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Assessment of Niger Delta Lateritic Soil Mixed with Bentonite as a Landfill Barrier.

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***Abstract-** This research examines the geotechnical properties of laterite-bentonite blends through a series of tests, including specific gravity, sieve analysis, Atterberg limits, maximum dry density, optimum water content, and permeability. Specific gravity testing reveals an average value of 2.5472, indicating moderate density. Sieve analysis demonstrates that the soil particles fall within the range of silt and sandy soils. Atterberg limits classify the soil as having intermediate plasticity, with a liquid limit of 22.00, plastic limit of 14.29, and plastic index of 7.71. Maximum dry density and optimum water content tests reveal varying trends, highlighting the intricate interaction between laterite and bentonite. The maximum dry density is observed at a mix ratio of 30% bentonite, with a value of 2.1 g/cm3, while the optimum water content occurs at a mix ratio of 20% bentonite, with a value of 20.25. Permeability testing indicates an inverse relationship between bentonite content and permeability, with permeability decreasing from 0.00004 at 0% bentonite to 0.000015 at a 35% bentonite mix ratio, suggesting potential applications in scenarios requiring low permeability. The findings offer valuable insights for engineering assessments and customized soil mixtures in construction and environmental engineering projects.*

***Keywords:** Laterite-Bentonite Blends, Geotechnical Properties, Specific Gravity, Sieve Analysis, Atterberg Limits, Maximum Dry Density, Optimum Water Content, Permeability.*

I. INTRODUCTION

The Niger Delta, a region in Nigeria known for its diverse ecology and abundant biodiversity, faces significant environmental challenges stemming from decades of oil exploration, deforestation, and industrial activities (Alayaaki et al., 2015). Among these challenges is the proper management of waste, often facilitated through landfilling practices. However, conventional landfill sites present risks of environmental contamination, particularly through the infiltration of leachate into the soil and groundwater (Lukiantchuki and et al., 2010).

To address these challenges, there is a growing need for innovative landfill barrier systems capable of effectively containing leachate. While various materials and construction methods have been explored, further investigation into alternative materials is necessary to enhance landfill barrier performance. Lateritic soil, which is abundant in the Niger Delta, possesses low permeability, making it suitable for minimizing liquid flow (Kumar et al., 2022). However, using lateritic soil alone may have limitations in achieving the desired impermeability for effective leachate containment (Kumar et al., 2022).

Complementing lateritic soil, bentonite—a clay known for its swelling properties and impermeable barrier formation—offers potential as a landfill liner material (Shirazi et al., 2010; Amadi et al., 2013). Blending these materials could present a viable solution for creating effective landfill barriers, harnessing the advantages of both while mitigating their individual limitations.

This research aims to assess the viability of using a blend of Niger Delta lateritic soil and bentonite as a landfill barrier. It seeks to address environmental concerns by mitigating risks of groundwater contamination and promoting sustainable waste management practices in the Niger Delta region. Through comprehensive laboratory testing and material characterization, the study aims to evaluate the effectiveness of the blended material in containing leachate and maintaining the integrity of landfill barriers.

Landfill barriers play a pivotal role in waste containment, leachate control, and environmental protection. By reviewing past studies, this aims to elucidate the evolution of landfill barrier technologies, material performance, and the lessons learned from both successful and unsuccessful endeavors. Such insights are invaluable for informing future research, guiding practical applications, and shaping policy decisions in landfill engineering and waste management (Townsend, et al., 2015).

Traditional landfill barrier materials encompass a range of options, including geomembranes, geosynthetic clay liners (GCLs), compacted clay liners, and natural materials like lateritic soils, crushed shales, and red mud (Bouazza et al., 2002). Geosynthetics, such as nonwoven geotextiles and geomembranes, offer various functions like separation, filtration, drainage, and hydraulic barrier (Bouazza et al., 2002). However, improper design and construction of geosynthetic systems can lead to stability issues and landfill failures (Mitchell et al., 1993). Compacted clay liners have been a traditional choice due to their low hydraulic conductivity (Nithi et al., 2017). They can be augmented with materials like bentonite-sand mixtures to improve strength and prevent shrinkage cracks (Sivapullaiah et al., 2000). Additionally, lateritic soils abundant in tropical regions like the Niger Delta offer suitable properties for waste containment (Townsend et al., 1971). Other alternatives, like crushed shales and red mud, provide cost-effective options where natural clay availability is limited (Y.E.-A. Mohamedzein et al., 2005; Kalkan, 2005). While traditional materials offer advantages such as cost-effectiveness and proven performance, they also have limitations like permeability, space requirements, and vulnerability to environmental conditions. The choice of landfill barrier material depends on factors such as site conditions, waste characteristics, budget, and regulatory standards.

The Niger Delta region, characterized by its complex geological formation known as the Niger Delta basin, holds significant economic value due to its productive petroleum system (Tuttle et al., 2015). Covering a vast area with various geological formations, the basin's structure indicates its formation processes and regional tectonics. This geological complexity is illustrated in Figure 2.3, which highlights key oil fields in the region.

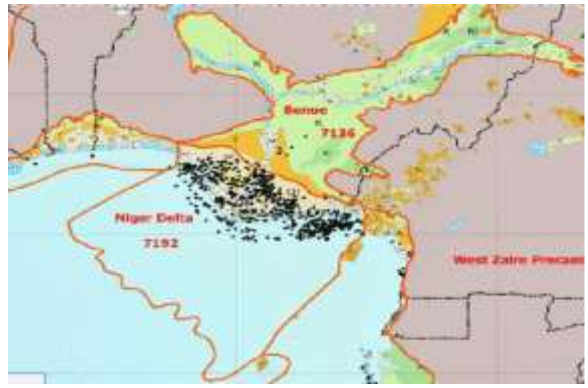

Figure 1: Geologic map of the Niger Delta Basin and the Benue trough, and the oil fields in the region.

The Niger Delta Basin originated from a failed rift junction during the separation of the South American and African plates, marking the opening of the South Atlantic. Rifting began in the late Jurassic and concluded in the mid-Cretaceous, forming several thrust faults and depositing syn-rift sands and shales by the late Cretaceous, indicating a regression in the shoreline

Lateritic soils in the Niger Delta region result from intense weathering under tropical and subtropical conditions, accumulating hydrated iron and aluminum oxides. These soils are prevalent in both eastern and western Niger Delta regions, overlaying thick Tertiary sandy and clayey deltaic deposits. The study area's geology primarily comprises three subsurface lithostratigraphic units: the Akata, Agbada, and Benin Formations. The geomorphology of the region encompasses five main environments: active and abandoned coastal beaches, saltwater mangrove swamps, freshwater swamps, backswamps deltaic plains, alluvium and meander belts, dry deltaic plains with abundant swamp zones, and dry flat lands and plains (Short and Stauble, 1967).

The construction sector in the Niger Delta region has extensively utilized lateritic soils for road construction due to their abundance, but these soils are often unsuitable in their natural state, necessitating proper classification and stabilization methods. Several studies have investigated the engineering geological properties of lateritic soils in the region, addressing their suitability for construction purposes (Alabo et al.,1987; Alabo et al., 1983; Arumala and Akpokodje, 1987; Leton and Omotosho, 2004; Omotosho and Eze-Uzomaka, 2008).

The use of laterite soil as an alternative material for geopolymer production has garnered attention in recent research studies. Gualtieri et al. (2015) explored the feasibility of utilizing laterite soil in geopolymer production with the aid of phosphoric acid and alkaline sodium silicate solution. They found that raw laterite soil-based geopolymer exhibited minimal strength gain during prolonged curing at temperatures up to 60ºC. The researchers concluded that the calcination of laterite soil is essential for the dehydroxylation of kaolinite, which contributes to the formation of the alumino-silicate phase necessary for sufficient hardening.

Kaze et al. (2021) investigated the use of calcined laterite soil in geopolymer synthesis using sodium silicate and sodium hydroxide solutions under various curing conditions. They observed that increasing temperature from 20ºC to 80ºC enhanced the solubility of elements such as Al, Si, and Fe, leading to additional formation of the geopolymer network and improved performance.

Furthermore, Lemougna et al. (2017) studied the incorporation of various blending materials, including blast furnace slag and calcite, along with laterite soil for producing inorganic polymers with sodium silicate solution. They found that laterite soil blended with slag exhibited higher strength compared to that blended with calcite.

In road construction, laterite soil has been utilized successfully in various countries. The performance of lateritic soil road pavements depends on factors such as compaction degree, saturation condition, internal soil structure, climate, and drainage conditions. To enhance the properties of laterite soil-based pavements, stabilization with materials like lime and cement is commonly employed. Lime stabilization improves workability, reduces plasticity, and enhances subgrade elasticity modulus, while cement addition promotes the formation of a homogeneous microstructure, thus improving mechanical properties.

Apart from road construction, laterite soil finds applications in other areas such as backfill materials, arsenic absorbent, coagulant for dye degradation, and defluoridation. Researchers have explored its potential as a buffer/backfill material for removing radioactive impurities from ground and sea water, as an arsenic adsorbent for water treatment, for dye degradation in wastewater treatment, and for defluoridation of potable water.

II. MATERIALS AND METHOD

2.1 Research design

The research was conducted in the Niger Delta, which is the delta of the Niger River located directly on the Gulf of Guinea on the Atlantic Ocean in Nigeria. This region, known for its petroleum-rich resources, has been the center of international concern due to extensive pollution, particularly from oil spills by multinational corporations in the petroleum industry. The research aimed to address the environmental challenges faced by the Niger Delta by evaluating the feasibility and effectiveness of utilizing blended materials, specifically lateritic/laterite soils mixed with bentonite, for landfill barrier applications.

Sampling sites were strategically selected within the Niger Delta region, focusing on areas characterized by lateritic/laterite soils and relevant to landfill barrier applications. Soil samples were collected using a systematic approach, capturing the vertical soil profile at various depths. High-quality sodium bentonite clay was sourced from reliable suppliers in Port Harcourt, ensuring consistency and reliability in the blending experiments.

In the laboratory, collected soil samples underwent meticulous preparation procedures, including drying, sieve analysis, and homogenization. Geotechnical tests were conducted to assess the engineering properties of the blended materials, including specific gravity, particle size distribution, Atterberg limits, permeability, shear strength, and stability. These tests provided valuable insights into the performance of blended materials compared to traditional landfill barrier materials.

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Data obtained from laboratory tests were analyzed to evaluate the engineering properties, environmental implications, and sustainability aspects of using blended materials. Comparative analysis was conducted to assess the performance of blended materials in terms of permeability, shear strength, stability, and environmental impact. Findings were interpreted in the context of landfill barrier applications in the Niger Delta region, highlighting the potential benefits and limitations of using blended materials.

2.2 Study Area
The Niger Delta is the delta of the Niger River sitting directly on the Gulf of Guinea on the Atlantic Ocean in Nigeria (Michael, 2013; Umoh et al, 2022). It is located within nine coastal southern Nigerian states, which include: all six states from the South South geopolitical zone, one state (Ondo) from South West geopolitical zone and two states (Abia and Imo) from South East geopolitical zone.

The delta is a petroleum-rich region and has been the center of international concern over extensive pollution which is often used as an example of ecocide (UNPO, 2023). The principal cause is major oil spills by multinational corporations of the petroleum industry.

The Niger Delta, as now defined officially by the Nigerian government, extends over about 70,000 km2 (27,000 sq mi) and makes up 7.5% of Nigeria's land mass. Historically and cartographically, it consists of present-day Bayelsa, Delta, and Rivers States. In 2000, however, Obasanjo's regimeincluded Abia, Akwa-Ibom, CrossRiver State, Edo, Imo and Ondo States in the region (Otoabasi, 2011). Figure 3.1 presents the map of the study area.

Figure 2: Map of Study area

The materials utilized for the research include laterite soil samples collected from various locations within the Niger Delta region to represent the diversity of soil compositions. Additionally, high-quality sodium bentonite clay was sourced from reliable suppliers in Port Harcourt to conduct blending experiments and tests. Distilled or deionized water was used for mixing the lateritic soil and bentonite blend to ensure the absence of impurities that could affect the material's properties. Geotechnical testing specimens, laboratory consumables, and equipment such as sieves, mixers, permeameter apparatus, compaction equipment, data acquisition systems, safety equipment, and measuring instruments were employed for conducting experiments in a well-equipped laboratory facility (Michael, 2013; Umoh et al, 2022; UNPO, 2023; Otoabasi, 2011).

The equipment list includes sieves and a sieve shaker for particle size analysis, mixers and blenders for homogenizing the laterite soil and bentonite blend, permeameter apparatus for measuring permeability, standard compaction molds and equipment for preparing compacted specimens, a data acquisition system for recording and analyzing data, safety equipment such as lab coats and gloves, laboratory facilities with benches and storage facilities, precision balances and weighing scales, measuring instruments like tapes, rulers, and calipers, and lab furniture for organizing materials and equipment (Michael, 2013; Umoh et al, 2022; UNPO, 2023; Otoabasi, 2011).

2.3 Field and Data collection
For sample collection and preparation, five sampling locations were strategically chosen across Rivers and Bayelsa States based on geographical distribution,

accessibility, and soil heterogeneity. At each site, a systematic approach was employed to collect soil samples at various depths to capture the vertical soil profile. Soil augers, hand augers, and soil coring equipment were used for sample collection. To ensure representativeness, soil samples were collected at varying depths, typically ranging from the ground surface to a depth of 3 meters. Samples were labeled according to depth intervals, and adequate soil volume was collected to facilitate subsequent laboratory testing. Special care was taken to minimize disturbance and compaction during sample collection, preserving the soil's natural state and moisture content. Preserving sample integrity is crucial to prevent contamination and maintain natural characteristics. Samples were labeled with essential information and sealed airtight to prevent moisture loss and contamination during transportation. Sealed samples were stored under controlled environmental conditions in the laboratory, with refrigeration utilized for samples prone to microbial degradation.

In the laboratory, the soil samples collected from the field underwent meticulous preparation procedures prior to testing. This involved several steps to ensure the accuracy and reliability of the experimental results.

Firstly, some of the samples were air-dried to determine their natural moisture content, while others were preserved with their original moisture content, depending on the specific tests to be conducted. This differentiation allowed for a comprehensive understanding of the soil's characteristics under different moisture conditions.

Next, representative subsamples from the dried soil samples were obtained and subjected to sieve analysis. This process involved passing the samples through a series of sieves to separate particles of different sizes. The resulting particle size distribution provided valuable insights into the soil's composition and texture.

Furthermore, careful homogenization of the samples was performed to ensure uniformity and consistency in subsequent testing. This step aimed to eliminate any inconsistencies or variations within the samples that could affect the test results.

One of the crucial tests conducted on the prepared soil samples was the Specific Gravity Test. This test aimed to characterize the density and buoyancy of the lateritic soil and bentonite blend, providing insights into the compactness and porosity of the soil-bentonite mixture. Both air-dried and moisture-preserved samples were utilized for this test to assess the material's characteristics under different conditions.

The Sieve Analysis Test, performed using the Hydrometer Method, was another essential aspect of the research methodology. This test determined the particle size distribution of the lateritic soil, providing valuable information for further analysis and interpretation.

Additionally, Atterberg Limits, including Liquid Limit, Plastic Limit, and Shrinkage Limit, were determined to understand the soil's behavior and consistency under different moisture conditions. These limits served as significant indicators in assessing the soil's plasticity, shrinkage, and compressibility characteristics.

The Maximum Dry Density and Optimum Moisture Content tests were conducted to evaluate the compaction characteristics of the soil-bentonite blends. These tests provided critical parameters for designing an effective landfill barrier, influencing the stability and permeability of the barrier material.

Permeability testing was also carried out to assess the impact of Bentonite content on the soil's permeability. Falling head permeability tests were conducted following ASTM guidelines, and the obtained data were analyzed statistically to establish the relationship between Bentonite content and soil permeability.

Throughout the testing process, quality control measures were implemented to ensure the reliability and validity of the experimental results. Regular calibration of instruments, multiple trials for each test, and the use of certified reference materials were

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some of the measures employed to maintain quality standards.

III. RESULTS AND DISCUSSION

Comprehensive results of various tests conducted on laterite-bentonite blended mixes, providing insights into the geotechnical properties of the soil. The discussion encompasses maximum dry density, optimum water content, and permeability. The outcomes of these tests are analysed to understand the influence of bentonite content on the engineering behavior of the laterite-bentonite blends.

3.1 Maximum Dry Density and Optimum Moisture Content Test

The results derived from the compaction test on the blended laterite and bentonite mix are shown for each blended mix with its corresponding percentage mix of bentonite (0, 10, 20, 30, 35%) respectively.

0% Bentonite (100% Laterite)

Table 1: Wet density determination of the mix with 0% bentonite (100% laterite).

Mold No.:	1	2	3	4
Wt. Of Mold + wet Sample (g)	12122	12666	12482	12282
Wt. Of Mold (g)	7694	7694	7694	7694
Wt. Of Sample (g)	4428	4972	4788	4588
Vol. Of mold (cm^3)	2250	2250	2250	2250
Wet density (g/cm^3)	1.97	2.21	2.13	2.04

Table 2: Water content determination of the mix with 0% bentonite (100% laterite).

Sample No.	1	2	3	4
Moisture Can No.	A	B	C	D
Wt. Of can + wet Soil	163.00	188.00	174.00	182.00
Wt. Of can + dry Soil	148.00	167.00	152.00	156.00
Wt. Of water	15.00	21.00	22.00	26.00
Wt. Of Can	43.00	44.00	45.00	42.00
Wt. Of Dry Soil	105.00	123.00	107.00	114.00
Moisture content %	14.29	17.07	20.56	22.81
Avg.	14.3	17.1	20.6	22.8
Dry Density g/cm^3	1.72	1.89	1.77	1.66

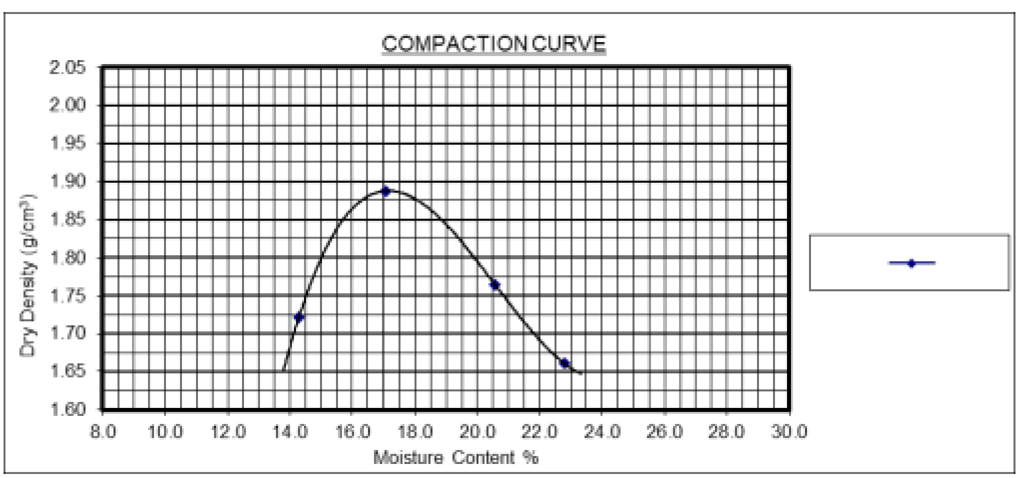

Figure 3: Compaction curve of the mix with 0% bentonite (100% laterite).

5% Bentonite

Table 4: Wet density determination of the mix with 5% bentonite.

Mold No.:	1	2	3	4
Wt. Of Mold + wet Sample	12000	12400	12500	12350
Wt. Of Mold	7694	7694	7694	7694
Wt. Of Sample	4306	4706	4806	4656
Vol. Of mold	2250	2250	2250	2250
Wet density g/cm^3	1.91	2.09	2.14	2.07

Table 5: Water content determination of the mix with 5% bentonite.

Sample No.	1	2	3	4
Moisture Can No.	E	F	G	H
Wt. Of can + wet Soil	120.00	128.00	128.00	130.00
Wt. Of can + dry Soil	112.00	118.00	117.00	118.00
Wt. Of water	8.00	10.00	11.00	12.00
Wt. Of Can	45.00	47.00	46.00	47.00
Wt. Of Dry Soil	67.00	71.00	71.00	71.00
Moisture content %	11.94	14.08	15.49	16.90
Avg.	11.9	14.1	15.5	16.9
Dry Density g/cm^3	1.71	1.83	1.85	1.77

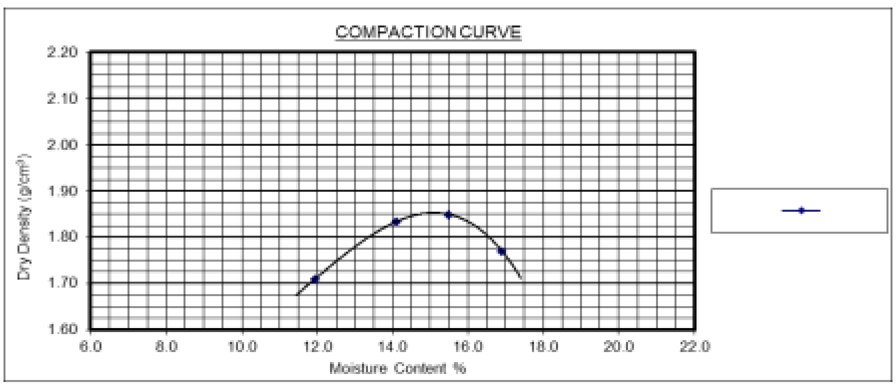

Figure 4: Compaction curve of the mix with 5% bentonite.

10% Bentonite

Table 6: Wet density determination of the mix with 10% bentonite.

Mold No.:	1	2	3	4
Wt. Of Mold + wet Sample	12436	12600	12400	12300
Wt. Of Mold	7694	7694	7694	7694
Wt. Of Sample	4742	4906	4706	4606
Vol. Of mold	2250	2250	2250	2250
Wet density g/cm^3	2.11	2.18	2.09	2.05

Table 7: Water content determination of the mix with 10% bentonite.

Sample No.	1	2	3	4
Moisture Can No.	I	J	K	L
Wt. Of can + wet Soil	135.00	132.00	123.00	140.00
Wt. Of can + dry Soil	126.00	121.00	111.00	125.00
Wt. Of water	9.00	11.00	12.00	15.00
Wt. Of Can	44.00	47.00	42.00	47.00
Wt. Of Dry Soil	82.00	74.00	69.00	78.00
Moisture content %	10.98	14.86	17.39	19.23

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Avg.	11.0	14.9	17.4	19.2
Dry Density g/cm^3	1.90	1.90	1.78	1.72

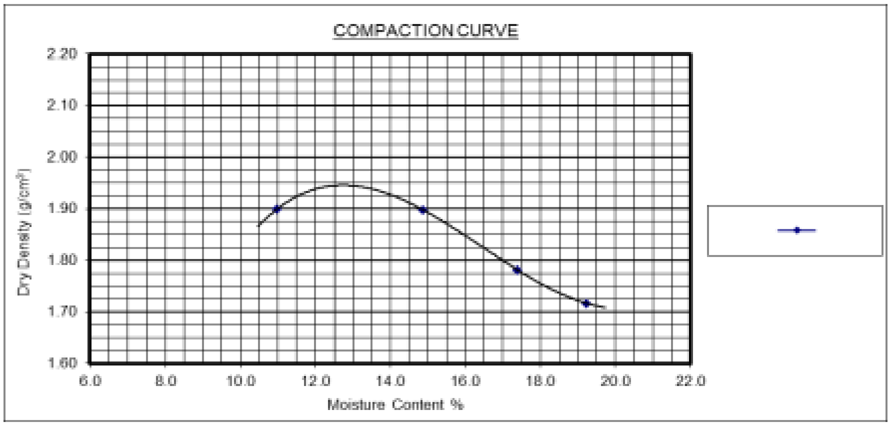

Figure 5: Compaction curve of the mix with 10% bentonite.

20% Bentonite

Table 8: Wet density determination of the mix with 20% bentonite.

Mold No.:	1	2	3	4
Wt. Of Mold + wet Sample	11600	11900	12100	11700
Wt. Of Mold	7694	7694	7694	7694
Wt. Of Sample	3906	4206	4406	4006
Vol. Of mold	2250	2250	2250	2250
Wet density g/cm^3	1.74	1.87	1.96	1.78

Table 9: Water content determination of the mix with 20% bentonite.

Sample No.	1	2	3	4
Moisture Can No.	C	E	H	I
Wt. Of can + wet Soil	123.00	130.00	142.00	125.00
Wt. Of can + dry Soil	111.00	116.00	126.00	110.00
Wt. Of water	12.00	14.00	16.00	15.00
Wt. Of Can	43.00	41.00	44.00	43.00
Wt. Of Dry Soil	68.00	75.00	82.00	67.00
Moisture content %	17.65	18.67	19.51	22.39
Avg.	17.6	18.7	19.5	22.4
Dry Density g/cm^3	1.48	1.58	1.64	1.45

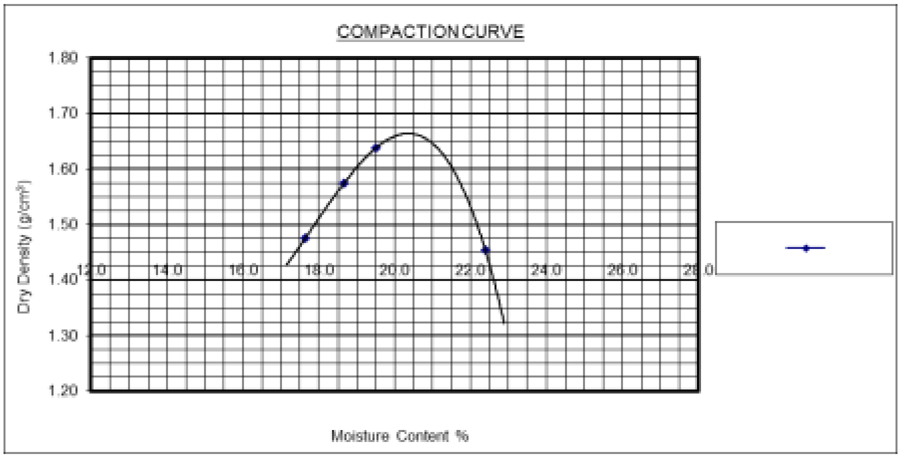

Figure 6: Compaction curve of the mix with 20% bentonite.

30% Bentonite

Table 10: Wet density determination of the mix with 30% bentonite.

Mold No.:	1	2	3	4
Wt. Of Mold + wet Sample	12400	12900	12500	12300
Wt. Of Mold	7694	7694	7694	7694
Wt. Of Sample	4706	5206	4806	4606
Vol. Of mold	2250	2250	2250	2250
Wet density g/cm^3	2.09	2.31	2.14	2.05

Table 11: Water content determination of the mix with 30% bentonite.

Sample No.	1	2	3	4
Moisture Can No.	Q	R	S	T
Wt. Of can + wet Soil	125.00	127.00	129.00	133.00
Wt. Of can + dry Soil	117.00	118.00	119.00	122.00
Wt. Of water	8.00	9.00	10.00	11.00
Wt. Of Can	40.00	46.00	46.00	45.00
Wt. Of Dry Soil	77.00	72.00	73.00	77.00
Moisture content %	10.39	12.50	13.70	14.29
Avg.	10.4	12.5	13.7	14.3
Dry Density g/cm^3	1.89	2.06	1.88	1.79

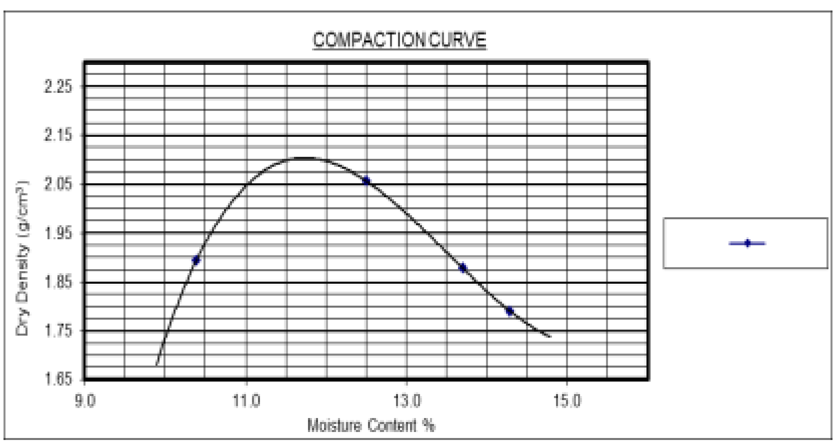

Figure 7: Compaction curve of the mix with 30% bentonite.

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35% Bentonite

Table 12: Wet density determination of the mix with 35% bentonite.

Mold No.:	1	2	3	4
Wt. Of Mold + wet Sample	11300	12500	12000	11500
Wt. Of Mold	7694	7694	7694	7694
Wt. Of Sample	3606	4806	4306	3806
Vol. Of mold	2250	2250	2250	2250
Wet density g/cm^3	1.60	2.14	1.91	1.69

Table 13: Water content determination of the mix with 35% bentonite.

Sample No.	1	2	3	4
Moisture Can No.	U	V	W	X
Wt. Of can + wet Soil	126.00	123.00	132.00	134.00
Wt. Of can + dry Soil	118.00	114.00	121.00	121.90
Wt. Of water	8.00	9.00	11.00	12.10
Wt. Of Can	42.00	41.00	44.00	42.00
Wt. Of Dry Soil	76.00	73.00	77.00	79.90
Moisture content %	10.53	12.33	14.29	15.14
Avg.	10.5	12.3	14.3	15.1
Dry Density g/cm^3	1.45	1.90	1.67	1.47

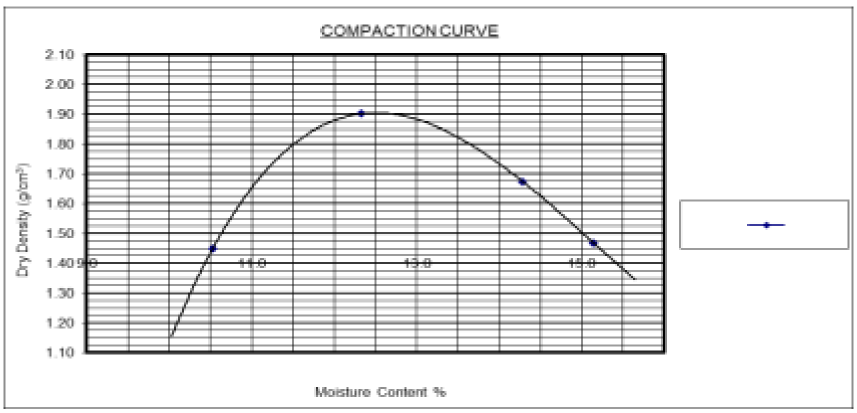

Figure 8: Compaction curve of the mix with 35% bentonite.

The MDD values show considerable variability with the addition of bentonite, suggesting changes in the soil's compaction characteristics.

Generally, as the percentage of bentonite increases, the MDD tends to fluctuate, reaching a peak at 30% bentonite and then slightly decreasing at 35%.

The OWC values exhibit a trend of decrease until the 30% bentonite mix, indicating a reduced water requirement for compaction. However, the 35% bentonite mix sees a slight increase in OWC compared to the 30% mix.

The 30% bentonite mix stands out with a notably high MDD, which may be beneficial for certain engineering applications where higher density is desirable.

The varying trends in MDD and OWC highlight the complex interaction between laterite and bentonite, indicating that the addition of bentonite significantly influences the compaction behavior of the soil.

The results suggest that there is an optimal range of bentonite content that achieves the desired compaction properties, and exceeding this range may lead to diminishing returns.

Engineers and construction professionals can use this data to tailor soil mixes for specific applications, optimizing compaction efforts and ensuring stability in construction projects.

The findings emphasize the importance of understanding the specific requirements of a project

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and selecting the appropriate bentonite content to achieve the desired compaction characteristics.

3.2 Permeability Test

The falling head permeability test was used to determine the permeability of the laterite-bentonite blended mix. The results derived from the test on the blended laterite and bentonite mix are shown for each blended mix with its corresponding percentage mix of bentonite (0, 10, 20, 30, 35%) respectively.

0% Bentonite (100% Laterite)

Table 14: Falling head permeability test for the mix with 0% bentonite (100% laterite).

S/N	Specimen Diameter	Specimen Area	Burette Area	Initial Standpipe Reading	Final Standpipe Reading	Time Of Collection (Sec)	Difference In Standpipe Levels	Length Of Sample Column	K= aL/At Inh$_o$/h$_1$ cm/s
Test NO	cm	cm^2	a(cm^2)	h$_O$ (cm)	h$_1$ (cm)	t sec	hcm = (h$_0$-h)	L cm	
1	6.3	31.18	0.5	98	15	851	83	13.0	0.000041
2	6.3	31.18	0.5	96	1`4	853	82	13.0	3.85234E-05
							AVERAGE		0.000040

5% Bentonite

Table 15: Falling head permeability test for the mix with 5% bentonite.

S/N	Specimen Diameter	Specimen Area	Burette Area	Initial Standpipe Reading	Final Standpipe Reading	Time Of Collection (Sec)	Difference In Standpipe Levels	Length Of Sample Column	K= aL/At Inh$_o$/h$_1$ cm/s
Test NO	cm	cm^2	a(cm^2)	h$_O$ (cm)	h$_1$ (cm)	t sec	hcm = (h$_0$-h)	L cm	
1	6.3	31.18	0.5	99	69	675	30	13.0	0.000369
2	6.3	31.18	0.5	70	42	673	28	13.0	0.000283828
							AVERAGE		0.000326

10% Bentonite

Table 16: Falling head permeability test for the mix with 10% bentonite.

S/N	Specimen Diameter	Specimen Area	Burette Area	Initial Standpipe Reading	Final Standpipe Reading	Time Of Collection (Sec)	Difference In Standpipe Levels	Length Of Sample Column	K= aL/At Inh$_o$/h$_1$ cm/s
Test NO	cm	cm^2	a(cm^2)	h$_O$ (cm)	h$_1$ (cm)	t sec	hcm = (h$_0$-h)	L cm	
1	6.3	31.18	0.5	100	58	800	42	13.0	0.000226

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2	6.3	31.18	0.5	95	55	795	40	13.0	0.000226822
							AVERAGE		0.000226

20% Bentonite

Table 17: Falling head permeability test for the mix with 20% bentonite.

Specimen Diameter	Specimen Area	Burette Area	Initial Standpipe Reading	Final Standpipe Reading	Time Of Collection (Sec)	Difference In Standpipe Levels	Length Of Sample Column	K= aL/At Inh_o/h_1 cm/s
Cm	cm^2	a(cm^2)	h_O (cm)	h_1 (cm)	t sec	hcm = (h_0-h)	L cm	
6.3	31.18	0.5	85.5	67	1565	18.5	13.0	0.000204
6.3	31.18	0.5	82	65	1563	17	13.0	0.000209868
						AVERAGE		0.000207

30% Bentonite

Table 18: Falling head permeability test for the mix with 30% bentonite.

Specimen Diameter	Specimen Area	Burette Area	Initial Standpipe Reading	Final Standpipe Reading	Time Of Collection (Sec)	Difference In Standpipe Levels	Length Of Sample Column	K= aL/At Inh_o/h_1 cm/s
Cm	cm^2	a(cm^2)	h_O (cm)	h_1 (cm)	t sec	hcm = (h_0-h)	L cm	
6.3	31.18	0.5	90	45	7998	45	13.0	0.000018
6.3	31.18	0.5	80	40	7990	40	13.0	1.80849E-05
						AVERAGE		0.000018

35% Bentonite

Table 19: Falling head permeability test for the mix with 35% bentonite.

Specimen Area	Burette Area	Initial Standpipe Reading	Final Standpipe Reading	Time Of Collection (Sec)	Difference In Standpipe Levels	Length Of Sample Column	K= aL/At Inh_o/h_1 cm/s
cm^2	a(cm^2)	h_O (cm)	h_1 (cm)	t sec	hcm = (h_0-h)	L cm	
31.18	0.5	70	40	10600	30	13.0	0.000017
31.18	0.5	81	39.2	10702	41.8	13.0	1.28866E-05
					AVERAGE		0.000015

The permeability of a soil mixture is a crucial parameter in geotechnical engineering, indicating how easily water can flow through the material. The results presented in Table 4.24 show the permeability

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values for different blends of laterite and bentonite. Let's discuss the relationship between the increasing bentonite content and the observed permeability:

0% Bentonite (100% Laterite):
Permeability: 0.000040 cm/s
This serves as a reference point for the natural permeability of 100% laterite.

5% Bentonite:
Permeability: 0.000326 cm/s
The introduction of 5% bentonite significantly increases the permeability compared to the 0% bentonite mix. Bentonite, with its swelling and binding properties, may contribute to the alteration of the soil structure, affecting the flow of water.
10% Bentonite:
Permeability: 0.000226 cm/s
The permeability decreases compared to the 5% bentonite mix, indicating a potential threshold where the addition of bentonite begins to influence the soil structure and reduce water permeability.

20% Bentonite:
Permeability: 0.000207 cm/s
The permeability further decreases, suggesting that the addition of bentonite continues to alter the soil structure, reducing the ease of water flow.

30% Bentonite:
Permeability: 0.000018 cm/s
A significant decrease in permeability is observed, indicating a considerable impact on the soil structure as more bentonite is added. The soil becomes less permeable.

35% Bentonite:
Permeability: 0.000015 cm/s
The permeability continues to decrease with the highest percentage of bentonite, implying that the soil has undergone substantial changes in structure, leading to very low water permeability.

The results demonstrate a clear inverse relationship between the percentage of bentonite added and the permeability of the laterite-bentonite blend.

As the percentage of bentonite increases, the soil becomes more compact and less permeable, likely due to the binding and swelling properties of bentonite, which fills voids and restricts water flow.

The addition of bentonite at higher percentages has a more pronounced impact on reducing permeability, indicating potential applications in scenarios where low permeability is desirable, such as in the construction of barriers or liners.

Understanding the permeability characteristics of the laterite-bentonite mix is crucial for making informed decisions in geotechnical engineering, especially in applications where water flow control is critical, such as in containment structures or environmental protection measures.

IV. CONCLUSION

The findings in this research underscore the significant influence of bentonite on both compaction characteristics and permeability of laterite mixes.

The Maximum Dry Density (MDD) values exhibit considerable variability with the addition of bentonite, reaching a peak at 30% bentonite and slightly decreasing at 35%. For instance, the MDD for the 30% bentonite mix ranges from approximately 1.88 g/cm³ to 2.06 g/cm³, indicating a notable increase in density compared to other blends. The Optimum Moisture Content (OWC) generally decreases with increasing bentonite content until the 30% mix, where it ranges from approximately 10.4% to 14.3%. However, the 35% mix shows a slight increase in OWC compared to the 30% mix.

Regarding permeability, the values demonstrate an inverse relationship with the percentage of bentonite added. For instance, the permeability decreases from approximately 0.000040 cm/s for the 0% bentonite mix (100% laterite) to 0.000015 cm/s for the 35% bentonite mix. Notably, the 30% bentonite mix exhibits a significant decrease in permeability, indicating a substantial impact on soil structure and water flow restriction.

These specific values obtained provide engineers and construction professionals with quantitative data to guide soil mix selection and optimization efforts for stability and performance in construction projects. Understanding these properties is essential for making informed decisions in geotechnical engineering, particularly in applications where water flow control and soil compaction are critical.

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