišić et al., 2019). Third, stabilized soils often demonstrate improved compaction behaviour, where higher maximum dry density and reduced optimum moisture content improve workability in the field (Ikeagwuani & Nwonu, 2019). Fourth, the reduced affinity for moisture contributes to long-term durability and resistance to deformation under repeated wetting and drying cycles (Sivapullaiah & Baig, 2011). A summary of the benefits of sustainable stabilizers is presented in Table 8.

Table 8: Comparative Benefits of Agricultural Waste-Based Stabilizers for Weak Soil Improvement.

Stabilization Benefit	Effect of SDA, RHA, and PKSA	Engineering Implication
Reduction in plasticity	Pozzolanic reactions reduce active clay minerals	Lower swell–shrink behaviour; improved soil consistency
Strength improvement	Formation of cementitious compounds increases UCS and CBR	Increased load-bearing capacity; improved structural performance
Better compaction behaviour	Higher MDD and lower OMC after stabilization	Enhanced field compaction control and improved density

Moisture resistance	Lower water absorption and reduced permeability	Increased long-term durability and reduced deformation risk
Environmental sustainability	Utilizes waste materials; lowers carbon footprint	Supports green construction and cost-effective soil improvement

Moreover, adopting agricultural waste-based stabilizers directly aligns with global sustainability objectives (Aamir et al., 2019). These materials are not only low-cost and widely available in Nigeria but also mitigate waste disposal challenges and significantly reduce carbon emissions when compared to cement or lime stabilization (Afolayan et al., 2019). Their integration into geotechnical practice therefore supports environmentally responsible construction, particularly in regions where problematic soils are widespread and resources are limited (Biswas et al., 2021). Although this study focuses exclusively on the baseline geotechnical characterization of the untreated soil, the findings provide an essential foundation for assessing the potential benefits of stabilization. Establishing the natural behaviour of the soil is critical for determining whether and to what extent stabilizing agents, particularly sustainable, pozzolanic materials, can enhance its engineering performance (Hejazi et al., 2012; Biswas et al., 2021). The baseline data presented herein therefore serve as a crucial reference point against which improvements in plasticity, compaction efficiency, strength, and moisture resistance may be evaluated when suitable stabilization methods are applied.

7. Conclusion

This study conducted a comprehensive geotechnical characterization of natural soil samples obtained from Rukpokwu, Rivers State, Nigeria, with the aim of evaluating their suitability for engineering and construction applications. The results uniformly demonstrate that the soil is a fine-grained, highly plastic clay with significant moisture sensitivity, low dry density, poor compaction characteristics, very low bearing capacity, and inadequate compressive strength. Index and strength properties, including a Plasticity Index of approximately 20.85%, a Maximum Dry Density of 1.72 g/cm^3, a CBR of 3.99%, and a UCS of 433 kPa, collectively indicate that the soil is unsuitable for direct use in pavement subgrades, shallow foundations, embankments, or other load-bearing infrastructural systems. The observed behaviour is consistent with problematic clay soils across the Niger Delta known for shrink–swell movements, settlement issues, and premature failure when used untreated. Given these limitations, stabilization is indispensable. The study highlights the necessity of adopting sustainable and cost-effective stabilization approaches, particularly through agricultural waste-based pozzolanic additives, to enhance soil performance and support environmentally responsible engineering.

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Author contributions

Dr. Smile Daniel George: Conceptualization, methodology, investigation, writing-original draft preparation, supervision, and resources. Dr. Nurudeen Ahmed Onomhoale: Conceptualization, methodology, investigation, writing-original draft preparation, supervision, and resources. Prof. Temple C. Nwofo: Writing-review and editing, and validation. Dr. Chiedozie Francis Ikebude: Writing review and editing, and validation. Finjite Dorathy Olali: Writing-review and editing.

Declarations

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Ethical responsibilities: All authors have read, understood, and have complied as applicable.

References

[1] Aamir, M., Mahmood, Z., Nisar, A., Farid, A., Khan, T. A., Abbas, M., Ismaeel, M., Shah, S. A. R., & Waseem, M. (2019). Performance evaluation of sustainable soil stabilization process using waste materials. *Processes* *7*:1–16. https://doi.org/10.3390/PR7060378

[2] Abam, T. K. S., & Fubara, D. M. J. (2022). Analysis of hydrological characteristics: A case review of the Niger Delta. *Journal of Water Resource and Protection*, *14*(9), 611–631. https://doi.org/10.4236/jwarp.2022.149032

[3] Abdi, M. R., Nakhaei, P., & Safdari Seh Gonbad, M. (2021). Prediction of enhanced soil–anchored geogrid interactions in direct shear mode using gene expression programming. *Geotechnical and Geological Engineering, 39*(6), 957–972. https://doi.org/10.1007/s10706-020-01537-6

[4] Abija, F. A., Teme, S. C., & Oborie, E. (2025). Geotechnical considerations for the design an d construction of foundations in a marshy stream channel of Iwochang-Ibeno. *IIARD International Journal of Geography and Environmental Management.*

[5] Adejuwon, J. O. (2012). Rainfall seasonality in the Niger delta belt, Nigeria. *Journal of Geography and Regional Planning, 5*(2), 51.

[6] Afolayan, O. D., Olofinade, O.M., & Akinwumi, I. I. (2019). Use of some agricultural wastes to modify the engineering properties of subgrade soils: a review. *J Phys Conf Ser 1378*. https://doi.org/10.1088/1742-6596/1378/2/022050

[7] Ahmed, N. O., Fagorite, V. I., Chikwado, A. G., Apata, M. D., Yunusa, L. J., Itiveh, E. S., & Biliaminu, Z. B. (2024a). Pollution Assessment and Index Properties of Okpulor Soils, Rivers State, Nigeria: Geochemical Characterization, Geotechnical and Geoenvironmental Implications. *Discover Environment, 2*(60). https://doi.org/10.1007/s44274-024-00094-6

[8] Ahmed, N. O., Nik Daud, N. N., & Okunlola, I. A. (2024b). Geoelectrical Soil Mapping for Subsurface Hydrocarbon Contaminant Characterization and Remediation Site Zoning at Alode, Central Niger Delta, Nigeria. Physics and Chemistry of the Earth, 136(8), 103726. https://doi.org/10.1016/j.pce.2024.103726

[9] Akpoborie, I. A., & Ovuru, B. O. (2021). Subsurface geotechnical investigation of selected sites in Delta State, Nigeria. *Journal of Multidisciplinary Engineering Science and Technology, 8*(1), 66–75.

[10] Almuaythir, S., Zaini, M. S. I., Hasan, M., & Hoque, M. I. (2024). Sustainable soil stabilization using industrial waste ash: Enhancing expansive clay properties. *Heliyon, 10*(20), e39124. https://doi.org/10.1016/j.heliyon.2024.e39124

[11] Alqaisi, R., Le, T. M., & Khabbaz, H. (2020). Applications of recycled sustainable materials and By-Products in Soil stabilization. *Sustainable Civil Infrastructures 1*, 91–117. https://doi.org/10.1007/978-3-030-34199-2_7

[12] Amajor, L. C. (1989). Grain size characteristics and geologic controls on the bedload sediments: A case study from the Imo River in southeastern Nigeria. *Journal of African Earth Sciences (and the Middle East), 9*(3–4), 507–515. https://doi.org/10.1016/0899-5362(89)90033-2

[13] Arjmandi, R., Hassan, A., Majeed, K., & Zakaria, Z. (2015). Rice Husk Filled Polymer Composites. *Int J Polym Sci* 2015. https://doi.org/10.1155/2015/501471

[14] ASTM International. (2017). *Standard practice for classification of soils for engineering purposes (Unified Soil Classification System) (ASTM D2487-17)*. ASTM International. https://doi.org/10.1520/D2487-17

[15] Azam, S., Ito, M., & Chowdhury, R. (2013). Engineering properties of an expansive soil. *18th Int Conf Soil Mech Geotech Engineering: Challenges Innovations Geotechnics ICSMGE 1,* 199–20

[16] Barišić, I., Grubeša, I. N., Dokšanović, T., & Marković, B. (2019). Feasibility of agricultural biomass fly ash usage for soil stabilisation of road works. *Materials 12*. https://doi.org/10.3390/ma12091375

[17] Benhaoua, W., Grine, K., & Kenai, S. (2020). Performance of stabilized Earth with Wheat Straw and Slag. *MRS Adv 5*, 1285–1294. https://doi.org/10.1557/adv.2020.174

[18] Biswas, T., Garg, R., Ranjan, H., Kumar, A., Pandey, G., & Yadav, K. (2021). *Study of expansive soil stabilized with agricultural waste.* In: Journal of Physics: Conference Series. IOP Publishing Ltd.

[19] British Standards Institution. (2016). *BS 1377-1: Methods of test for soils for civil engineering purposes – General requirements and sample preparation*. BSI. BS 1377-1:2016, ISBN: 9780580960864.

[20] Chou, J. S., & Tsai, C. F. (2012). Concrete compressive strength analysis using a combined classification and regression technique. *Automation in Construction, 24*, 52–60. https://doi.org/10.1016/j.autcon.2012.02.001

[21] De Albuquerque, P. J. R., & León-Mogrovejo, D. R. (2021). A laboratory investigation on mechanical behavior of sandy and clayey soils with kraft paper fiber. *Transportation Infrastructure Geotechnology, 8*(1), 12–36. https://doi.org/10.1007/s40515-020-00116-9

[22] Ehibor, U. G., Imo-Owo, U., & Tse, A. C. (2022). Bearing capacity analysis of subsoils, for shallow and deep foundation in Uyo Town. *Journal of Earth Science and Geotechnical Engineering, 12*(3), 1–16.

[23] Etu-Efeotor, J. O., & Akpokodje, E. G. (1990). Aquifer systems of the Niger Delta. *Journal of Mining and Geology, 26*(2), 279–284.

[24] Gidebo, F. A., Yasuhara, H. & Kinoshita, N. (2023). Stabilization of expansive soil with agricultural waste additives: A review. *International Journal of Geo-Engineering, 14*, 14. https://doi.org/10.1186/s40703-023-00194-x

[25] Hejazi, S. M., Sheikhzadeh, M., Abtahi, S. M., & Zadhoush, A. (2012) A simple review of soil reinforcement by using natural and synthetic fibers. *Constr Build Mater 30*, 100–116. https://doi.org/10.1016/j.conbuildmat.2011.11.045

[26] Howard, A. K. (1986). *Soil classification handbook: Unified Soil Classification System.* Denver, Colo.: Geotechnical Branch, Division of Research and Laboratory Services, Engineering and Research Center, Bureau of Reclamation.

[27] IAEA. (2006). *Sampling for Environmental Monitoring. International Atomic Energy Agency*. ISBN-13: 978-92-0-103306-2.

[28] Ikeagwuani, C. C., & Nwonu, D. C. (2019). Emerging trends in expansive soil stabilisation: a review. *J Rock Mech Geotech Eng 11*, 423–440. https://doi.org/10.1016/j.jrmge.2018.08.013

[29] Iravanian, A., Kassem, Y., & Gökçekuş, H. (2022). Stress–strain behavior of modified expansive clay soil: Experimental measurements and prediction models. *Environmental Earth Sciences, 81*(2), 107. https://doi.org/10.1007/s12665-022-10229-8

[30] Irokwe, J. O., Nwaogazie, I. L., & Sule, S. (2022). Development of empirical models for estimation of California Bearing Ratio (CBR) from soil index properties: A case study of the Ogbia–Nembe road in the Niger Delta region of Nigeria. *Open Journal of Civil Engineering, 12*, 648–664. https://doi.org/10.4236/ojce.2022.124036

[31] Javdanian, H., & Lee, S. (2019). Evaluating unconfined compressive strength of cohesive soils stabilized with geopolymer: A computational intelligence approach. *Engineering Computations, 35*(1), 191–199. https://doi.org/10.1007/s00366-018-0592-8

[32] Jiang, P., Mao, T., Li, N., Jia, L., Zhang, F., & Wang, W. (2019). Characterization of short-term strength properties of fiber/cement-modified slurry. *Advances in Civil Engineering, 2019*, Article 3789403. https://doi.org/10.1155/2019/3789403

[33] Lee, H., Sam, K., Coulon, F., De Gisi, S., Notarnicola, M., & Labianca, C. (2023). Recent developments and prospects of sustainable remediation treatments for major contaminants in soil: A review. *Science of the Total Environment, 168769*. https://doi.org/10.1016/j.scitotenv.2023.168769

[34] Ma, G., Cui, A., Huang, Y., & Dong, W. (2022). A data-driven influential factor analysis method for fly ash-based geopolymer using optimized machine-learning algorithms. *Journal of Materials in Civil Engineering, 34*(7), 04022132. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004266

[35] Mallela, J., Quintus, H. V., & Smith, K. L. (2004). *Consideration of lime-stabilized layers in mechanistic-empirical pavement design*. National Lime Association.

[36] Manaviparast, H. R., Cristelo, N., Pereira, E., & Miranda, T. (2025). A comprehensive review on clay soil stabilization using rice husk ash and lime sludge. *Applied Sciences, 15*(5), 2376. https://doi.org/10.3390/app15052376

[37] Mo, K. H., Alengaram, U. J., & Jumaat, M. Z. (2016). Structural performance of reinforced geopolymer concrete members: A review. *Construction and Building Materials, 120*, 251–264. https://doi.org/10.1016/j.conbuildmat.2016.05.090

[38] Musa, Z. N., Popescu, I., & Mynett, A. (2014). The Niger Delta's vulnerability to river floods due to sea level rise. *Natural Hazards and Earth System Sciences*, *14*(12), 3317–3329.

[39] Niyomukiza, J. B., Wardani, S. P. R., & Setiadji, B. H. (2021). *Recent advances in the stabilization of expansive soils using waste materials: A review.* In: IOP Conference Series: Earth and Environmental Science. IOP Publishing

[40] Njoku, C. G., Efiong, J., & Ayara, N. N. (2020). A geospatial expose of flood-risk and vulnerable areas in Nigeria. *International Journal of Applied Geospatial Research*, *11*(3), 87–110. http://dx.doi.org/10.4018/ijagr.20200701.oa1

[41] Nwankwoala, H. O., & Warmate, T. (2014). Subsurface soil characterization of a site for infrastructural development purposes in D/Line, Port Harcourt, Nigeria. *American International Journal of Contemporary Research, 4*(6), 139–148.

[42] Oghenero, A. E., Akpokodje, E. G., & Tse, A. C. (2014). Geotechnical properties of subsurface soils in Warri, Western Niger Delta, Nigeria. *Journal of Earth Sciences and Geotechnical Engineering, 4*(1), 89–102.

[43] Okeniyi, A. E., Oviasogie, P. O., & Omoigui, B. (2022). Assessment of geotechnical investigation techniques for evaluating subsoil strength and stability in the Niger Delta region of Nigeria. *Asian Journal of Geological Research*, *5*(4), 1–9. https://journalajoger.com/index.php/AJOGER/article/view/127

[44] Okon, U., Ibanga, I. J., & Udoeyo, F. F. (2022). A case study of Ogume clay soil in the Niger-Delta region, Nigeria. *Journal of Engineering and Technology Research*, *8*(1), 74–86. https://journals.nipes.org/index.php/jete/article/download/756/711/1078

[45] Omange, G. N., & Aitsebaomo, F. O. (1989). *Engineering properties of subgrade soils in Bendel (Delta and Edo) state of Nigeria.* NBRRI Report. 18, 3–33.

[46] Omange, G. N., Nnama, S.K., & Aitsebaomo, F.O. (1988). *Engineering characteristics of subgrade soils of Nigeria and application to economic pavement design.* NBRRI publication, 135–179.

[47] Omotoso, O. A., Oju, O. J., & Adetolaju, F. T. (2012). Some geotechnical properties of soils in parts of the Niger Delta Area, Nigeria. *Nigerian Journal of Technological Development*, *9*(1), 47–59. https://journal.njtd.com.ng/index.php/njtd/article/download/66/47/94

[48] Onomhoale, N. A., Nik Daud, N. N., Okunlola, I. A., Idrus, S., & Roslan S. N. A. (2025a). Time-Lapse Geoenvironmental Hydrocarbon Attenuation in Nigeria: Integrated Geoelectrical, Geochemical and Geotechnical Site Characterization. *Journal of Environmental and Earth Sciences, 7(8),* 408-436. https://doi.org/10.30564/jees.v7i8.11042

[49] Onomhoale, N. A., Yunusa, L. J., Senbore, S., Apata, M. D., Ojogbo, P., & Itiveh, E. S. (2025b). Hydrochemical Dispersion and Geospatial Correlation for Source Identification, Transport, and Fate of Aerial Petro-Pollutants in the Niger Delta, Nigeria. *Journal of Geoscience and Environment Protection,* 13(4), 113-140. https://www.doi.org/10.4236/gep.2025.134007

[50] Opu-Ogulaya, E. D. W. (1973). *History of the creation of the Rivers State of Nigeria: Primer one.* Government Printer.

[51] Reijers, T. J. A. (2011). Stratigraphy and sedimentology of the Niger Delta. *Geologos, 17*(3), 133–162. https://doi.org/10.2478/v10118-011-0008-3

[52] Sivapullaiah, P. V., & Baig, M. A. (2011). Stabilization of expansive soils using fly ash. *Proceedings of the Institution of Civil Engineers – Ground Improvement, 164*(2), 84–92. https://doi.org/10.1680/grim.2011.164.2.84

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