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Index Properties and Compaction Characteristics of Vermi-Remediated Crude Oil-Contaminated Lateritic Soil Stabilized with Locust Bean Waste Ash

J. E. Sani, M. S. Dalhat, G. Moses, Z. I. Ummisawa
Civil Engineering Department,
Nigerian Defence Academy (NDA), Kaduna State, Nigeria

ABSTRACT

This study characterizes the index properties and compaction characteristics of vermi-remediated crude oil-contaminated lateritic soil (VRCOCS) stabilized with varying percentages (0, 4, 8, 12 and 16%) of locust bean waste ash (LBWA), with a view to assessing its suitability as landfill liner and cover material. Vermi-remediation reduced the total petroleum hydrocarbon (TPH) content of the crude oil-contaminated soil from an average of 4500 mg/kg to 3300 mg/kg, representing a 27% removal efficiency, prior to stabilization. The untreated vermi-remediated soil was classified as A-7-5 according to AASHTO and CL (lean clay) according to the Unified Soil Classification System, with 72.42% of particles passing the BS No. 200 sieve. Specific gravity increased from 2.0 for the untreated soil to a peak of 2.4 at 4% LBWA before fluctuating between 2.2 and 2.3 at higher ash contents. Particle size distribution improved markedly with LBWA addition, as the percentage of fines passing the No. 200 sieve fell sharply from 35.5% (untreated) to between 2.5% and 5.8% for the stabilized mixtures, reflecting flocculation and agglomeration of clay particles induced by pozzolanic reaction. The liquid limit varied only slightly with LBWA content (52.3%–57.0%), while the plastic limit rose from 32.3% to a maximum of 35.1% at 4% LBWA before declining to about 30.5–30.7% at 12–16% LBWA. The plasticity index reached a minimum of 18.5% at 8% LBWA, indicating the greatest improvement in workability and volume-change potential at this stabilization level. Compaction results showed that the maximum dry density (MDD) increased with increasing compactive effort and peaked at 1.89 Mg/m³ at 4% LBWA under British Standard Heavy (BSH) energy, before decreasing at higher ash contents owing to the lower specific gravity of excess unreacted ash. The optimum moisture content (OMC) exhibited only minor variation with LBWA content, generally decreasing with increasing compactive effort and rising slightly at 16% LBWA due to the greater water demand of the additional ash. Overall, the results indicate that 4–8% LBWA produces the most favourable combination of reduced plasticity, improved gradation and enhanced compaction response, supporting its use as a sustainable, low-cost stabilizer for vermi-remediated lateritic soils intended for landfill liner and cover applications.

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Corresponding author: J. E. Sani
jesani@nda.edu.ng
Civil Engineering Department, Nigerian Defence Academy (NDA), Kaduna State, Nigeria.

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INTRODUCTION

Soil remains one of the most valuable natural resources, providing the foundation for agriculture, civil engineering infrastructure and environmental sustainability. Increasing industrialization, mining, oil exploration and improper waste disposal have, however, resulted in widespread soil contamination, with petroleum hydrocarbons among the most pervasive contaminants (Maddela et al., 2022). Crude oil exploration, production, transportation and storage frequently result in accidental spills that alter the physical, chemical and engineering properties of soils, including their index properties and compaction behaviour, thereby reducing their suitability for geotechnical applications such as landfill liners and cover systems (Mekkiyah et al., 2023; Akwenuke, 2025).

Vermi-remediation, which uses earthworms together with indigenous soil microorganisms to accelerate the degradation of petroleum hydrocarbons, has emerged as an environmentally friendly and cost-effective biological treatment technique (Singh et al., 2023; Datta et al., 2016). Although vermi-remediation is effective in reducing hydrocarbon concentration, the treated soil frequently retains index and compaction properties that are inadequate for direct use as a landfill liner or cover material, necessitating further stabilization (Moses & Sani, 2022).

Locust bean waste ash (LBWA), an agricultural waste product rich in reactive silica, alumina and calcium compounds, has recently attracted attention as a sustainable pozzolanic stabilizer. The pozzolanic reaction between LBWA and clay minerals promotes flocculation and the formation of cementitious compounds that alter particle size distribution, specific gravity, plasticity and compaction response, while offering an environmentally friendly and economical alternative to cement and lime (Abdullahi et al., 2021; Amu et al., 2011; Fadugba et al., 2025).

The index properties of a soil — specific gravity, particle size distribution and Atterberg limits — together with its compaction characteristics (maximum dry density and optimum moisture content), constitute the primary geotechnical parameters used to classify soils and evaluate their suitability for engineered barrier systems (Das, 2016; Lambe & Whitman, 2008). For compacted clay liners in particular, adequate fines content, moderate plasticity and an appropriately dense, well-compacted structure are essential to achieving the low hydraulic conductivity and dimensional stability required of waste containment systems (Daniel & Wu, 1993; Rowe, 2005).

This study therefore investigates the index properties and compaction characteristics of vermi-remediated crude oil-contaminated lateritic soil treated with varying percentages of locust bean waste ash, with the aim of establishing the LBWA content that produces the most favourable combination of gradation, plasticity and compaction response for potential use as landfill liner and cover material.

MATERIALS AND METHODS

Materials

Lateritic Soil

The lateritic soil used for this study was collected by the method of disturbed sampling from a lateritic soil formation located in Shika, Zaria, Kaduna State (Latitude 11°15' N and Longitude 7°45' E), at a depth of 1.5–2.0 m to eliminate the influence of topsoil and organic matter. The soil was air-dried, pulverized, and passed through a 4.75 mm (BS No. 4) sieve prior to testing, and representative samples were obtained by quartering.

Crude Oil

Bonny Light crude oil obtained from the Nigerian National Petroleum Company Limited (NNPCL) was used to artificially contaminate the lateritic soil at a rate of 75 cl of crude oil per 10 kg of soil and 1000 ml of water. The contaminated soil was cured for one month prior to vermi-remediation.

Earthworms

Mature Eisenia fetida earthworms, acclimatized under laboratory conditions, were introduced into the contaminated soil at a rate of

Corresponding author: J. E. Sani
jesani@nda.edu.ng
Civil Engineering Department, Nigerian Defence Academy (NDA), Kaduna State, Nigeria.

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40–80 worms per 40 kg of contaminated soil (300 worms per 200 kg of soil in total). The soil was placed in a perforated, aerated tank and moistened daily for one month to allow remediation to proceed.

Locust Bean Waste Ash (LBWA)

Locust bean waste was collected from local processing centres in Kaduna State, air-dried, and calcined under controlled conditions. The resulting ash was cooled, pulverized and sieved through a 75 µm sieve to obtain a uniform stabilizing material.

Total Petroleum Hydrocarbon (TPH) Determination

The gravimetric (toluene cold extraction) method, in accordance with USEPA Method 9071B, was used to determine TPH content before and after vermi-remediation, to confirm the baseline condition of the soil prior to index and compaction characterization. TPH was computed from the mass of soil before and after solvent extraction.

Specific Gravity

Specific gravity was determined in accordance with BS 1377 (1990), Part 2, Test B, using the density bottle method. The mass of the empty density bottle (M_1), the bottle with dry soil (M_2), the bottle with soil and water (M_3), and the bottle filled with water only (M_4) were recorded, and specific gravity computed as:

$$Gs = (M_2 - M_1) / [(M_2 - M_1) - (M_3 - M_4)] \quad (1)$$

Three determinations were made for each mixture, and the average value was adopted.

Particle Size Distribution

Particle size analysis was carried out in accordance with BS 1377 (1990), Part 2. A 200 g sample of soil was soaked in water for 24 hours and washed through a BS No. 200 sieve (0.075 mm aperture). The material retained was oven-dried for 24 hours and dry-sieved through a nest of sieves to determine the particle size distribution. The procedure was repeated for the untreated soil and for each stabilized mixture (4, 8, 12 and 16% LBWA).

Atterberg Limits

The liquid limit, plastic limit and plasticity index of the natural and stabilized soils were determined in accordance with BS 1377 (1990), Part 2.

Liquid Limit

The liquid limit (LL) was determined using the Casagrande apparatus. Soil passing the BS No. 40 sieve (425 µm) was mixed with water to form a homogeneous paste, placed in the cup, grooved, and the number of blows required to close the groove over a 13 mm length was recorded at several moisture contents. The results were plotted on a semi-logarithmic graph of moisture content against number of blows, and the liquid limit taken as the moisture content corresponding to 25 blows.

Plastic Limit

The plastic limit (PL) was determined by rolling threads of soil on a glass plate until they reached a diameter of approximately 3 mm and began to crumble. The corresponding moisture content was recorded as the plastic limit.

Plasticity Index

The plasticity index (PI) was calculated as the difference between the liquid limit and plastic limit:

$$PI = LL - PL \quad (2)$$

Compaction

Compaction tests were performed on the natural and stabilized soils in accordance with Head (1994), BS 1377 (1990) Part 4, the Nigerian General Specifications (NGS, 1997) and BS 1924 (1990), using three compactive efforts: British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH). BSL compaction was achieved using 27 blows of a 2.5 kg rammer dropped from 300 mm on each of three layers of soil in a 1000 cm³ mould. WAS compaction used 10 blows of a 4.5 kg rammer dropped from 450 mm on each of five layers, while

Corresponding author: J. E. Sani
jesani@nda.edu.ng
Civil Engineering Department, Nigerian Defence Academy (NDA), Kaduna State, Nigeria.

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BSH compaction used 27 blows of a 4.5 kg rammer dropped from 450 mm on each of five layers, both in the same 1000 cm³ mould. Water was added to the soil in successive 8% increments, and the moisture content corresponding to the maximum dry density (MDD), obtained from the plot of dry density against moisture content, was taken as the optimum moisture content (OMC). Bulk density (ρ^b) and dry unit weight (ρ^d) were computed as:

$$\rho^b = M_s / V_s \quad (3)$$

$$\rho^d = \rho^b / (1 - w) \quad (4)$$

where Ms is the mass of compacted soil (g), Vs is the volume of the mould (cm³), and w is the moisture content (%).

RESULTS AND DISCUSSION

Total Petroleum Hydrocarbon Removal and Baseline Soil Properties

Vermi-remediation reduced the average TPH concentration of the crude oil-contaminated lateritic soil from 4500 mg/kg to 3300 mg/kg, representing a 27% removal efficiency, confirming that the biological treatment was effective in reducing petroleum contamination prior to stabilization (Li et al., 2021; Adewuyi et al., 2022). The resulting vermi-remediated crude oil-contaminated soil (VRCOCS) was characterized to establish its baseline geotechnical properties, summarized in Table 1, before evaluating the effect of LBWA stabilization.

Table 1: Baseline Geotechnical Properties of the Untreated Vermi-Remediated Crude Oil-Contaminated Lateritic Soil (VRCOCS)

Property	Value
Percentage passing BS No. 200 sieve (%)	72.42
Liquid limit (%)	53.01
Plastic limit (%)	32.30
Plasticity index (%)	20.71
Specific gravity	2.00
AASHTO classification	A-7-5
USCS classification	CL
Maximum dry density – BSL / WAS / BSH (Mg/m³)	1.68 / 1.69 / 1.71
Optimum moisture content – BSL / WAS / BSH (%)	20.38 / 17.18 / 15.78

The soil contained 72.42% fines passing the BS No. 200 sieve, exceeding the 35–40% minimum generally recommended for compacted clay liners (Das, 2016), and was classified as A-7-5 (AASHTO) and CL, lean clay, (USCS), consistent with a soil of low-to-medium plasticity suitable in principle for liner applications (Lambe & Whitman, 2008). Its specific gravity of 2.0, however, is lower than the 2.6–2.8 typical of most clay soils, an effect attributable to residual hydrocarbons and organic matter retained after contamination and remediation (Kumar & Singh, 2024). This baseline characterization provided the reference against which the effects of LBWA stabilization on index properties and compaction behaviour were evaluated.

Specific Gravity

The variation of specific gravity with LBWA content is presented in Figure 1. Specific gravity is defined as the ratio of the density of soil solids to that of water and provides insight into the mineralogical composition and density characteristics of the soil (Moses & Sani, 2022; Olatunji et al., 2023). The untreated VRCOCS recorded a specific gravity of 2.0, a relatively low

Corresponding author: J. E. Sani
jesani@nda.edu.ng
Civil Engineering Department, Nigerian Defence Academy (NDA), Kaduna State, Nigeria.

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value attributable to residual hydrocarbons adhering to soil particles, which are lighter than typical mineral solids (Kumar & Singh, 2024). With the addition of LBWA, specific gravity increased markedly to a peak of 2.4 at 4% LBWA, reflecting the introduction of mineral-rich ash particles containing silica and alumina oxides, which increase particle density, together with enhanced flocculation and aggregation of soil particles (Amadi & Eberemu, 2025).

At higher LBWA contents, specific gravity fluctuated, decreasing to 2.2 at 8% LBWA, rising slightly to 2.3 at 12% LBWA, and decreasing again to 2.2 at 16% LBWA. This behaviour is attributed to the lightweight, porous nature of the ash: at higher dosages, the internal voids within excess unreacted ash particles begin to dominate the soil–ash mixture, lowering the overall density and partially offsetting the densifying effect of the pozzolanic reaction products (Sani et al., 2021; Fadugba et al., 2025). Overall, 4% LBWA produced the greatest improvement in specific gravity, while excessive ash content diminished this benefit.

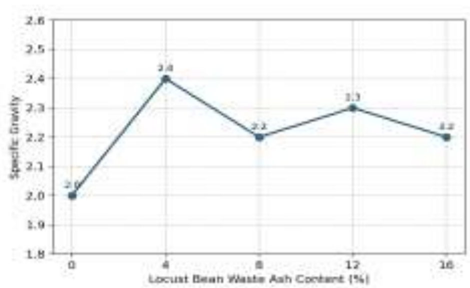

Figure 1: Variation of Specific Gravity with LBWA Content.

Particle Size Distribution

The particle size distribution of the untreated and LBWA-stabilized VRCOCS is presented in Figure 2. The untreated soil recorded 35.5% passing the BS No. 200 sieve using the coarse gradation series and 72.42% passing when re-sieved as reported in Table 1, reflecting the very fine, clay-dominated nature of the untreated material. With the addition of LBWA, the percentage of fines passing the No. 200 sieve decreased sharply to 4.71% at 4% LBWA, and remained low at 4.95%, 2.54% and 5.82% for the 8%, 12% and 16% LBWA mixtures, respectively, indicating a substantial and consistent coarsening of the overall gradation across all stabilization levels.

This marked reduction in fines content is attributed to the pozzolanic reaction between LBWA and the clay fraction of the soil. Calcium ions released from the ash react with reactive silica and alumina in the presence of water to form cementitious compounds, principally calcium silicate hydrate (C–S–H), which bind individual clay particles into larger flocs and aggregates. This flocculation process effectively transfers material from the fine to the coarse fraction of the gradation curve, without any change in the actual mineral particles present (Mezie et al., 2024; Moses et al., 2024). The slight variation observed among the 8–16% LBWA mixtures (2.54–5.82% fines) reflects differences in the proportion of ash that remained unreacted and available to reintroduce fine particles into the matrix (Fadugba et al., 2025; Sani et al., 2021).

This apparent coarsening of gradation is a common and well-documented effect of pozzolanic stabilization; it does not, in itself, indicate that the soil has lost its clay mineralogy, and the Atterberg limits (Section 3.4) remain the more direct indicator of the soil's active plasticity following treatment. Nonetheless, the improved gradation is generally favourable for compaction, as better-graded soils permit more efficient particle packing, reduced void ratio and, ultimately, a denser and more stable compacted structure (Bewaji et al., 2024; Moses & Sani, 2022).

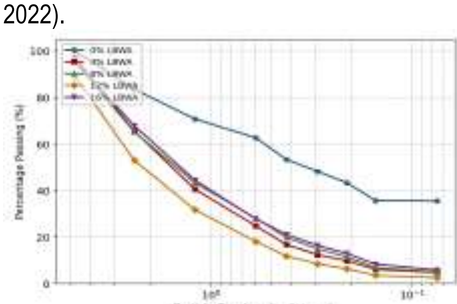

Figure 2: Particle Size Distribution of Vermi-Remediated Lateritic Soil at Varying LBWA Content.

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jesani@nda.edu.ng
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Atterberg Limits

Liquid Limit

The variation in liquid limit with LBWA content is shown in Figure 3. The liquid limit exhibited only slight variation, increasing from 53.0% in the untreated soil to a maximum of 57.0% at 4% LBWA, decreasing to 52.3% at 8% LBWA, and then rising gradually to about 52.9% at 16% LBWA. The initial increase at 4% LBWA may be attributed to the filling of soil voids by ash particles and their interaction with clay minerals, which increases water absorption (Olorunsogo & Ogedengbe, 2019), while the subsequent decrease at 8% LBWA suggests that further ash addition began to disrupt the continuity of the clay matrix. The gradual increase from 12% to 16% LBWA is consistent with continued pozzolanic reaction and particle aggregation moderately enhancing the soil's water-retention capacity (Akinwumi & Oladipo, 2020).

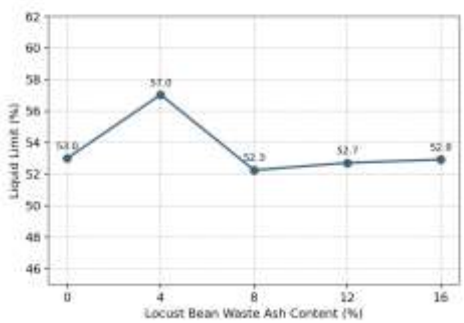

Figure 3: Variation of Liquid Limit with LBWA Content.

Plastic Limit

The plastic limit increased from 32.3% in the untreated soil to a peak of 35.1% at 4% LBWA (Figure 4), attributable to the fine ash particles and reactive oxides that enhanced inter-particle bonding and cohesion, allowing the soil to retain more water before reaching a semi-solid state (Moses & Sani, 2022; Oladipo et al., 2020). At 8% LBWA, the plastic limit decreased slightly to 33.8%, indicating that further ash addition began to occupy void spaces and reduce water absorption, while at 12% and 16% LBWA the plastic limit fell further to 30.5% and 30.7%, respectively. This reduction is attributed to dilution of the clay fraction by excessive ash, lowering cohesion and reducing the water content required for the soil to remain plastic (Eze et al., 2021).

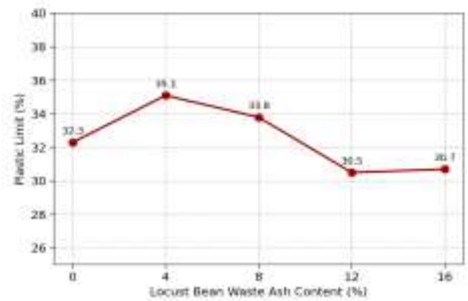

Figure 4: Variation of Plastic Limit with LBWA Content.

Plasticity Index

The plasticity index (Figure 5) decreased from 20.7% in the untreated soil to a minimum of 18.5% at 8% LBWA, indicating the greatest improvement in soil workability and the greatest reduction in the dominance of clay minerals at this stabilization level (Moses & Sani, 2022; Zhang et al., 2019). At higher LBWA contents of 12% and 16%, the plasticity index increased to 22.2% and 22.2%, respectively, suggesting that excessive ash introduced additional fine particles and altered particle interactions, slightly increasing plasticity and shrink–swell potential (Oladipo et al., 2020; Eze et al., 2021). Based on the plasticity index results, 8% LBWA produced the most favourable reduction in plasticity, while the plasticity index of all mixtures remained within the 15–30% range generally recommended for compacted clay liner materials (Casagrande, 1948).

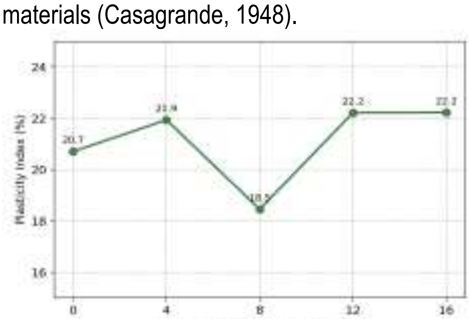

Figure 5: Variation of Plasticity Index with LBWA Content.

Corresponding author: J. E. Sani
jesani@nda.edu.ng
Civil Engineering Department, Nigerian Defence Academy (NDA), Kaduna State, Nigeria.

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Compaction Characteristics

Maximum Dry Density

The variation of maximum dry density (MDD) with LBWA content under BSL, WAS and BSH compactive efforts is presented in Figure 6. For the untreated soil, MDD increased with increasing compactive effort, recording 1.68, 1.69 and 1.71 Mg/m³ under BSL, WAS and BSH, respectively, consistent with the general principle that higher compactive energy promotes better particle rearrangement and reduces void space (Akinwumi et al., 2018; Oladipo et al., 2020). The addition of 4% LBWA increased MDD to 1.66, 1.69 and 1.89 Mg/m³ under BSL, WAS and BSH, respectively, with the substantial increase under BSH indicating that moderate LBWA content enhanced particle packing and promoted the formation of cementitious compounds that improved densification under high compactive energy.

At 8% LBWA, MDD remained largely unchanged under BSL (1.66 Mg/m³) and increased slightly under WAS (1.73 Mg/m³), while the BSH value decreased to 1.78 Mg/m³, a reduction attributable to the increasing proportion of ash of relatively lower specific gravity in the soil–ash mixture. Further increases in LBWA content to 12% and 16% resulted in a gradual reduction in MDD under BSL (1.58 Mg/m³ at both levels) and WAS (1.60 and 1.59 Mg/m³, respectively), while BSH values remained comparatively stable at 1.78 and 1.81 Mg/m³. The reduction in dry density at higher ash contents is attributed to the lower specific gravity of LBWA relative to the natural soil and the increased proportion of fine, porous ash particles, which reduce particle-to-particle contact and increase void volume at lower compactive energies (Rahman et al., 2020). Overall, 4% LBWA produced the highest maximum dry density, particularly under BSH compactive effort, indicating that moderate LBWA addition combined with high compactive energy is most effective for achieving a dense, well-compacted soil structure.

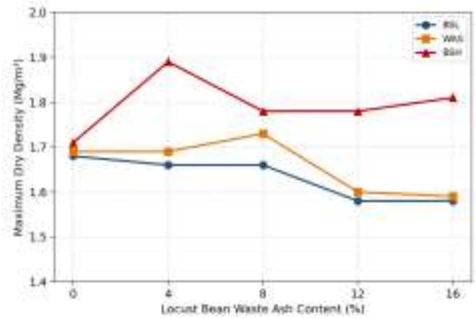

Figure 6: Variation of Maximum Dry Density with LBWA Content under BSL, WAS and BSH Compactive Efforts.

Optimum Moisture Content

The variation of optimum moisture content (OMC) with LBWA content under BSL, WAS and BSH compactive efforts is presented in Figure 7. For the untreated soil, OMC decreased with increasing compactive effort, recording 20.38%, 17.18% and 15.78% under BSL, WAS and BSH, respectively, reflecting the standard compaction principle that higher compactive energy requires less water to achieve maximum density (Akinwumi et al., 2018). With the addition of 4% LBWA, OMC decreased slightly under BSL (18.51%) but increased marginally under WAS (17.27%) and BSH (16.17%) relative to the untreated soil, indicating that the fine ash particles and reactive oxides influenced the water demand of the mixture (Moses & Sani, 2022).

At 8% and 12% LBWA, OMC values under BSL remained close to the untreated soil (18.87–19.0%), while WAS and BSH values increased slightly (17.23–18.27% and 17.06–17.57%, respectively), suggesting that moderate LBWA content had only a limited influence on the water requirement for compaction. At 16% LBWA, OMC increased across all compactive efforts, reaching 19.25%, 17.97% and 17.82% under BSL, WAS and BSH, respectively, an increase attributed to the greater water absorption capacity of the additional ash particles, which require more moisture for lubrication during compaction (Rahman et al., 2020). Overall, LBWA addition had only a modest influence on OMC compared with its effect on MDD, although excessive ash

Corresponding author: J. E. Sani
jesani@nda.edu.ng
Civil Engineering Department, Nigerian Defence Academy (NDA), Kaduna State, Nigeria.

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content increased the moisture requirement because of the higher water absorption capacity of the stabilizing material.

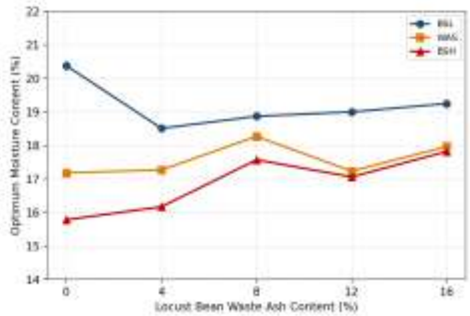

Figure 7: Variation of Optimum Moisture Content with LBWA Content under BSL, WAS and BSH Compactive Efforts.

Summary of Index and Compaction Behaviour

Table 2: Summary of Index Properties and Compaction Characteristics of VRCOCS Stabilized with LBWA

LBWA (%)	Gs	Fines Passing No. 200 (%)	LL (%)	PL (%)	PI (%)	MDD-BSH (Mg/m³)	OMC-BSH (%)
0	2.0	35.5	53.0	32.3	20.7	1.71	15.78
4	2.4	4.71	57.0	35.1	21.9	1.89	16.17
8	2.2	4.95	52.3	33.8	18.5	1.78	17.57
12	2.3	2.54	52.7	30.5	22.2	1.78	17.06
16	2.2	5.82	52.9	30.7	22.2	1.81	17.82

Table 2 summarizes the combined effect of LBWA content on the index properties and BSH compaction response of the vermi-remediated soil. Considered together, the results indicate that no single LBWA content simultaneously optimizes every index parameter: 4% LBWA produces the highest specific gravity and maximum dry density, whereas 8% LBWA produces the lowest, most favourable plasticity index. Both the 4% and 8% LBWA levels, however, produce a substantially improved gradation and a denser compacted structure relative to the untreated soil, and represent the most favourable stabilization range identified in this study for further evaluation of strength and hydraulic performance.

CONCLUSION

This study evaluated the index properties and compaction characteristics of vermi-remediated crude oil-contaminated lateritic soil stabilized with locust bean waste ash. Vermi-remediation reduced the TPH concentration of the contaminated soil by 27%, from 4500 mg/kg to 3300 mg/kg, confirming the effectiveness of the biological pre-treatment. The untreated vermi-remediated soil was classified as A-7-5 (AASHTO) and CL (USCS), with a specific gravity of 2.0 and 72.42% fines passing the BS No. 200 sieve.

Stabilization with LBWA increased specific gravity to a peak of 2.4 at 4% LBWA before fluctuating between 2.2 and 2.3 at higher ash contents, while particle size distribution improved markedly, with fines content passing the No. 200 sieve falling from 35.5% to between 2.5% and 5.8% across all stabilization levels, reflecting flocculation of clay particles induced by the pozzolanic reaction. The liquid limit varied only slightly with LBWA content, the plastic limit peaked at 4% LBWA, and the plasticity index

Corresponding author: J. E. Sani
jesani@nda.edu.ng
Civil Engineering Department, Nigerian Defence Academy (NDA), Kaduna State, Nigeria.

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reached its lowest, most favourable value of 18.5% at 8% LBWA.

Compaction results showed that maximum dry density increased with increasing compactive effort and peaked at 1.89 Mg/m³ at 4% LBWA under British Standard Heavy compaction, before declining at higher ash contents because of the lower specific gravity of excess unreacted ash. Optimum moisture content exhibited only minor variation with LBWA content, generally decreasing with increasing compactive effort and rising slightly at the highest ash content.

Overall, 4–8% LBWA produced the most favourable combination of improved gradation, reduced plasticity and enhanced compaction response, indicating that locust bean waste ash is a promising, sustainable and low-cost stabilizer for improving the index and compaction properties of vermi-remediated crude oil-contaminated lateritic soil. These findings provide a basis for subsequent evaluation of the strength and hydraulic performance of the stabilized soil in relation to landfill liner and cover requirements.

REFERENCES

Abdullahi, M., Eberemu, A. O., & Osinubi, K. J. (2021). Stabilization of lateritic soil using agricultural waste ash for engineering applications. Nigerian Journal of Technology, 40(2), 233–242.

Adewuyi, A. P., Ibrahim, H. B., & Musa, J. J. (2022). Earthworm-mediated biodegradation of petroleum hydrocarbons in tropical soils. Journal of Environmental Management, 305, 114379.

Akinwumi, I. I., Diwa, D., & Obianigwe, N. (2018). Compaction characteristics of lateritic soils stabilized with agricultural waste materials. International Journal of Geotechnical Engineering, 12(5), 476–484.

Akinwumi, I. I., & Oladipo, A. O. (2020). Engineering properties of lateritic soils treated with agro-based stabilizers. Journal of Materials in Civil Engineering, 32(7), 04020185.

Akwenuke, C. (2025). Effect of crude oil contamination on the geotechnical properties of lateritic soils. International Journal of Geotechnical Engineering, 19(1), 55–68.

Amadi, A. A., & Eberemu, A. O. (2025). Influence of agricultural waste ash on the geotechnical properties of tropical soils. International Journal of Pavement ZhangEngineering, 26(3), 315–328.

Amu, O. O., Ogunniyi, S. A., & Oladeji, O. O. (2011). Geotechnical properties of lateritic soil stabilized with agricultural waste ash. International Journal of Engineering and Technology, 3(4), 367–372.

Bewaji, T. A., Fadugba, S. O., & Moses, G. G. (2024). Particle size distribution and stabilization characteristics of ash-treated lateritic soils. Nigerian Journal of Engineering Research, 29(1), 65–77.

British Standards Institution. (1990). BS 1377: Methods of test for soils for civil engineering purposes. British Standards Institution.

British Standards Institution. (1990). BS 1924: Methods of test for stabilized soils. British Standards Institution.

Casagrande, A. (1948). Classification and identification of soils. Transactions of the American Society of Civil Engineers, 113(1), 901–930.

Daniel, D. E., & Wu, Y. K. (1993). Compacted clay liners and cover systems for arid sites. Journal of Geotechnical Engineering, 119(2), 223–237.

Das, B. M. (2016). Principles of geotechnical engineering (9th ed.). Cengage Learning.

Datta, R., Kelkar, A., Baraniya, D., Molaei, A., Moulick, A., Meena, R., & Formanek, P. (2016). Enzymatic degradation of petroleum hydrocarbons in soil using vermiremediation technology. Environmental Technology & Innovation, 5, 104–112.

Eze, C. J., Ugwu, E. I., & Nwankwo, J. I. (2021). Influence of agricultural waste ash on the compaction and plasticity characteristics of lateritic soils. Journal of Civil Engineering Research, 11(2), 45–56.

Fadugba, S. O., Moses, G. G., & Mezie, O. (2025). Pozzolanic stabilization of contaminated lateritic soils using agro-waste ash.

Corresponding author: J. E. Sani
jesani@nda.edu.ng
Civil Engineering Department, Nigerian Defence Academy (NDA), Kaduna State, Nigeria.

Construction Materials and Structures, 8(1), 14–27.

Head, K. H. (1994). Manual of soil laboratory testing: Volume 1, Soil classification and compaction tests (2nd ed.). Pentech Press.

Kumar, R., & Singh, P. (2024). Effect of hydrocarbon contamination on the specific gravity and compaction behavior of clay soils. Environmental Earth Sciences, 83(4), 120–132.

Lambe, T. W., & Whitman, R. V. (2008). Soil mechanics. John Wiley & Sons.

Li, J., Lu, Q., Odey, E. A., Lok, K. S., Pan, B., Zhang, Y., & Shim, H. (2021). Coupling of biostimulation and bioaugmentation for enhanced bioremoval of chloroethylenes and BTEX from clayey soil. Ecotoxicology, 30(7), 1446–1453.

Maddela, N. R., Kakarla, D., García, L. C., Chakraborty, S., Venkateswarlu, K., & Megharaj, M. (2022). Soil contamination by emerging pollutants and sustainable remediation technologies. Environmental Technology & Innovation, 25, 102170.

Mekkiyah, A. M., Salih, N. B., & Kareem, H. A. (2023). Impact of petroleum hydrocarbon contamination on geotechnical properties of soils: A review. Case Studies in Construction Materials, 18, e01745.

Mezie, O. K., Sani, J. E., & Moses, G. G. (2024). Performance of vermiremediated crude oil contaminated soils stabilized with pozzolanic additives. International Journal of Geoengineering, 15(2), 89–103.

Moses, G. G., & Sani, J. E. (2022). Geotechnical evaluation of vermiremediated hydrocarbon contaminated lateritic soil. Nigerian Journal of Soil and Environmental Research, 20(1), 55–70.

Moses, G. G., Sani, J. E., & Mezie, O. K. (2024). Influence of locust bean waste ash on engineering properties of remediated crude oil contaminated soil. Journal of Materials and Geoenvironment, 13(2), 101–118.

Nigerian General Specifications. (1997). General specifications for roads and bridges. Federal Ministry of Works and Housing.

Oladipo, A. O., Akinwumi, I. I., & Yusuf, M. A. (2020). Engineering behavior of agro-waste stabilized lateritic soils under varying compactive efforts. Geotechnical and Geological Engineering, 38(6), 6291–6304.

Olatunji, O. M., Adeyemi, G. O., & Sani, J. E. (2023). Specific gravity and mineralogical evaluation of stabilized tropical soils. International Journal of Engineering Research in Africa, 62, 97–108.

Olorunsogo, F. T., & Ogedengbe, M. O. (2019). Influence of agricultural ash on the consistency limits of tropical lateritic soils. Journal of Engineering and Applied Sciences, 14(9), 2985–2992.

Rahman, M. A., Karim, M. R., & Islam, M. N. (2020). Effect of agricultural waste ash on compaction characteristics of fine-grained soils. International Journal of Pavement Research and Technology, 13(4), 402–410.

Rowe, R. K. (2005). Long-term performance of contaminant barrier systems. Géotechnique, 55(9), 631–678.

Sani, J. E., Moses, G. G., & Eberemu, A. O. (2021). Stabilization of contaminated lateritic soil using agro-waste ash for sustainable engineering applications. Nigerian Journal of Environmental Engineering, 16(3), 118–129.

Singh, J., Kalamdhad, A. S., & Ali, M. (2023). Vermitechnology for sustainable remediation of contaminated soils. Environmental Science and Pollution Research, 30(14), 41235–41252.

Zhang, Y., Li, X., & Chen, W. (2019). Effects of bio-based ash additives on the plasticity and compaction properties of clay soils. Applied Clay Science, 181, 105234.

Corresponding author: J. E. Sani
jesani@nda.edu.ng
Civil Engineering Department, Nigerian Defence Academy (NDA), Kaduna State, Nigeria.