Strength and Durability of Vermi-Improved Crude Oil Contaminated Lateritic Soil Stabilised with Iron Ore Tailings for Road Subgrade Applications

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ORIGINAL RESEARCH

Abstract— Crude oil contamination degrades the shear strength and durability of lateritic soils used for road construction, and while vermi-improvement can reduce hydrocarbon content, the resulting soil typically still lacks adequate load-bearing capacity; combining biological remediation with waste-derived mineral stabilisers such as iron ore tailings (IOT) offers a largely unexplored dual pathway for reclaiming such soils for pavement use. This study investigated the strength and durability characteristics of vermi-improved crude oil contaminated lateritic soil stabilised with iron ore tailings (IOT) for road subgrade applications. Following vermi-improvement with Eudrilus eugeniae (African nightcrawler earthworm) and stabilisation with 0-8% IOT, unconfined compressive strength (UCS), California bearing ratio (CBR), and durability were evaluated under British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) compactive efforts. Linear regression analysis demonstrated highly significant positive correlations between IOT content and UCS at 28 days for all compactive efforts (R^2 = 0.851-0.978, $p < 0.05$). Soaked CBR exceeded the 8% subgrade minimum at 8% IOT across all compactive efforts (BSL WAS, BSH), with the strongest correlation under BSH compaction (R^2 = 0.943, p = 0.006). Durability improved significantly with IOT addition, particularly under BSH compaction. SEM analysis revealed denser microstructures with increasing IOT content and curing age. These findings confirm that the combination of vermi-improvement and IOT stabilisation produces a material with adequate strength and durability for road subgrade construction, offering pavement engineers a practical, waste-based dual remediation-stabilisation strategy for reclaiming petroleum-contaminated land for road infrastructure development.

Keywords— Crude oil contamination, California bearing ratio, durability, Iron ore tailings, Unconfined compressive strength, Vermi-improvement, Scanning electron microscopy.

1 INTRODUCTION

Crude oil contamination poses a significant environmental and engineering challenge in petroleum-producing regions of Nigeria, where decades of exploration activities have resulted in extensive land degradation (Akinyemi et al., 2022; Oduola et al., 2023). The presence of petroleum hydrocarbons alters the geotechnical properties of soils by reducing the shear strength, load-bearing capacity, and durability; thereby rendering affected lands unsuitable for infrastructure development without remediation (Sulaimon et al., 2023; Adamu et al., 2024).

Vermi-improvement has emerged as an environmentally sustainable approach to treating petroleum-contaminated soils, employing earthworms such as Eudrilus eugeniae (the African nightcrawler) to degrade hydrocarbons through enhanced microbial activity and enzymatic processes (Adeyemi et al., 2023; Fatima and Singh, 2024). While effective in reducing contaminant concentrations, vermi-improved soils often require additional stabilisation to achieve the engineering properties necessary for construction applications (Adamu et al., 2024).

Conventional chemical stabilisers, including cement, lime, fly ash, and rice husk ash (RHA), have long been used to improve the strength of lateritic and other problem soils (Ola, 1978; Osinubi et al., 2017; Okunade, 2010), and blended lime-RHA and lime-cement systems have also been applied directly to soil-mine tailing mixtures for highway construction (Ojuri et al., 2017; Osinubi et al., 2019). These stabilisers are, however, constrained in the Nigerian context by the cost and carbon footprint of imported cement clinker, the moisture sensitivity and carbonation susceptibility of lime, and the localised, often unreliable supply of fly ash and RHA, which are tied to specific power or milling industries. Iron ore tailings, by contrast, are generated in large and growing volumes as a by-product of the expanding Nigerian iron and steel sector, are locally available near several ore-processing sites including Kaduna State, and combine pozzolanic reactivity with a naturally high specific gravity that conventional agricultural-waste ashes lack, making them an attractive low-cost alternative stabiliser deserving of focused investigation.

Iron ore tailings (IOT), the waste by-product of iron ore beneficiation processes, have demonstrated considerable potential as soil stabilisers due to their pozzolanic properties and high specific gravity (Akinyemi et al., 2023; Jibril et al., 2024). Previous studies have shown that IOT addition can significantly enhance the strength and

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durability of stabilised soils through filler effects and partial cementitious reactions (Olufemi et al., 2023; Amu et al., 2024). However, limited research has examined the combined effects of vermi-improvement and IOT stabilisation on the strength and durability characteristics of crude oil contaminated lateritic soils. The novelty of the present study lies specifically in this integration: rather than treating biological remediation and mineral stabilisation as sequential, unrelated processes, the two are combined into a single treatment pathway in which IOT stabilisation directly compensates for the residual strength deficit that vermi-improvement alone cannot resolve. This coupling has not, to the authors' knowledge, been previously reported for crude oil contaminated lateritic soils, and it distinguishes the present work from prior studies that examined either biological remediation (Adeyemi *et al*., 2023; Fatima and Singh, 2024) or IOT stabilisation of uncontaminated or non-bioremediated soils (Akinyemi et al., 2023; Olufemi et al., 2023) in isolation. This study evaluates the unconfined compressive strength (UCS), California bearing ratio (CBR), and durability characteristics of vermi-improved crude oil contaminated lateritic soil stabilised with iron ore tailings, supplemented by scanning electron microscopy (SEM) analysis to elucidate the microstructural mechanisms governing the observed macroscopic behaviour. The expected scientific contribution of this work is twofold: it provides the first documented strength and durability dataset for vermi-improved, IOT-stabilised crude oil contaminated lateritic soil across three compactive efforts, and it offers pavement engineers and environmental regulators in petroleum-producing regions of Nigeria an evidence-based, low-cost pathway for converting contaminated land into usable road subgrade material while simultaneously valorising a mineral-processing waste stream that would otherwise require disposal.

2 MATERIALS AND METHODS

2.1 Materials and Sample Preparation

The lateritic soil was obtained from Shika, Zaria, Nigeria, and artificially contaminated with crude oil at 5% by dry weight. The contaminated soil was subjected to vermi-improvement using Eudrilus eugeniae earthworms at a density of 20 worms per kilogram of soil for four weeks under controlled laboratory conditions. Following vermi-improvement, the soil was stabilised with iron ore tailings (IOT) procured from Gujeni, Kagarko, Kaduna State, at proportions of 0%, 2%, 4%, 6%, and 8% by dry weight of soil. The chemical composition of the IOT, determined by X-ray fluorescence (XRF) analysis, is presented in Table 1. The vermi-improved soil, with 72.42% passing the No. 200 sieve, is classified as an A-7-6(12) material under the AASHTO system and as CL (low-plasticity clay, dominant clay mineral kaolinite) under the Unified Soil Classification System. The 5% crude oil contamination level was selected as representative of contamination severities reported to significantly impair the geotechnical properties of lateritic soils in petroleum-producing areas of Nigeria without rendering the soil entirely unworkable (Akinyemi et al., 2022; Sulaimon et al., 2023), while the 0-8% IOT range was chosen to bracket the optimum stabiliser contents reported for comparable pozzolanic industrial waste stabilisers applied to lateritic and tailing-bearing soils (Akinyemi et al., 2023; Amu et al., 2024; Ojuri et al., 2017). Vermi-improvement in this study was directed at geotechnical rather than agricultural endpoints: whereas agricultural vermicomposting is evaluated primarily by nutrient release (nitrogen, phosphorus, potassium) and organic matter mineralisation for plant growth, the present application instead tracked changes in Atterberg limits, specific gravity, and residual total petroleum hydrocarbon (TPH) content, since excess residual organic matter and altered clay-water interactions are known to interfere with subsequent pozzolanic cementation reactions in stabilised soils. The reduction in plasticity index and the partial TPH removal reported in Section 3.1 were therefore evaluated specifically for their bearing on subsequent IOT stabilisation performance, rather than for soil fertility. The crude oil, sourced from Warri, Delta State, was mixed with the air-dried, pulverised lateritic soil at a rate of 75 cl per 10 kg of soil together with 1000 ml of water to achieve a homogeneous, thoroughly wetted mixture; the contaminated soil was then left for one month to allow full contamination before vermi-improvement was initiated.

2.2 Testing Methods

The unconfined compressive strength (UCS) test was conducted in accordance with BS 1377 (1990) on specimens cured for 7, 14, and 28 days. The California bearing ratio (CBR) test was performed under both soaked (4-day immersion) and unsoaked conditions. Durability was assessed through wet-dry cycling in accordance with ASTM D559 (2003), involving alternating immersion in water and oven drying. Scanning electron microscopy (SEM) analysis was conducted on selected specimens to examine the microstructural characteristics of the stabilised soil. Linear regression and one-way ANOVA were employed for statistical analysis at alpha = 0.05. The linear regression models fitted to IOT content were checked against the standard assumptions of ordinary least-squares regression, namely linearity of the IOT-response relationship, independence of observations, homoscedasticity of residuals, and approximate normality of residuals, consistent with the small-sample (five-level) design employed. One-way ANOVA was similarly conducted on the assumption of

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normally distributed, homoscedastic groups. Minitab, R was used for the regression and ANOVA analyses.

3 RESULTS AND DISCUSSION

3.1 Properties of Vermi-Improved Soil and IOT Characterisation

The properties of the natural and vermi-improved lateritic soil are presented in Table 2. Vermi-improvement reduced the liquid limit from 47.00% to 39.50% and the plasticity index from 19.70% to 10.70%, while increasing the plastic limit from 27.30% to 28.80%. The specific gravity decreased from 2.66 to 2.40 due to residual hydrocarbon compounds. Total petroleum hydrocarbon analysis revealed a reduction from 4500 mg/kg to 3300 mg/kg, corresponding to a 27% removal efficiency.

This 27% TPH removal efficiency is more modest than the reductions of up to 70% reported for vermi-remediation of petroleum-contaminated soils over comparable timeframes (Oluwaseun et al., 2023), a difference likely attributable to the shorter four-week treatment period and the relatively high initial TPH loading used in this study. The corresponding reduction in plasticity index is nonetheless consistent with the general pattern observed in earthworm-based bioremediation of contaminated fine-grained soils, in which the partial breakdown of hydrophobic hydrocarbon coatings on clay particles restores some capacity for water interaction (Adamu et al., 2024).

Table 1. Chemical Composition of Iron Ore Tailings (XRF Analysis)

Oxide	Composition (%)
SiO2	45.64
Fe2O3	47.70
Al2O3	3.36
CaO	0.607
MgO	0.393
LOI	3.00

This oxide composition carries a clear implication for the IOT's suitability as a stabiliser: the combined silica (45.64%) and alumina (3.36%) content provides the reactive aluminosilicate phases needed to form C-S-H and C-A-H cementitious gels once activated, while the dominant iron oxide (47.70%) content, though not itself pozzolanically reactive, contributes the high specific gravity that densifies the stabilised matrix and fills interparticle voids through a filler effect. The comparatively low combined CaO, MgO, Na2O, and K2O content (around 2%) indicates that the IOT carries little inherent self-cementing (lime-like) capacity of its own; the pozzolanic reaction therefore depends on calcium made available from the host lateritic soil and from carbonation/hydration products, which is consistent with the progressive, curing-age-dependent strength gain reported in Section 3.2 rather than a rapid, cement-like set.

Table 2. Properties of Natural and Vermi-Improved Lateritic Soil

Property	Natural Soil	Vermi-Improved
Liquid Limit (%)	47.00	39.50
Plastic Limit (%)	27.30	28.80
Plasticity Index (%)	19.70	10.70
Specific Gravity	2.66	2.40
TPH (mg/kg)	4500	3300

The reduction in liquid limit and plasticity index following vermi-improvement is attributed to the partial microbial degradation of the crude oil coating on the clay particle surfaces within the earthworms' gut and casts, which reduces the hydrophobic interference with clay-water interaction and allows the finer particles to re-establish more normal plasticity behaviour. The slight increase in plastic limit is consistent with the incorporation of mucus and organic casting material excreted by the earthworms during gut passage, which retains moisture at the plastic limit even as the liquid limit falls, together narrowing the plasticity index. The decrease in specific gravity from 2.66 to 2.40 reflects the residual lighter hydrocarbon fraction and organic casting material still present in the soil matrix after four weeks of treatment, since these constituents are less dense than the mineral soil grains they are mixed with. The 27% reduction in TPH is the direct product of hydrocarbon-degrading microbial activity stimulated in the earthworms' digestive tract and surrounding rhizosphere-like microenvironment, consistent with the mechanism widely reported for Eudrilus eugeniae-based bioremediation (Oluwaseun et al., 2023).

3.2 Unconfined Compressive Strength

The UCS results for the IOT-stabilised vermi-improved soil at 7, 14, and 28 days of curing are presented in Fig. 1. The UCS consistently increased with IOT content, curing period, and level of compaction energy across all test conditions. At 28 days, the UCS under BSL compaction increased from 211.2 kN/m² at 0% IOT to 295.4 kN/m² at 8% IOT (39.9% improvement). Under WAS compaction, the 28-day UCS increased from 219.5 kN/m² to 385.4 kN/m² (75.6% improvement). The BSH compaction energy level produced the highest values, with 28-day UCS increasing from 240.1 kN/m² to 401.6 kN/m² (67.3% improvement).

Linear regression analysis of the 28-day UCS data revealed statistically significant positive correlations with IOT content for all compactive efforts: BSL ($R^2 = 0.978$, $p = 0.001$), WAS ($R^2 = 0.917$, $p = 0.011$), and BSH ($R^2 = 0.851$, $p = 0.026$). The strength development is attributed to the pozzolanic reactions between the silica (45.64%) and alumina (3.36%) in the IOT and the calcium compounds in the soil, which form cementitious compounds that bind soil particles together (Olufemi et al., 2023; Osinubi et al., 2024). The progressive gain in strength with curing period

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further confirms the ongoing nature of these pozzolanic reactions. The magnitude of these UCS gains (39.9-75.6% across compactive efforts) is broadly consistent with, though somewhat more modest than, improvements reported for other pozzolanic waste stabilisers applied to lateritic and tailing-bearing soils, such as lime-cement stabilised soil-mine tailing mixtures (Ojuri et al., 2017) and RHA-lime stabilised soils (Osinubi et al., 2019), suggesting that IOT performs comparably to established waste-derived binders while additionally serving a remediation function absent from those studies.

It is important to clarify the apparent tension, visible in Fig. 1, between the UCS values obtained (up to 401.6 kN/m²) and the substantially higher TRRL threshold of 1725 kN/m² shown for reference. The TRRL criterion was originally developed for cement- or lime-stabilised base and sub-base layers that carry structural pavement loads directly beneath the surfacing, whereas the present material was designed and evaluated as a subgrade improvement, a layer subjected to substantially lower design stresses and governed instead by the CBR-based criteria discussed in Section 3.3. The UCS results should therefore be interpreted against subgrade-, not base-course, strength requirements; the TRRL line is retained in figure 1 only to indicate the strength margin that would need to be closed should the material be considered for a bound base or sub-base application in future work.

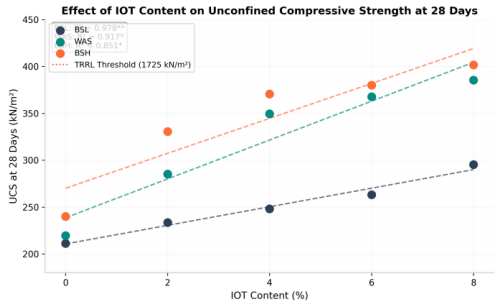

Fig. 1. Effect of IOT content on UCS at 28 days with linear regression (BSL: R^2=0.978**, WAS: R^2=0.917*, BSH: R^2=0.851*). TRRL threshold = 1725 kN/m2 shown for comparison.

3.3 California Bearing Ratio

The soaked and unsoaked CBR results are presented in Table 3 The soaked CBR values demonstrated substantial improvement with increasing IOT content across all compactive efforts. Under BSL compaction, the soaked CBR increased from 6.5% at 0% IOT to 15.2% at 8% IOT (133.8% improvement). The WAS compaction energy produced an increase from 8.5% to 21.5% (152.9% improvement), while the BSH compaction regime yielded the most significant improvement, from 11.4% to 30.2% (164.9% improvement).

Linear regression analysis confirmed statistically significant positive correlations between IOT content and soaked CBR for all compactive efforts: BSL (R^2 = 0.955, p = 0.004), WAS (R^2 = 0.846, p = 0.027), and BSH (R^2 = 0.943, p = 0.006). At 8% IOT content, all compactive efforts produced soaked CBR values exceeding the 8% minimum requirement specified by the Nigerian Federal Ministry of Works and Housing (2016) for medium to heavy traffic road subgrades. The unsoaked CBR values followed a similar trend, with the BSH energy level producing the highest value of 61.2% at 8% IOT.

This improvement in CBR mirrors the UCS mechanism discussed in Section 3.2: the pozzolanic reaction between the IOT's silica/alumina fraction and calcium available in the soil forms C-S-H and C-A-H gels that bind particles together, while the IOT's high specific gravity contributes a filler effect that reduces void space. Together these effects lower the soil's susceptibility to softening on water ingress, which is why the soaked CBR gains reported here are of comparable, and in some cases greater, magnitude than the corresponding unsoaked gains: the stabilisation is acting principally on moisture resistance rather than on dry-state penetration resistance alone.

These soaked CBR gains (133.8-164.9% across compactive efforts) exceed the subgrade minimum by a comfortable margin at 8% IOT and are of a similar order to CBR improvements reported for lime-cement stabilised soil-mine tailing blends used for highway construction (Ojuri et al., 2017), reinforcing that IOT stabilisation, even after the strength-reducing effects of prior crude oil contamination, can restore soil performance to levels competitive with stabilisers applied to uncontaminated soils.

Table 3. California Bearing Ratio Results (%)

IOT (%)	BSL-U	BSL-S	WAS-U	WAS-S	BSH-U	BSH-S
0	16.5	6.5	18.1	8.5	24.5	11.4
2	18.9	8.5	20.4	7.4	26.4	14.2
4	22.5	9.1	24.5	10.4	46.1	16.5
6	23.5	12.6	31.8	19.4	53.6	23.1
8	28.4	15.2	39.6	21.5	61.2	30.2

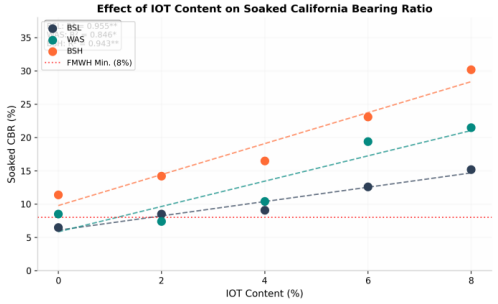

Fig. 2. Effect of IOT content on soaked CBR with linear regression (BSL: R^2=0.955**, WAS: R^2=0.846*, BSH: R^2=0.943**). FMWH minimum = 8% shown.

3.4 Durability Characteristics

The durability of the IOT-stabilised soil, assessed through wet-dry cycling, is presented in Table 4. The durability

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increased progressively with IOT content across all compactive efforts. Under BSL compaction, the durability index improved from 31.5% at 0% IOT to 63.5% at 8% IOT. The WAS compaction regime produced values increasing from 28.5% to 40.6%, while the BSH compactive effort yielded increases from 25.0% to 34.1%. The highest durability index of 63.5% was recorded at 8% IOT under BSL compaction. The durability improvement is attributed to the cementitious bonds formed through pozzolanic reactions, which enhance the resistance of the soil matrix to the disruptive effects of moisture cycling. The higher durability values under BSL compaction compared to BSH at equivalent IOT contents warrant closer engineering scrutiny, since higher compactive effort would ordinarily be expected to produce a denser, more durable matrix. A plausible explanation is that BSH compaction, delivered at the same moulding moisture content used for BSL, compacted the soil-IOT blend dry of its pozzolanic optimum, limiting the degree of saturation available to sustain C-S-H and C-A-H gel formation during curing; alternatively, the higher compactive energy may have induced partial degradation of the friable IOT particles or of early-stage cementitious bonds before they gained sufficient maturity, reducing the refinement of the pore structure relative to the more gently compacted BSL specimens. This behaviour mirrors observations in some cement- and lime-stabilised tropical soils where moisture-density balance, rather than compactive energy alone, governs long-term durability (Osinubi et al., 2019).

Table 4. Durability Index After Wet-Dry Cycling (%)

IOT (%)	BSL (%)	WAS (%)	BSH (%)
0	31.5	28.5	25.0
2	46.5	31.5	26.5
4	48.2	36.5	35.5
6	58.3	41.5	33.5
8	63.5	40.6	34.1

3.5 Scanning Electron Microscopy Analysis

Scanning electron microscopy analysis was conducted on selected specimens to investigate the microstructural changes accompanying IOT stabilisation. The SEM micrographs revealed significant morphological differences between the unstabilised and IOT-stabilised soil samples. At 0% IOT, the soil microstructure exhibited a loose, porous arrangement of particles with visible void spaces and minimal interparticle bonding. The particle surfaces appeared relatively smooth with no evidence of cementitious product formation.

At 4% IOT content, the SEM micrographs showed the initial stages of cementitious bond formation, with needle-like ettringite crystals and amorphous calcium-silicate-hydrate (C-S-H) gel beginning to bridge between soil particles. The pore spaces showed initial signs of reduction, and particle-to-particle contact points exhibited thin coatings of reaction products.

At the optimum 8% IOT content, the microstructure was characterised by dense interlocking of soil and IOT particles, with extensive C-S-H gel formation and calcium-aluminate-hydrate (C-A-H) products filling the interparticle voids. The resulting microstructure was significantly denser and more homogeneous compared to the unstabilised soil, directly corresponding to the 39.9-75.6% UCS gain (Section 3.2), the 133.8-164.9% soaked CBR gain (Section 3.3), and the doubling of the durability index (Section 3.4) recorded between 0% and 8% IOT: the progressive filling of interparticle voids by C-S-H and C-A-H products is the physical mechanism underlying all three macroscopic improvements. These microstructural observations are consistent with the findings of Osinubi et al. (2024) and Eberemu et al. (2025) for iron-rich industrial waste stabilised tropical soils.

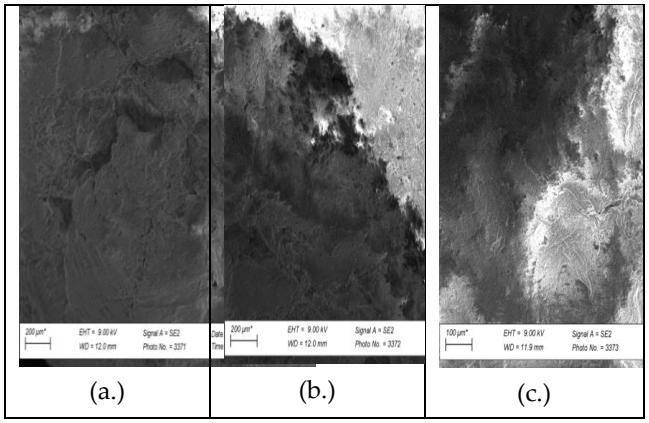

Fig. 3. (Plate I) SEM Micrograph of (a). 0 % IOT Specimen at 28 Days Curing (200µm scale) (b.) 4 % IOT Specimen at 28 Days Curing (200µm scale) (c.) 8 % IOT Specimen at 28 Days Curing (200µm scale)

3.6 Statistical Analysis

The results of the linear regression and ANOVA analyses are summarised in Table 5. All strength and CBR parameters demonstrated statistically significant positive correlations with IOT content. The strongest correlation was observed for UCS under BSL compaction ($R^2 = 0.978$, $p = 0.001$), followed by soaked CBR under BSL compaction ($R^2 = 0.955$, $p = 0.004$). One-way ANOVA confirmed significant differences in 28-day UCS across compactive efforts ($F = 14.23$, $p < 0.001$).

These R-squared values indicate that IOT content alone explains between 85% and 98% of the variance in strength and CBR outcomes across the five stabiliser levels tested, which is a very strong degree of association by conventional geotechnical standards (R-squared above 0.80 is generally considered a strong linear relationship for compaction- and stabilisation-based soil testing). The consistently higher R-squared values under BSL compaction (0.978 for UCS, 0.955 for soaked CBR) compared to WAS and BSH suggest that IOT dosage is the most reliably predictive variable at the lowest compactive effort, where scatter introduced by compaction-related variability is smallest; at higher

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compactive efforts, additional factors such as localised over-compaction or particle degradation (discussed in Section 3.4) introduce more variability that a simple linear IOT term does not fully capture, which is reflected in the modestly lower R-squared values recorded under WAS and BSH. The significant one-way ANOVA result ($F = 14.23$, $p < 0.001$) confirms that these strength differences across compactive efforts are not attributable to random experimental variation, supporting the use of compactive effort, alongside IOT content, as a genuine engineering design variable.

Table 5. Summary of Linear Regression Analysis

Parameter	Regression Equation	R^2	p-value
UCS 28d (BSL)	UCS=210.7+9.9IOT	0.978	0.001**
UCS 28d (WAS)	UCS=238.6+20.7IOT	0.917	0.011*
UCS 28d (BSH)	UCS=270.1+18.6IOT	0.851	0.026*
CBR soaked (BSL)	CBR=6.08+1.08IOT	0.955	0.004**
CBR soaked (WAS)	CBR=5.84+1.90IOT	0.846	0.027*
CBR soaked (BSH)	CBR=9.78+2.33IOT	0.943	0.006**

4 CONCLUSION

Based on the experimental results and statistical analyses, the following conclusions were drawn:

1. Combining vermi-improvement with IOT stabilisation addresses the two limitations of biological remediation alone: it partially degrades the petroleum hydrocarbon contamination while simultaneously supplying, through the IOT's silica and iron oxide content, the mineralogical basis for the pozzolanic reactivity needed to restore the soil's load-bearing capacity.
2. The strong, statistically significant dependence of UCS on IOT content across all compactive efforts confirms that stabiliser dosage, rather than compactive effort alone, is the dominant control on strength recovery, giving field engineers a practical single lever for tuning subgrade performance to a required strength target.
3. Because the soaked CBR criterion, rather than the higher UCS-based base-course threshold, governs subgrade acceptance, the IOT-stabilised material meets the regulatory bar for medium- to heavy-traffic subgrades at a comparatively modest 8% IOT dosage, indicating that full base-course-level strength is not a prerequisite for beneficial reuse of this contaminated soil.
4. Durability improved substantially with IOT addition, with the highest durability index of 63.5% recorded at 8% IOT under BSL compaction.
5. SEM analysis revealed progressive densification of the soil microstructure with increasing IOT content and curing period, characterised by C-S-H and C-A-H cementitious product formation and reduced porosity.
6. The integration of vermi-improvement with 8% IOT stabilisation and the British Standard Heavy compaction regime was found optimal for producing a material with adequate strength and durability for road subgrade applications.

Taken together, these findings support the broader engineering implication that biologically remediated, IOT-stabilised lateritic soil is a viable, low-cost subgrade material for roads passing through petroleum-impacted land in Nigeria, converting an environmental liability into a construction resource. The principal scientific contribution of this study is the demonstration that vermi-improvement and IOT stabilisation are complementary rather than redundant treatments, jointly resolving the environmental and mechanical dimensions of crude-oil-contaminated soil that neither treatment addresses alone; future work should extend this evaluation to field-scale trials and to the durability-compaction interaction identified in Section 3.4.

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