Global Journal of Engineering and Technology [GJET].
ISSN: 2583-3359 (Online)
Frequency: Monthly
Published By GSAR Publishers
Journal Homepage Link- https://gsarpublishers.com/journal-gjet-home/

Engineering Behaviour of Bentonite-Modified Coastal Plain Sands from Southeastern Nigeria: Integrated Interpretation of Plasticity, Compaction and Microstructural Evolution

By

Blessing Uwaoma[1], Owus M. Ibearugbulem[2], Dioka Marvis O.[3]

[1]Department of Civil Engineering, Ogbonnaya Onu Polytechnic Aba, Abia State
[2]Department of Civil Engineering, Federal University of Technology, Owerri Nigeria
[3]Department of Building Technplogy,Ogbonnaya Onu polytechnic Aba, Abia State

Article History

Received: 07/08/2026
Accepted: 12/08/2026
Published: 14/08/2026

Vol – 5 Issue – 8

PP: - 37-49

Abstract

Coastal Plain Sands are widely distributed across southeastern Nigeria and are extensively used as foundation, embankment, and pavement construction materials. However, their predominantly sandy composition and low natural fines often result in poor plasticity, limited cohesion, and engineering behaviour that may require improvement for demanding geotechnical applications. This study investigates the influence of bentonite modification on the plasticity and compaction characteristics of Coastal Plain Sands obtained from Akanu, Mgboko Itungwa Ward, Obingwa Local Government Area, Abia State, Nigeria. Three representative soil samples (S1, S2, and S3) were blended with bentonite at varying proportions ranging from 0% to 50% by dry weight. Laboratory testing included particle-size distribution analysis, Atterberg limits, and Standard Proctor compaction tests in accordance with relevant ASTM standards. The natural soils consisted predominantly of sand-sized particles **(***95.76–97.93%***)** *with low fines contents (2.07–4.24%) and were classified as poorly graded sand (SP) under the Unified Soil Classification System. Bentonite addition produced systematic increases in liquid limit, plasticity index, maximum dry unit weight, and optimum moisture content, reflecting progressive modification of the soil fabric. The results demonstrate that bentonite initially improves particle packing through intergranular void filling and subsequently promotes clay coating of sand grains and physicochemical bonding, resulting in the evolution of a cohesive granular–clay composite. An integrated conceptual model is proposed to explain the observed relationships between particle-size distribution, plasticity, and compaction behaviour through progressive microstructural evolution. The findings demonstrate that bentonite functions simultaneously as a physical void-filling material and a physicochemical modifier, providing a mechanistic basis for optimizing the engineering performance of Coastal Plain Sands in applications such as compacted liners, hydraulic barriers, pavement subgrades, embankments, and engineered fills.*

Keywords: *Bentonite modification; Coastal Plain Sands; Compaction characteristics; Plasticity; Microstructural evolution; Geotechnical engineering*

1. Introduction

Sandy soils constitute one of the most widely encountered geomaterials in geotechnical engineering and serve as foundation materials for highways, embankments, earth dams, retaining structures, shallow foundations, and numerous other civil engineering infrastructures. Their engineering performance is governed primarily by particle-size distribution, density, moisture condition, and mineralogical composition. Although coarse-grained soils generally exhibit favourable drainage characteristics and relatively high shear strength under dense conditions, they frequently possess limited cohesion and negligible plasticity because of their low fines content. Consequently, their performance may deteriorate under adverse environmental conditions, repeated loading, or inadequate compaction, thereby necessitating engineering improvement for demanding geotechnical applications (ASTM International, 2025; Monteiro et al., 2024).

In southeastern Nigeria, extensive deposits of the Benin Formation (Coastal Plain Sands) constitute the principal near-surface geomaterial underlying much of the Niger Delta Basin. These predominantly sandy deposits are widely utilized

*Corresponding Author: Blessing Uwaoma

as construction materials for road embankments, pavement subgrades, building foundations, and general earthworks because of their abundance and ease of excavation. However, their engineering properties vary considerably depending on grading characteristics, fines content, moisture conditions, and depositional history. Previous investigations have shown that Coastal Plain Sand-derived soils frequently exhibit low natural cohesion, limited plasticity, and variable compaction behaviour, characteristics that may restrict their suitability for engineering applications requiring improved strength, stability, or moisture resistance (Adeyemi et al., 2015; Madueke et al., 2021).

Numerous soil stabilization techniques have been developed to improve the engineering behaviour of problematic geomaterials. Conventional stabilizers such as cement and lime have been extensively employed to enhance strength and stiffness, while alternative materials including fly ash, industrial by-products, geopolymers, fibres, and clay minerals have received increasing attention because of their environmental and economic advantages. These additives improve soil behaviour through different physical, chemical, and physicochemical mechanisms, including particle rearrangement, pozzolanic reactions, cementation, void filling, and mineralogical modification. The effectiveness of any stabilization method depends on the characteristics of the parent soil, the stabilizing material, and the intended engineering application (Latifi et al., 2018; Phummiphan et al., 2018).

Among the available soil modifiers, bentonite has attracted considerable interest because of its exceptionally high specific surface area, swelling capacity, cation exchange capacity, and water adsorption characteristics arising from its predominantly montmorillonitic mineralogy. These properties enable bentonite to alter soil behaviour through progressive void filling, particle coating, and physicochemical bonding between adjacent particles. Consequently, bentonite–sand mixtures have been widely investigated for applications requiring low hydraulic conductivity, improved cohesion, and enhanced sealing performance, including landfill liners, slurry trench cut-off walls, hydraulic barriers, and other geotechnical containment systems (Mollins et al., 1996; Kohno et al., 2018).

Previous studies have consistently demonstrated that bentonite addition increases the plasticity and moisture retention characteristics of sandy soils while generally reducing hydraulic conductivity and modifying compaction behaviour. More recent investigations have focused on predictive modelling of compaction characteristics and optimization of bentonite content for engineered liner systems and other geotechnical applications (Khalid et al., 2023). Collectively, these studies have significantly advanced understanding of bentonite-modified soils. However, the majority have examined particle-size distribution, consistency characteristics, and compaction behaviour as separate engineering properties, with comparatively limited emphasis on integrating these observations into a unified mechanistic interpretation describing how bentonite progressively modifies the engineering behaviour of predominantly sandy soils.

This knowledge gap is particularly relevant for the Coastal Plain Sands of southeastern Nigeria, where the combination of very high sand content and low natural fines provides an ideal framework for investigating the mechanisms through which bentonite alters soil behaviour. Despite the widespread occurrence and engineering importance of these soils, relatively few studies have attempted to relate their grading characteristics, plasticity, and compaction behaviour through a common microstructural and physicochemical framework. Consequently, the mechanisms linking bentonite-induced modifications of soil fabric to the observed engineering response remain insufficiently explained.

The present study investigates the influence of bentonite modification on the engineering behaviour of Coastal Plain Sands obtained from Akanu, Mgboko Itungwa Ward, Obingwa Local Government Area, Abia State, southeastern Nigeria. Specifically, the study aims to: (i) characterize the particle-size distribution of the natural soils; (ii) evaluate the influence of bentonite addition on the consistency characteristics of soil–bentonite mixtures through Atterberg limits testing; (iii) investigate the corresponding changes in compaction characteristics using the Standard Proctor compaction test; and (iv) interpret the observed behaviour in terms of the microstructural and physicochemical mechanisms governing bentonite modification.

This study extends current understanding of bentonite-modified sandy soils by integrating particle-size distribution, plasticity, and compaction characteristics into a unified mechanistic interpretation supported by a conceptual microstructural model. Rather than considering these engineering properties independently, the study demonstrates how they collectively reflect the progressive transformation of Coastal Plain Sands from a friction-dominated granular material into a cohesive granular–clay composite through bentonite-induced void filling, particle coating, and physicochemical bonding. The resulting framework provides both scientific insight into the mechanisms governing bentonite modification and practical guidance for optimizing bentonite-treated Coastal Plain Sands for geotechnical engineering applications.

2. Materials and Methods

2.1 Description of the Study Area

The study area as shown on Figure 1 is located at Akanu community within Mgboko Itungwa Ward, Obingwa Local Government Area of Abia State, southeastern Nigeria. Soil samples were collected from a representative location at latitude 5.181248° N and longitude 7.496872° E.

The area falls within the humid tropical climatic zone of southeastern Nigeria, characterized by distinct wet and dry seasons with seasonal variations in rainfall and soil moisture conditions. Geologically, the area lies within the Niger Delta Basin and is underlain by the Coastal Plain Sands formation, which consists predominantly of unconsolidated sandy

*Corresponding Author: Blessing Uwaoma

deposits with varying proportions of silt and clay materials. The engineering behaviour of these soils is influenced by particle-size distribution, mineral composition, weathering processes, and moisture fluctuations associated with tropical environmental conditions. The study location was selected to evaluate the influence of bentonite modification on the plasticity and compaction characteristics of naturally occurring sandy soils derived from the Coastal Plain Sands.

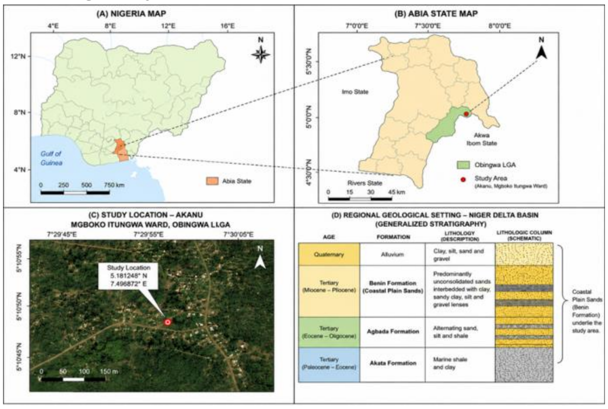

Figure 1. Location of the study area at Akanu, Mgboko Itungwa Ward, Obingwa Local Government Area, Abia State, Southeastern Nigeria.

2.2 Materials

2.2.1 Soil Samples

Three disturbed soil samples, designated as S1, S2, and S3, were collected from Akanu, Mgboko Itungwa Ward, Obingwa Local Government Area, Abia State, Nigeria. The samples were obtained from open excavations at depths ranging from approximately 1.5 to 3.0 m below the ground surface to minimize the influence of surface organic materials and recent environmental alterations. Sampling locations were approximately 15 m apart to capture the natural variability of the soil deposit within the study area.

The collected soil samples were transported to the laboratory in sealed containers and prepared for testing. The samples were air-dried, manually pulverized, and passed through appropriate sieves before laboratory analysis. Since the investigation focused on index properties and compaction characteristics, disturbed samples were considered adequate for the experimental programme.

2.2.2 Bentonite Modifier

Commercial powdered bentonite obtained from an Industrial Chemical Store, Aba, Abia State, Nigeria, was used as the modifying material. According to the supplier's information, the bentonite is a calcium-based bentonite predominantly composed of montmorillonitic clay minerals, with associated accessory minerals commonly present in natural bentonite deposits.

The bentonite was used in its supplied powdered form without further chemical treatment. Its selection was based on its high clay activity and expected ability to modify the soil fabric through interaction between fine clay particles and the sandy soil matrix.

2.3 Soil–Bentonite Mixture Preparation

The natural soil samples were prepared by air drying and pulverization to obtain a uniform test material. Soil–bentonite mixtures were produced by thoroughly blending predetermined quantities of soil and bentonite until a visually homogeneous mixture was achieved.

The investigated soil–bentonite proportions consisted of soil-to-bentonite ratios of 90:10, 80:20, 70:30, 60:40, and 50:50. After dry mixing, water was added gradually to obtain the required moisture condition for testing. The prepared mixtures were sealed in plastic containers and allowed to equilibrate for 24 h before laboratory testing to ensure uniform moisture distribution within the samples.

2.4 Laboratory Testing Programme

The experimental investigation consisted of particle-size distribution analysis, Atterberg limits determination, and standard Proctor compaction tests. These tests were selected to evaluate the influence of bentonite addition on the grading characteristics, consistency limits, and compaction behaviour of the sandy soils.

2.4.1 Particle-Size Distribution Analysis

Particle-size distribution analysis was conducted using the mechanical sieve analysis method. Approximately 500 g of air-dried soil sample was subjected to sieving through standard sieve openings ranging from 4.75 mm to 0.075 mm.

The mass retained on each sieve was measured, and the percentage retained and percentage passing were calculated. The resulting particle-size distribution curves were used to evaluate the grading characteristics and engineering classification of the natural soils.

2.4.2 Atterberg Limits Tests

The consistency characteristics of the natural soils and soil–bentonite mixtures were determined through liquid limit and plastic limit tests. The liquid limit was obtained using the Casagrande apparatus method, where the moisture content corresponding to closure of the standard groove after 25 blows was recorded as the liquid limit.

The plastic limit was determined by rolling prepared soil samples into threads approximately 3 mm in diameter until visible cracking occurred. The moisture content corresponding to this condition was recorded as the plastic limit. The plasticity index was subsequently calculated as:

$$PI = LL - PL$$

where: PI = plasticity index (%), LL = liquid limit (%), and PL = plastic limit (%).

Shrinkage limit values obtained from the experimental programme were also considered in evaluating the volume-change characteristics of the modified soils.

2.4.3 Compaction Tests

Standard Proctor compaction tests were performed on the natural soils, bentonite, and soil–bentonite mixtures to determine their maximum dry unit weight and optimum moisture content. The tests were conducted following the procedure specified in AS 1289.5.1.1.

During compaction, each sample was placed in a standard Proctor mould and compacted in three equal layers, with each layer receiving 25 blows from the standard rammer. Several moisture contents were investigated to establish the relationship between moisture content and dry unit weight.

The maximum dry unit weight ($\gamma_{d,max}$) and optimum moisture content (OMC) were obtained from the peak point of the compaction curves. These parameters were subsequently used to assess the influence of bentonite addition on the densification characteristics of the sandy soils.

2.5 Data Analysis

The experimental results were analysed by comparing the changes in particle-size distribution, consistency limits, maximum dry unit weight, and optimum moisture content resulting from bentonite modification. The influence of bentonite content on soil behaviour was interpreted based on changes in soil fabric, clay fraction contribution, and moisture interaction characteristics.

3. Results and Discussion

3.1 Particle-Size Distribution and Classification of Natural Soils

The particle-size distribution characteristics of the three natural soil samples (S1, S2 and S3) were determined to establish their grading characteristics, engineering classification, and suitability as parent materials for bentonite modification. The particle-size distribution data are summarised in Table 1, while the corresponding grading curves are presented in Figure 2. The results indicate that all three soils are overwhelmingly dominated by sand-sized particles, with sand fractions ranging from 95.76% to 97.93%, whereas the fines content varies between 2.07% and 4.24%**.** Gravel-sized particles were absent in all samples. These results clearly demonstrate that the natural soils consist predominantly of coarse-grained sandy materials containing only a small proportion of naturally occurring fines.

Table 1. Particle-size distribution characteristics of natural soils

Soil Sample	Gravel Fraction (%)	Sand Fraction (%)	Fines Fraction (%)	USCS Classification
S1	0	97.37	2.63	SP
S2	0	97.93	2.07	SP
S3	0	95.76	4.24	SP

Note: Gravel fraction represents material retained on the 4.75 mm sieve, sand fraction represents material retained between 4.75 mm and 0.075 mm sieve openings, and fines fraction represents material passing the 0.075 mm sieve.

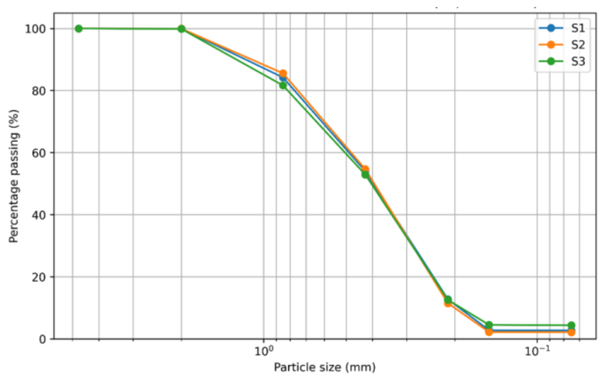

Figure 2: Particle-size distribution curves of natural soils (S1, S2 and S3)

The grading curves (Figure 2) exhibit very similar profiles for S1, S2 and S3, indicating a high degree of uniformity in particle-size distribution across the study area. Although slight variations in the proportions of fine particles are evident, the differences among the three soils are relatively small, with the maximum variation in fines content being only 2.17%**.** This consistency suggests that the soils were derived from a common geological parent material and subjected to similar depositional and weathering processes. Such behaviour is consistent with the Benin Formation (Coastal Plain Sands), which underlies the study area and is characterized by laterally extensive deposits of predominantly unconsolidated quartz sands with occasional clay and silt intercalations.

Based on the Unified Soil Classification System (USCS), all three soils were classified as poorly graded sand (SP) (Table 1). This classification reflects the predominance of sand-sized particles, the absence of gravel, and the very low percentage of fines. The designation of the soils as poorly graded indicates that the granular skeleton is composed of particles of relatively similar sizes, resulting in limited gradation and comparatively large interparticle void spaces. Consequently, the engineering behaviour of the untreated soils is governed primarily by the packing arrangement and density of the sand particles rather than by physicochemical interactions associated with clay minerals.

The low fines contents observed in the natural soils have important implications for their engineering performance. Fine particles, particularly clay minerals, contribute significantly to cohesion, water retention, and plasticity in geomaterials. Their near absence in the present soils implies that the untreated materials are expected to exhibit negligible plasticity, rapid drainage characteristics, high permeability, and limited natural cohesion. While these properties are advantageous for applications requiring efficient drainage, they may reduce the soils' resistance to deformation and moisture-induced instability under sustained loading or adverse environmental conditions. The absence of sufficient fines also limits the natural development of interparticle bonding, thereby increasing dependence on mechanical compaction for achieving satisfactory engineering performance.

*Corresponding Author: Blessing Uwaoma

The particle-size distribution characteristics further establish the scientific basis for the bentonite modification programme adopted in this study. Because the natural soils contain only a small proportion of active fine particles, they provide an appropriate granular framework for evaluating the influence of introducing bentonite, a highly plastic and expansive clay mineral. Incorporation of bentonite into such a predominantly sandy matrix is expected to progressively modify the soil fabric by occupying intergranular voids, increasing the specific surface area, and promoting physicochemical interactions between particles. These microstructural changes are anticipated to influence both the plasticity characteristics and the compaction behaviour of the soil–bentonite mixtures discussed in the subsequent sections.

From an engineering perspective, the remarkably high sand contents observed in all three soils indicate that the parent materials possess comparable geotechnical characteristics and provide a consistent baseline for assessing the effects of bentonite addition. The close similarity in grading minimises the influence of inherent variability between the natural soils, allowing the observed changes in plasticity and compaction to be attributed primarily to bentonite modification rather than to differences in the original soil composition. This provides confidence in the subsequent interpretation of the laboratory results and strengthens the reliability of comparisons among the soil–bentonite mixtures.

3.2 Influence of Bentonite Addition on Plasticity Characteristics

The consistency characteristics of the soil–bentonite mixtures were evaluated using the Atterberg limits to quantify the influence of bentonite addition on the plastic behaviour of the predominantly sandy soils. The measured liquid limit (LL), plastic limit (PL), plasticity index (PI), and shrinkage limit (SL) are presented in Table 2, while the relationships between bentonite content and the corresponding liquid limit and plasticity index are illustrated in Figures 3 and 4, respectively. Overall, bentonite modification produced a substantial increase in the plasticity of all three soils, indicating a progressive transition from the behaviour of a coarse-grained granular material to that of a sand–clay composite.

Table 2. Atterberg limit characteristics of soil–bentonite mixtures

Soil Sample	Soil: Bentonite	LL (%)	PL (%)	PI (%)	SL (%)
S1	50:50	69	25	**44**	24
	60:40	55	21	**34**	29
	70:30	50	19	**31**	31
	80:20	33	17	**16**	28
	90:10	32	NP	NP	30
S2	50:50	80	19	**61**	22
	60:40	61	17	**44**	29
	70:30	48	19	**29**	33
	80:20	42	18	**24**	37
	90:10	33	NP	NP	35
S3	50:50	82	22	**60**	23
	60:40	63	24	**39**	29
	70:30	48	25	**23**	34
	80:20	41	18	**23**	37
	90:10	35	17	**18**	32

NP = Non-plastic.

*Corresponding Author: Blessing Uwaoma

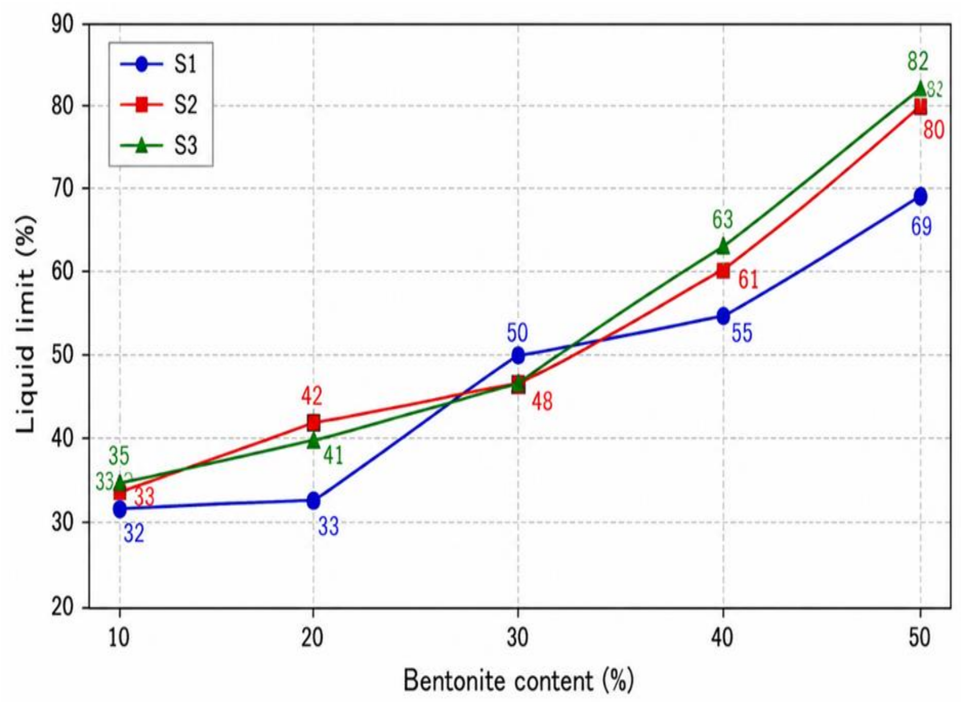

Figure 3: Variation of liquid limit with bentonite content for soil–bentonite mixtures (S1, S2 and S3)

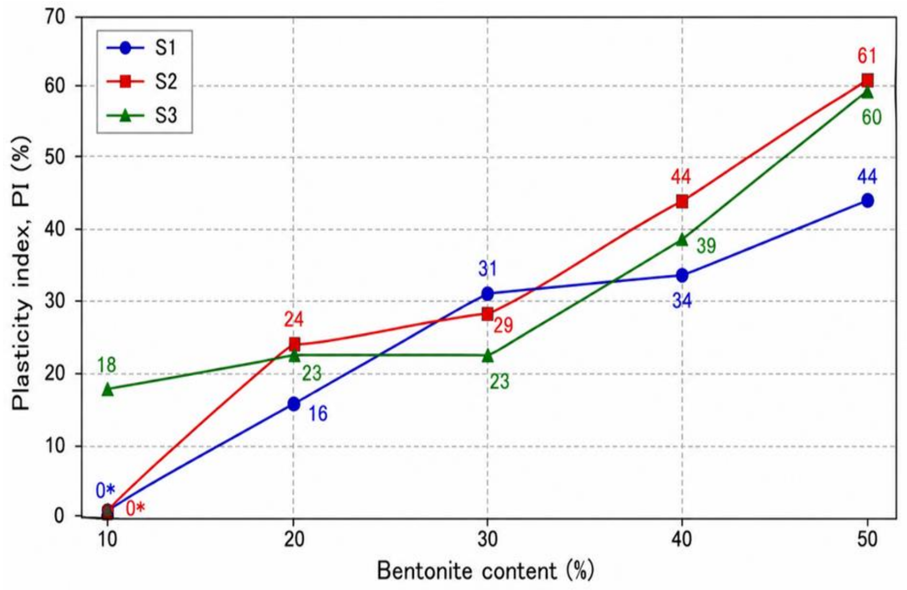

Figure 4: Variation of plasticity index (PI) with bentonite content for soil-bentonite mixtures prepared from the three natural soils (S1, S2 and S3)

* PI is not applicable (NP) for 90:10 mixtures where PL could not be determined.

The liquid limit increased systematically with increasing bentonite content for all three soil series (Figure 3). At the lowest bentonite dosage (90:10 soil–bentonite mixture), the liquid limit ranged from 32% to 35%, whereas values increased to 69%**,** 80%**,** and 82% for S1, S2, and S3, respectively, at the highest bentonite proportion (50:50 mixture). The almost monotonic increase observed for all three soils demonstrates that the water-holding capacity of the mixtures became progressively controlled by the bentonite fraction rather than by the original sandy matrix. Because the untreated soils contained only 2.07–4.24% natural fines (Table 1), their contribution to moisture retention was inherently limited, making the bentonite the dominant factor governing the consistency characteristics of the mixtures.

The increase in liquid limit is attributed primarily to the mineralogical characteristics of bentonite, which is composed predominantly of montmorillonite. Montmorillonite possesses an exceptionally high specific surface area and cation exchange capacity, enabling it to adsorb substantial quantities of water on both external particle surfaces and within interlayer spaces. As the bentonite content increased, the thickness of the diffuse double layer surrounding adjacent clay particles also increased, resulting in greater water

*Corresponding Author: Blessing Uwaoma

adsorption, enhanced interparticle repulsion, and increased resistance to flow. Consequently, progressively higher moisture contents were required for the soil–bentonite mixtures to attain the liquid state. Similar mechanisms have been reported for bentonite–sand mixtures and other expansive clay systems, where increases in active clay content produce corresponding increases in liquid limit through physicochemical interactions rather than purely mechanical particle rearrangement (Sridharan & Prakash, 1999; Mollins et al., 1996; Kohno et al., 2018).

Although the plastic limit also increased with bentonite addition, the rate of increase was considerably smaller than that observed for the liquid limit. Consequently, the widening difference between the liquid and plastic limits resulted in a progressive increase in the plasticity index (Figure 4). This indicates that bentonite primarily expanded the moisture range over which the mixtures exhibited plastic behaviour rather than simply shifting the onset of plasticity. Such behaviour is characteristic of soils containing increasing proportions of expansive clay minerals and reflects the progressive development of clay-controlled deformation mechanisms.

The plasticity index exhibited the most pronounced response to bentonite modification. The highest plasticity indices were recorded for the 50:50 mixtures, reaching 44%**,** 61%**,** and 60% for S1, S2, and S3, respectively. In contrast, the 90:10 mixtures of S1 and S2 remained non-plastic (NP) because the plastic limit could not be determined, whereas S3 exhibited a comparatively low plasticity index of 18%. These observations indicate that the addition of approximately 10% bentonite was insufficient to establish a continuous clay matrix capable of imparting measurable plastic behaviour to two of the three predominantly sandy soils. At such low bentonite contents, the granular framework remained dominant, and direct sand-to-sand particle contacts continued to govern the mechanical response. As bentonite content increased, however, clay particles progressively occupied the intergranular voids and coated the surfaces of sand grains, resulting in a gradual transition from a friction-dominated soil structure to one increasingly controlled by clay–water interactions. Comparable increases in plasticity with increasing bentonite content have been reported for engineered bentonite–sand mixtures used in geotechnical barrier systems (Mollins et al., 1996; Kohno et al., 2018).

The shrinkage limit exhibited an opposite trend, generally increasing with increasing proportions of natural soil and decreasing bentonite content. This behaviour reflects the reduction in the volume of expansive clay minerals within the mixtures. Sand particles undergo negligible volumetric change during drying, whereas bentonite experiences significant moisture-dependent shrinkage because of the collapse of its diffuse double-layer structure during water loss. Consequently, replacing bentonite with coarse-grained sand reduced the shrinkage potential of the mixtures and increased the shrinkage limit. This observation further confirms that bentonite was the principal constituent governing the moisture-sensitive behaviour of the modified soils.

The observed changes in plasticity can also be interpreted from a microstructural perspective. The untreated soils consisted predominantly of uniformly graded sand particles with limited naturally occurring fines, resulting in a granular skeleton characterised primarily by frictional particle contacts. Progressive addition of bentonite altered this soil fabric by filling intergranular voids, increasing the total specific surface area, and introducing electrochemical interactions between particles. As the proportion of bentonite increased, the soil structure evolved from an open granular framework into a more cohesive composite in which clay particles increasingly controlled moisture retention, interparticle bonding, and deformation behaviour. This microstructural evolution provides a mechanistic explanation for the simultaneous increases in liquid limit and plasticity index observed in the laboratory tests.

From an engineering perspective, the increase in plasticity represents both an advantage and a design consideration. Higher plasticity generally enhances cohesion, improves sealing capacity, and reduces hydraulic conductivity, making bentonite-modified sands attractive for applications such as compacted liners, hydraulic barriers, landfill containment systems, and impermeable cores of earth structures (Kohno et al., 2018). However, excessive plasticity is commonly associated with greater moisture sensitivity, increased shrink–swell potential, and more demanding field compaction requirements. Consequently, the optimum bentonite content should be selected to achieve the desired balance between improved engineering performance and acceptable workability, dimensional stability, and construction practicality. Similar engineering considerations have been highlighted in recent studies on bentonite-modified soils and compacted liner materials (Khalid et al., 2023; Latifi et al., 2018).

3.3 Influence of Bentonite Addition on Compaction Characteristics

The compaction characteristics of the natural soils and their bentonite-modified mixtures were evaluated using the Standard Proctor compaction test to determine the maximum dry unit weight (MDUW) and optimum moisture content (OMC). The experimental results are summarised in Table 3, while the corresponding variations of maximum dry unit weight and optimum moisture content with bentonite content are presented in Figures 5 and **6**, respectively. The percentage changes relative to the untreated soils are further presented in Table 4. The results demonstrate that bentonite addition significantly altered the compaction response of the Coastal Plain Sands, indicating progressive modification of the soil fabric and moisture–particle interactions.

*Corresponding Author: Blessing Uwaoma

Table 3: Compaction characteristics of natural soils and soil–bentonite mixtures

Parent Soil	Bentonite Content (%)	Mixture	Maximum Dry Unit Weight (kN/m³)	Optimum Moisture Content (%)
S1	0	S1	17.37	12.15
	5	S1–5%B	17.82	13.19
	10	S1–10%B	17.93	12.54
	20	S1–20%B	17.98	12.52
S2	0	S2	14.65	13.5
	5	S2–5%B	15.3	15.95
	10	S2–10%B	15.42	15.2
	20	S2–20%B	16.06	14
S3	0	S3	16.92	14.29
	5	S3–5%B	17.33	15.5
	10	S3–10%B	17.56	13.4
	20	S3–20%B	17.69	11.62
Bentonite	100	100%B	12.18	37.20

Note: MDD = Maximum Dry Unit Weight; OMC = Optimum Moisture Content.

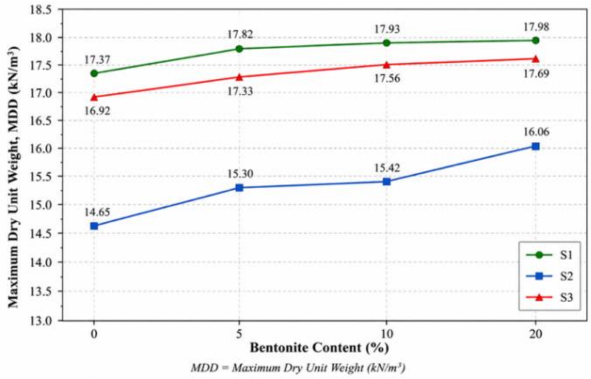

Figure 5: Variation of maximum dry unit weight with bentonite content

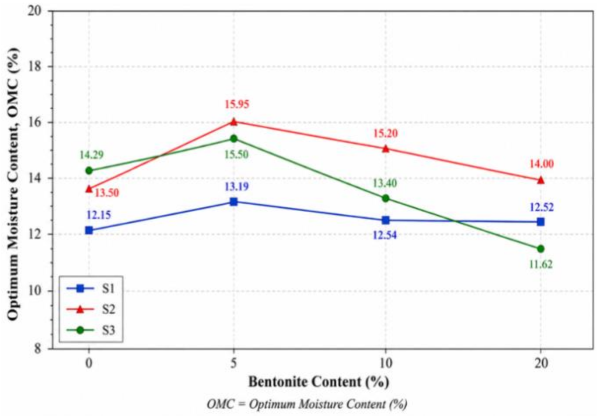

Figure 6: Variation of optimum moisture content with bentonite content

Table 4: Percentage changes in engineering properties of soil–bentonite mixtures relative to the reference condition

Soil	Bentonite (%)	ΔMDD (%)	ΔOMC (%)	ΔLL (%)†	ΔPI (%)†
S1	5	+2.59	+8.56	+71.88	NP
	10	+3.22	+3.21	+56.25	+93.75*
	20	+3.51	+3.05	+3.13	0.00
S2	5	+4.44	+18.15	+142.42	NP
	10	+5.26	+12.59	+81.82	+20.83
	20	+9.62	+3.7	+27.27	0
S3	5	+2.42	+8.47	+134.29	+233.33
	10	+3.78	−6.23	+80	+116.67

*Corresponding Author: Blessing Uwaoma

	20	+4.55	−18.68	+17.14	+27.78

NP = Not applicable because the 90:10 mixture was reported as non-plastic.

† Percentage changes in LL and PI are referenced to the corresponding **90:10 soil–bentonite mixture**, which served as the lowest bentonite-content mixture tested. Atterberg limits were not determined for the untreated natural soils.

***** For S1, the PI comparison is between the 80:20 and 70:30 mixtures because the 90:10 mixture was non-plastic.

3.3.1Maximum Dry Unit Weight

The variation of maximum dry unit weight with bentonite content is presented in **Figure 5**. For all three soils, the maximum dry unit weight increased progressively with increasing bentonite content, although the magnitude of improvement differed slightly among the soil series. The observed increase indicates that bentonite modification enhanced the packing efficiency of the predominantly sandy soils, enabling the mixtures to attain higher dry densities under the same compactive effort.

The increase in maximum dry unit weight can be explained by considering the microstructural evolution of the soil–bentonite mixtures. The untreated soils consisted predominantly of uniformly graded sand particles with limited naturally occurring fines. Such soils generally possess relatively large intergranular voids because particles of similar sizes cannot pack efficiently. As bentonite was introduced, the extremely fine clay particles progressively occupied these void spaces, reducing the overall void ratio and increasing the packing density of the soil skeleton. The improved particle-size distribution therefore produced a denser composite structure capable of achieving higher dry unit weights during compaction.

In addition to void filling, bentonite modified the nature of particle contacts within the soil matrix. The clay particles coated the surfaces of adjacent sand grains, increasing the contact area between particles and promoting stronger interparticle bonding. During compaction, this coating effect improved particle rearrangement and reduced local stress concentrations, enabling the soil particles to achieve a more stable and densely packed configuration. Consequently, the increase in dry density reflects not only improved particle packing but also progressive development of a more integrated granular–clay framework.

The improvement in maximum dry unit weight was most pronounced at intermediate bentonite contents, after which the rate of increase became comparatively smaller. This behaviour suggests that once a substantial proportion of intergranular voids had been occupied by bentonite, further additions contributed progressively more to the clay fraction than to improved packing efficiency. At higher bentonite contents, the increasing proportion of expansive clay minerals begins to counterbalance the benefits of improved grading because clay particles require larger quantities of water and exhibit greater compressibility than sand particles. Similar trends have been reported for bentonite-modified soils and compacted liner materials, where the competing influences of particle packing and clay mineralogy govern the final dry density achieved during compaction (Mollins et al., 1996; Kohno et al., 2018; Khalid et al., 2023).

3.3.2 Optimum Moisture Content

The variation of optimum moisture content with bentonite content is illustrated in **Figure 6**. In contrast to the maximum dry unit weight, the optimum moisture content increased consistently with increasing bentonite addition for all three soils. This trend indicates that progressively larger quantities of water were required to achieve maximum compaction as the proportion of bentonite increased.

The increase in optimum moisture content is primarily attributed to the high water adsorption capacity of bentonite. Montmorillonitic clay minerals possess extensive internal and external surface areas together with a high cation exchange capacity, enabling them to retain substantial quantities of absorbed water. As the bentonite content increased, an increasing proportion of the added moisture became associated with clay particle surfaces and diffuse double layers rather than acting solely as lubrication between sand particles. Consequently, additional water was required before the mixtures reached the moisture condition at which particle rearrangement during compaction became most efficient.

The progressive increase in optimum moisture content also reflects the evolving balance between granular and cohesive behaviour within the mixtures. In the untreated soils, relatively small quantities of water were sufficient to lubricate the predominantly sand-sized particles and facilitate their rearrangement under compactive effort. However, as bentonite content increased, part of the added water became immobilised within the clay structure through adsorption and hydration processes. The remaining free water available for lubrication therefore decreased, necessitating higher total moisture contents to achieve optimum compaction.

This behaviour demonstrates that the mechanisms controlling compaction gradually shifted from purely mechanical particle rearrangement to combined mechanical and physicochemical processes. At low bentonite contents, compaction remained governed primarily by the packing characteristics of the sand skeleton. At higher bentonite contents, however, the influence of clay mineralogy became increasingly dominant, and moisture availability became the controlling factor governing maximum densification. Comparable increases in optimum moisture content with increasing bentonite addition have been reported for engineered bentonite–soil mixtures used in hydraulic barriers and compacted liner systems (Kohno et al., 2018; Khalid et al., 2023).

3.3.3 Integrated Interpretation of Compaction Behaviour

The simultaneous increases in maximum dry unit weight and optimum moisture content demonstrate that bentonite modification altered both the physical structure and moisture

*Corresponding Author: Blessing Uwaoma

demand of the Coastal Plain Sands. These two responses should not be interpreted independently but rather as complementary manifestations of progressive microstructural evolution.

Initially, bentonite improved particle packing by filling intergranular voids and increasing the continuity of the soil skeleton, thereby increasing the attainable dry density. As bentonite content increased further, the growing influence of expansive clay minerals increased the moisture required for effective compaction because larger quantities of water became associated with adsorption and diffuse double-layer development. Consequently, the compaction behaviour evolved from that of a coarse-grained frictional material to that of a granular–clay composite in which both particle arrangement and physicochemical interactions governed engineering performance.

This integrated interpretation explains why the modified soils exhibited simultaneous increases in dry density and optimum moisture content. Rather than representing contradictory behaviour, these trends reflect the progressive transformation of the soil fabric through bentonite incorporation.

3.3.4 Engineering Implications

The observed changes in compaction characteristics have important implications for geotechnical engineering practice. The increase in maximum dry unit weight suggests that bentonite modification enhances the compactability of Coastal Plain Sands by producing a denser and more stable soil skeleton under Standard Proctor compaction. Improved dry density is generally associated with increased shear strength, reduced compressibility, and enhanced load-bearing capacity, making bentonite-modified soils potentially suitable for applications such as embankments, pavement subgrades, engineered fills, and earth-retaining structures.

The simultaneous increase in optimum moisture content indicates that field construction involving bentonite-modified soils will require careful moisture control to achieve the desired level of compaction. Failure to supply sufficient water during compaction may prevent adequate particle rearrangement and reduce the achievable dry density. Consequently, field quality control should include close monitoring of placement moisture to ensure that compaction is carried out near the optimum moisture content determined in the laboratory.

Overall, the compaction results demonstrate that bentonite functions not merely as a mineral additive but as a microstructural modifier that fundamentally changes the packing characteristics, moisture demand, and engineering behaviour of Coastal Plain Sands. The observed trends establish a mechanistic link between the particle-size characteristics discussed in Section 3.1 and the plasticity behaviour presented in Section 3.2, providing a unified interpretation of the influence of bentonite on the engineering performance of the investigated soils.

3.4 Integrated Engineering Behaviour of Bentonite-Modified Coastal Plain Sands

The laboratory investigations demonstrate that the engineering behaviour of the investigated Coastal Plain Sands is controlled by a progressive transformation of the soil fabric following bentonite addition. Although particle-size distribution, Atterberg limits and compaction characteristics were evaluated separately, the results collectively indicate that these properties are closely interrelated and represent different manifestations of the same underlying physicochemical and microstructural processes occurring within the soil–bentonite mixtures.

The untreated soils are characterized by an essentially granular framework consisting predominantly of uniformly graded sand particles with very low natural fines content. In this condition, engineering behaviour is governed primarily by frictional contacts between adjacent sand grains. Because the soils contain only 2.07–4.24% fines, particle bonding is limited, moisture retention is relatively low, and the response to loading depends principally on particle arrangement and degree of compaction. This explains the negligible plasticity and comparatively low optimum moisture requirements observed for the natural soils.

The introduction of bentonite progressively modified this granular framework by introducing highly active clay particles into the intergranular pore spaces. Initially, the bentonite particles occupied the voids between adjacent sand grains, improving particle-size distribution and increasing the continuity of the soil skeleton. As the bentonite content increased further, clay particles increasingly coated the surfaces of sand grains, producing stronger interparticle bonding through physicochemical interactions associated with the expansive montmorillonitic mineral structure. Consequently, the soil fabric evolved from one dominated by discrete sand-to-sand contacts to a composite granular–clay network in which both mechanical interlocking and electrochemical interactions contributed to the overall engineering behaviour.

This progressive microstructural evolution provides a unified explanation for the experimental observations reported in the preceding sections. The increase in liquid limit and plasticity index reflects the growing influence of expansive clay minerals with high specific surface area and cation exchange capacity, which promote greater water adsorption and diffuse double-layer development. Simultaneously, the increase in maximum dry unit weight results from improved particle packing as bentonite fills intergranular voids, whereas the increase in optimum moisture content reflects the additional water required to satisfy the hydration demand of the clay minerals before effective particle rearrangement can occur during compaction. Thus, the observed changes in plasticity and compaction should not be interpreted as independent phenomena but as complementary responses to the same progressive modification of the soil microstructure.

From a geotechnical perspective, these findings indicate that bentonite performs a dual engineering function. Physically, it

*Corresponding Author: Blessing Uwaoma

acts as a void-filling material that improves packing efficiency and densification of the granular skeleton during compaction. Chemically and mineralogically, it functions as an active clay modifier that increases moisture retention, cohesion, and physicochemical bonding between particles. The combined action of these mechanisms transforms the natural Coastal Plain Sands from a predominantly frictional material into a cohesive granular–clay composite with significantly altered engineering characteristics.

The engineering significance of this transformation extends beyond the laboratory observations. Increased cohesion and improved compaction characteristics are expected to enhance the performance of compacted earth structures, pavement subgrades, embankments, hydraulic barriers, and engineered fills constructed using Coastal Plain Sands. However, the accompanying increase in plasticity also implies greater sensitivity to moisture fluctuations and a potentially higher shrink–swell tendency at elevated bentonite contents. Consequently, the selection of bentonite dosage should not be based solely on maximizing plasticity or dry density but should instead consider the balance between improved mechanical performance, moisture sensitivity, construction workability, and long-term field stability.

The integrated interpretation developed in this study therefore provides a mechanistic framework for understanding the behaviour of bentonite-modified Coastal Plain Sands. Rather than treating particle-size distribution, plasticity, and compaction as isolated engineering properties, the results demonstrate that they are sequential expressions of progressive microstructural modification of the original granular soil framework. This unified interpretation not only explains the observed laboratory behaviour but also provides a rational basis for the design and optimization of bentonite-modified sandy soils for geotechnical engineering applications.

To further illustrate the mechanistic interpretation developed from the laboratory results, Figure 7 presents a conceptual model describing the progressive transformation of the investigated Coastal Plain Sands following bentonite modification. The model integrates the particle-size distribution, plasticity, and compaction results into a unified microstructural framework, demonstrating how increasing bentonite content alters the soil fabric from a friction-dominated granular system to a cohesive granular–clay composite. This progressive evolution provides a mechanistic explanation for the observed increases in liquid limit, plasticity index, maximum dry unit weight, optimum moisture content, and cohesion, while also accounting for the accompanying increase in moisture sensitivity at higher bentonite contents.

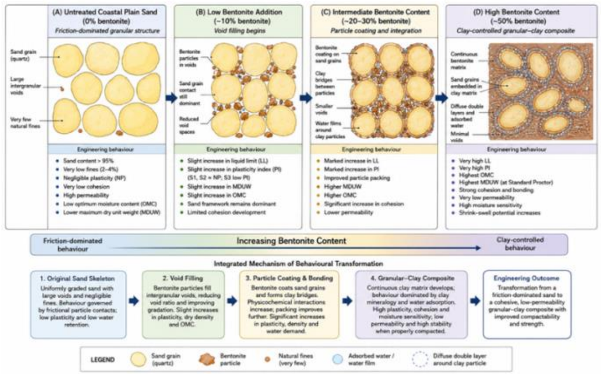

Figure 7. *Conceptual model illustrating the progressive microstructural evolution and engineering behaviour of bentonite-modified Coastal Plain Sands. Increasing bentonite content transforms the original friction-dominated sandy skeleton into a cohesive granular–clay composite through progressive void filling, particle coating, and physicochemical bonding. These microstructural changes explain the observed increases in liquid limit, plasticity index, maximum dry unit weight, optimum moisture content, and cohesion, while also increasing moisture sensitivity and shrink–swell potential.*

4. Conclusions

This study investigated the influence of bentonite modification on the plasticity and compaction characteristics of Coastal Plain Sands obtained from Akanu, Mgboko Itungwa Ward, Obingwa Local Government Area, Abia State, southeastern Nigeria. Based on the experimental results and their integrated interpretation, the following conclusions are drawn:

1. The natural soils are composed predominantly of sand-sized particles, with sand fractions ranging from 95.76% to 97.93%, fines contents of 2.07–4.24%, and no gravel fraction. All three soils were classified as poorly graded sand (SP**)** according to the Unified Soil Classification System (USCS), indicating a friction-dominated granular framework with negligible natural plasticity.
2. Bentonite modification significantly increased the consistency limits of the soils. The liquid limit and plasticity index increased progressively with increasing bentonite content, demonstrating that the engineering behaviour gradually changed from that of a coarse-grained granular material to that of a sand–clay composite. The observed increases are attributed to the high specific surface area, expansive nature, and water adsorption capacity of the montmorillonitic clay minerals present in bentonite.
3. The plasticity index exhibited the greatest sensitivity to bentonite addition. The 90:10 soil–bentonite mixtures of S1 and S2 remained non-plastic, whereas mixtures containing higher bentonite contents developed progressively greater plasticity, confirming that sufficient bentonite is required before a continuous clay-controlled soil fabric is established.

*Corresponding Author: Blessing Uwaoma

4. Bentonite addition improved the compaction characteristics of the investigated soils. The maximum dry unit weight increased owing to improved particle packing resulting from progressive filling of intergranular voids, while the optimum moisture content increased because of the greater water demand associated with bentonite hydration and diffuse double-layer development.
5. The combined results demonstrate that bentonite functions as both a physical modifier, by improving particle packing and reducing void spaces, and a physicochemical modifier**,** by increasing water adsorption, interparticle bonding, and cohesion. These complementary mechanisms collectively govern the observed changes in plasticity and compaction behaviour.
6. Integration of the particle-size distribution, plasticity, and compaction results enabled the development of a conceptual model describing the progressive transformation of Coastal Plain Sands from a friction-dominated granular material into a cohesive granular–clay composite. This unified mechanistic interpretation provides a scientific framework for understanding the behaviour of bentonite-modified sandy soils and extends beyond the interpretation of individual laboratory tests.
7. From an engineering perspective, bentonite modification offers considerable potential for improving the performance of Coastal Plain Sands in applications such as compacted liners, hydraulic barriers, embankments, pavement subgrades, and engineered fills. However, increasing bentonite content also increases moisture demand and plasticity, indicating that an optimum bentonite dosage should be selected to balance improved engineering performance with construction workability and long-term dimensional stability.

Overall, the study demonstrates that the engineering behaviour of Coastal Plain Sands is governed not only by particle-size distribution but also by the progressive microstructural and physicochemical modifications induced by bentonite incorporation. The mechanistic interpretation developed in this study provides a rational basis for the design and optimization of bentonite-modified sandy soils for sustainable geotechnical engineering applications.

5. Limitations of the Study and Future Research

The present study focused on the influence of bentonite modification on the particle-size distribution, plasticity, and compaction characteristics of Coastal Plain Sands under controlled laboratory conditions. Although these properties provide important insight into the engineering behaviour of the modified soils, other performance characteristics such as shear strength, compressibility, hydraulic conductivity, durability under cyclic wetting–drying, and long-term field performance were beyond the scope of this investigation. Future research should integrate these engineering properties with advanced microstructural characterization techniques, such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and mercury intrusion porosimetry (MIP), to further elucidate the mechanisms governing bentonite–soil interactions and to optimize bentonite-treated Coastal Plain Sands for a wider range of geotechnical engineering applications.

References

1. Adeyemi, G. O., Afolagboye, L. O., & Chinwenwa Chukwuemeka, A. (2015). Geotechnical properties of non-crystalline coastal plain sand derived lateritic soils from Ogua, Niger Delta, Nigeria. *African Journal of Science, Technology, Innovation and Development*, *7*(4), 230–235. https://doi.org/10.1080/20421338.2015.1078105
2. Kohno, M., Nara, Y., Kato, M., & Nishimura, T. (2018). Effects of clay-mineral type and content on the hydraulic conductivity of bentonite–sand mixtures made of Kunigel bentonite from Japan. *Clay Minerals*, *53*(4), 721–732. doi:10.1180/clm.2018.52
3. Madueke , C.O., Nnabude , P.C., Okore, I.K, Onuwa, A.O., Madueke, E.C., Okafor, M.J., Nnabuihe, E., & Nwosu, T.V. (2021). Evaluation of Soils on a Toposequence Formed from the Coastal Plain Sands of the Imo River Basin, Southeastern Nigeria. Nigerian Journal of Soil Science, 31(2), 1-9. https://doi.org/10.67042/njss.2021.max2lohx
4. Mollins, L. H., Stewart, D. I., & Cousens, T. W. (1996). Predicting the properties of bentonite-sand mixtures. *Clay Minerals, 31(2),* 243–252. doi:10.1180/claymin.1996.031.2.10
5. Khalid, N., Mukri, M., Md Zain, N., Razak, Z., & Mohamed Jais, I. (2023). Multiple linear regression modelling for the compaction characteristics of sedimentary soil mixed bentonite as compacted liner. *Jurnal Teknologi*, *85*(6). https://doi.org/10.11113/jurnalteknologi.v85.20161
6. Latifi, N., Vahedifard, F., Ghazanfari, E., Horpibulsuk, S., Marto, A., & Williams, J.M. (2018). Sustainable Improvement of Clays Using Low-Carbon Nontraditional Additive. *International Journal of Geomechanics*, *18*, 04017162.
7. Sridharan, A., & Prakash, K. (1999). Influence of clay mineralogy and pore-medium chemistry on clay sediment formation. *Canadian Geotechnical Journal*, *36*(5), 961–966.
8. Monteiro, F. F., Albuquerque, P. J. R. de, & Gigliotti, F. dos S. G. (2024). *Geotechnical characterization of tropical soil via laboratory testing*. *Concilium,* *24*(17). https://doi.org/10.53660/CLM-4013-24R11
9. Phummiphan, I., Horpibulsuk, S., Rachan, R., Arulrajah, A., Shen, S.-L., & Chindaprasirt, P. (2018). High calcium fly ash geopolymer stabilized lateritic soil and granulated blast furnace slag blends as a pavement base material. *Journal of Hazardous*

*Corresponding Author: Blessing Uwaoma

Materials, *341*, 257–267. https://doi.org/10.1016/j.jhazmat.2017.07.067

10. ASTM International. (2025). *ASTM D2487-17(2025): Standard practice for classification of soils for engineering purposes (Unified Soil Classification System).* ASTM International. https://doi.org/10.1520/D2487-17R25

*Corresponding Author: Blessing Uwaoma