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Index Properties and Compaction Characteristics of Cement-Stabilized, Vermi-Remediated Crude Oil-Contaminated Black Cotton Soil for Landfill Liner and Cover Applications

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Abstract-** Crude oil contamination of black cotton soil (BCS) alters its physical and index properties, limiting its reuse as a hydraulic barrier material unless it is remediated and stabilized. This study evaluates the index properties and compaction characteristics of vermiremediated crude oil-contaminated black cotton soil treated with 0, 2, 4, 6 and 8% ordinary Portland cement, with a view to assessing its suitability as landfill liner and cover material. Disturbed soil samples were collected from Deba Local Government Area, Gombe State, Nigeria, artificially contaminated, and subjected to vermiremediation using Eisenia fetida prior to cement stabilization. Index property tests (particle size distribution, specific gravity and Atterberg limits) and compaction tests under British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH) energies were carried out in accordance with BS 1377 (1990) and BS 1924 (1990). The untreated contaminated soil classified as CH (USCS) and A-7-6(13) (AASHTO), with a liquid limit of 59.10%, plasticity index of 20.10%, and a reduced specific gravity of 2.34. Vermiremediation achieved a 40% reduction in total petroleum hydrocarbon content prior to stabilization. Cement addition progressively reduced the percentage of fines passing the 0.075 mm sieve from 91.40% to 70.40%, increased specific gravity to a peak of 2.59 at 6% cement, and produced a general reduction in plastic limit alongside an increase in plasticity index. Maximum dry density increased with cement content up to 6% (1.637-1.670 Mg/m3 across the three compactive efforts) before marginally declining at 8%, while optimum moisture content rose consistently from about 15-20% (0% cement) to 17-22% (8% cement). These trends indicate progressive particle aggregation, flocculation and cementitious bonding. The results confirm that 4-6% cement combined with British Standard Heavy compactive effort produces the most favourable index and compaction behaviour for landfill liner and cover applications.

***Keywords:** Black Cotton Soil; Vermiremediation; Cement Stabilization; Index Properties; Compaction Characteristics; Landfill Liner*

I. INTRODUCTION

Crude oil contamination remains a critical environmental concern in petroleum-producing regions, where accidental spillage and leakage alter the physicochemical properties of soil, including its permeability, porosity and index behaviour, thereby limiting its suitability for engineering reuse (Adeyemi et al., 2019).

Black cotton soil (BCS), an expansive clay dominated by montmorillonite, already presents challenges of high plasticity, swelling and shrinkage under normal conditions (Kumar & Sharma, 2017); when contaminated with crude oil, its index properties and compaction behaviour are further compromised through increased hydrophobicity and altered interparticle bonding, complicating its safe reuse in geotechnical works.

Bioremediation techniques, particularly vermiremediation using earthworms such as Eisenia fetida, offer a sustainable route for reducing hydrocarbon load in contaminated soils prior to their engineering reuse (Domínguez, 2017; Suthar, 2009). However, vermiremediation alone does not restore the strength, plasticity and compaction characteristics required for use in critical containment applications such as landfill liners and covers.

Cement stabilization is a widely adopted technique for improving the index and compaction properties of problematic soils, as cement hydration products bind soil particles, modify plasticity, and improve density-moisture relationships (Mousavi & Hassan, 2020; Muntohar & Khasanah, 2018).

Index properties (particle size distribution, specific gravity and Atterberg limits) and compaction characteristics (maximum dry density and optimum moisture content) are fundamental classification and design parameters that govern the suitability of a soil for use as a compacted clay liner or cover, since they directly influence achievable density, permeability and shrink-swell behaviour in the field (Daniel, 1993; Benson et al., 1994).

Although previous studies have separately examined crude oil contamination, vermiremediation and cement stabilization of expansive soils, limited work has systematically documented how these indexes and compaction properties evolve when vermiremediated crude oil-contaminated black cotton soil is subsequently treated with cement.

This study therefore presents and discusses the index properties and compaction characteristics of vermiremediated crude oil-contaminated black cotton soil stabilized with varying percentages of cement, with the aim of establishing its suitability for landfill liner and cover applications.

II. MATERIALS AND METHODS

2.1. Study Area and Soil Sampling

Disturbed soil samples were collected at Deba Local Government Area (Latitude 10°13'N, Longitude 11°23'E) along Dadin Kowa, approximately 30 km from Gombe town, Gombe State, Nigeria.

The topsoil was removed to a depth of 0.5 m before sampling, and the soil was sealed in polythene bags to preserve its natural moisture content during transportation. The samples were subsequently air-dried and pulverized to pass the BS No. 4 sieve (4.76 mm aperture) in preparation for laboratory testing.

2.2. Materials

Ordinary Portland cement, sourced from a commercial outlet in Kaduna State, Nigeria, was used as the stabilizing admixture at 0, 2, 4, 6 and 8% by dry weight of soil. Potable water obtained from the Civil Engineering Soil Laboratory, Nigerian Defence Academy, Kaduna, was used for all mixing and compaction operations.

2.3. Contamination and Vermiremediation Pretreatment

The black cotton soil was artificially contaminated with crude oil and conditioned in the laboratory for 30 days to simulate field contamination, after which it was subjected to vermiremediation using Eisenia fetida to reduce the total petroleum hydrocarbon (TPH) content prior to cement stabilization.

Removal efficiency was determined gravimetrically from the initial and residual TPH concentrations. This pretreatment step is described only briefly here, as the present study focuses on the resulting index properties and compaction characteristics of the vermiremediated soil under cement stabilization.

2.4. Laboratory Testing Programme

Natural moisture content, specific gravity, particle size distribution (dry sieve analysis) and Atterberg limits (liquid limit, plastic limit and plasticity index) were determined for the untreated contaminated soil and for the vermiremediated soil treated with 0, 2, 4, 6 and 8% cement, in accordance with BS 1377 (1990) Parts 2 and 4.

Specific gravity was determined using the density bottle method, particle size distribution by dry sieving through a stack of sieves ranging from 5.00 mm to 75 µm, and Atterberg limits using the Casagrande apparatus (liquid limit) and thread-rolling method (plastic limit), with the plasticity index computed as the difference between the liquid and plastic limits.

Compaction characteristics were evaluated using British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH) compactive efforts in accordance with BS 1377 (1990) Part 4, BS 1924 (1990) and the Nigerian General Specifications (NGS, 1997).

BSL compaction was achieved using 27 blows of a 2.5 kg rammer falling from 300 mm on each of three soil layers in a 1000 cm3 mould; WAS compaction

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used 10 blows of a 4.5 kg rammer falling from 450 mm on each of five layers; and BSH compaction used 27 blows of a 4.5 kg rammer on each of five layers, all within the same mould volume.

For each compactive effort, 3000 g of dry soil-cement mixture was compacted at successive water contents incremented by 8% equivalent addition until a reduction in the bulk mass of the compacted soil was observed, after which the maximum dry density (MDD) and its corresponding optimum moisture content (OMC) were obtained from the peak of the dry density-moisture content curve.

III. RESULTS AND DISCUSSION

3.1. Index Properties of the Untreated Crude Oil-Contaminated Black Cotton Soil

The untreated crude oil-contaminated black cotton soil is a fine-grained material, with 95.1% passing the BS No. 200 (0.075 mm) sieve, confirming its clay-dominated character. It recorded a liquid limit of 59.10%, plastic limit of 26.15%, plasticity index of 20.10% and a natural moisture content of 18.4%, classifying it as a high-plasticity clay (CH under the Unified Soil Classification System and A-7-6(13) under AASHTO).

The dominance of montmorillonite is consistent with the high plasticity recorded, although the reduced specific gravity of 2.34, compared with the typical range of 2.60-2.75 for inorganic clays, reflects the influence of hydrocarbon contamination on particle density and mineral-fluid interaction (Mitchell & Soga, 2005; Kamon & Ahn, 2001).

Vermiremediation of this soil using Eisenia fetida achieved a 40% reduction in total petroleum hydrocarbon content, from 8800 mg/kg to 5300 mg/kg, providing the reduced-contamination starting material used for the subsequent cement stabilization and index/compaction assessment reported in this study.

Table 1: Index and Classification Properties of the Untreated Crude Oil-Contaminated Black Cotton Soil

Property	Value
Passing BS No. 200 sieve (%)	95.1
Natural moisture content (%)	18.4
Liquid limit (%)	59.10
Plastic limit (%)	26.15
Plasticity index (%)	20.10
Linear shrinkage (%)	2.34
Specific gravity, Gs	2.34
USCS classification	CH
AASHTO classification	A-7-6 (13)
Colour	Greyish black
Dominant clay mineral	Montmorillonite

3.2. Effect of Cement Content on Particle Size Distribution

Increasing cement content from 0% to 8% progressively reduced the percentage passing across all sieve sizes, particularly within the fine fraction (≤ 0.425 mm), reflecting structural modification of the vermiremediated soil by cementitious bonding.

At the coarse fraction (2.36 mm sieve), the percentage passing decreased slightly from 98.43% (0% cement) to 95.09% (8% cement), while at the 0.425 mm sieve it decreased from 93.76% to 80.35%. The most pronounced change occurred at the 0.075 mm sieve, where the percentage passing (fines content) fell from 91.40% to 70.40%, a reduction of about 21 percentage points.

This reduction in fines confirms that cement hydration products, particularly calcium silicate hydrate (C-S-H), bond fine particles into larger aggregates, effectively shifting the apparent particle size distribution towards coarser behaviour (Zhao & Wong, 2025; Rehman et al., 2025).

Similar flocculation and agglomeration effects have been reported for cement-treated lateritic and clayey soils (Sani et al., 2026a; Sani et al., 2026b), where gradation improvement was most pronounced between 4% and 6% cement, with diminishing change beyond this range.

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Table 2: Percentage Passing at Selected Sieve Sizes for the Vermiremediated Black Cotton Soil Treated with Cement

Sieve size (mm)	0% cement	8% cement
2.36	98.43	95.09
0.425	93.76	80.35
0.075	91.40	70.40

3.3. Effect of Cement Content on Specific Gravity

The specific gravity of the vermiremediated black cotton soil-cement mixtures increased progressively from 2.40 (0% cement) to 2.49, 2.58 and 2.59 at 2%, 4% and 6% cement respectively, before declining slightly to 2.53 at 8% cement (Figure 1).

The initial value of 2.40, below the typical range for natural inorganic clays (2.60-2.75), suggests the presence of residual light hydrocarbon fractions or contamination-related mineral alteration. The subsequent increase with cement content reflects the addition of denser cementitious solids and the formation of calcium-based reaction products within the soil matrix (Zhao & Wong, 2025).

The peak specific gravity at 6% cement, followed by a marginal reduction at 8%, mirrors trends reported for cement-stabilized lateritic soils, where an optimum stabilization level is typically reached before excessive binder content promotes structural rearrangement and mild micro-void formation rather than further densification (Sani et al., 2026a; Sani et al., 2026b).

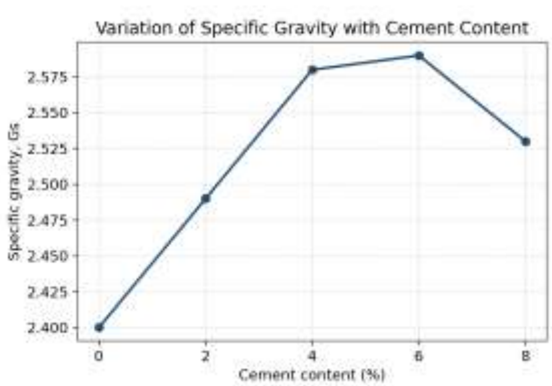

Figure 1: Variation of Specific Gravity with Cement Content

3.4. Effect of Cement Content on Atterberg Limits

The liquid limit of the vermiremediated soil showed only minor fluctuation with cement content, ranging from 57.96% (8% cement) to 59.22% (6% cement), with a value of 58.12% recorded at 0% cement (Figure 2).

This limited variation indicates that cement addition within the tested range does not substantially alter the water-holding capacity governing the liquid state, although a modest reduction at 8% cement suggests that hydration products begin to restrict the adsorbed water layer at higher binder contents (Mirzababaei, 2022; Estabragh, 2023).

In contrast, the plastic limit decreased markedly and consistently with increasing cement content, from 31.77% at 0% cement to 22.14% at 8% cement, a reduction of nearly 10 percentage points. This trend reflects the binding action of calcium silicate hydrate and calcium aluminate hydrate reaction products, which reduce the plastic-state water affinity of the clay fraction as cement content increases (Sorsa, 2022; Bhavya & Nagaraj, 2025).

Because the plasticity index is obtained as the difference between the liquid and plastic limits, the near-constant liquid limit combined with the steadily falling plastic limit produced a general increase in plasticity index, from 26.35% (0% cement) to 30.99% (2%), 28.46% (4%), 31.18% (6%) and 35.82% (8% cement).

This increase in plasticity index with cement content, rather than the reduction typically expected of pure clay stabilization, indicates that particle flocculation and re-arrangement induced by calcium ion exchange dominate over pure cementation across the range tested, a pattern also reported for cement-stabilized clays combined with prior biological treatment (Yohanna et al., 2024; Sani et al., 2026a; Sani et al., 2026b).

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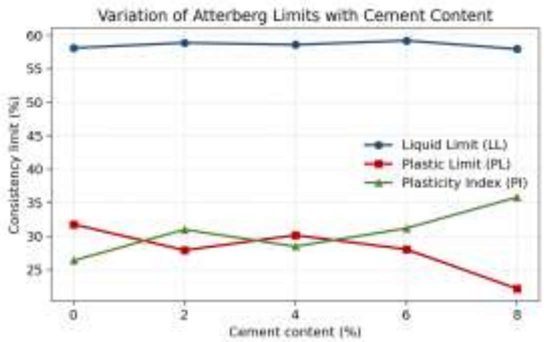

Figure 2: Variation of Atterberg Limits with Cement Content

3.5. Compaction Characteristics

3.5.1. Maximum Dry Density

Maximum dry density (MDD) increased progressively with cement content under all three compactive efforts (Figure 3). Under British Standard Light (BSL), MDD increased from 1.585 Mg/m3 (0% cement) to a peak of 1.637 Mg/m3 at 6% cement, before declining slightly to 1.610 Mg/m3 at 8%.

Under West African Standard (WAS) compaction, MDD rose from 1.613 Mg/m3 to 1.650 Mg/m3 at 6% cement, then decreased to 1.630 Mg/m3 at 8%. Under British Standard Heavy (BSH) compaction, MDD increased steadily from 1.624 Mg/m3 (0%) through 1.640 Mg/m3 (2%) and 1.650 Mg/m3 (4%) to a peak of 1.670 Mg/m3 at 6% cement, before falling to 1.640 Mg/m3 at 8%.

The consistent peak in MDD at 6% cement across all three compactive efforts is attributed to void-filling by cement particles, flocculation of fines, and improved particle packing under compactive energy.

The subsequent decline at 8% cement is likely due to micro-void formation within excessively flocculated aggregates, which reduces densification efficiency, consistent with findings for other cement-stabilized fine-grained soils (Zhao & Wong, 2025; Rehman et al., 2025; Sani et al., 2026a; Sani et al., 2026b).

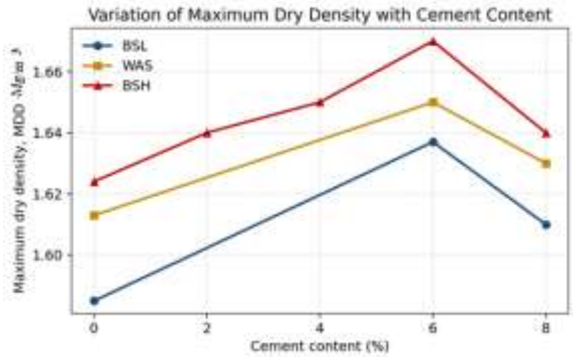

Figure 3: Variation of Maximum Dry Density with Cement Content under BSL, WAS and BSH Compactive Efforts

3.5.2. Optimum Moisture Content

Optimum moisture content (OMC) increased consistently with cement content under all three compactive efforts (Figure 4), reflecting the water demand of cement hydration and the increased surface area associated with flocculated fine particles.

Under BSL, OMC rose from 20.06% (0% cement) to 20.46% (2%), 21.75% (4%), 21.88% (6%) and 22.05% (8%). Under WAS, OMC increased from 17.25% (0%) to 18.66% (6%) and 19.04% (8%). Under BSH, OMC rose steadily from 15.42% (0%) through 16.70% (2%) and 16.85% (4%) to 17.03% (6%) and 17.20% (8%).

The steady rise in OMC, without the reversal observed for MDD at 8% cement, confirms that water consumption by hydration reactions continues even as densification efficiency declines, since the additional water is increasingly required to hydrate excess cement and lubricate flocculated aggregates rather than to fill voids (Rehman et al., 2025; Zhao & Wong, 2025).

The largest increment in OMC under BSL occurred between 2% and 4% cement, consistent with the intensification of hydration and flocculation reactions within this range before the rate of increase moderated at higher cement contents (Sani et al., 2026a; Sani et al., 2026b).

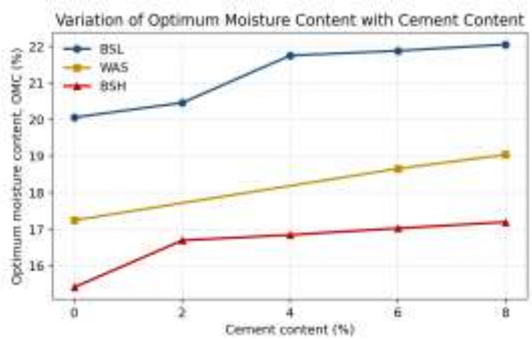

Figure 4: Variation of Optimum Moisture Content with Cement Content under BSL, WAS and BSH Compactive Efforts

3.6. Engineering Significance for Liner and Cover Application

The observed index property and compaction trends carry direct implications for the use of the vermiremediated, cement-stabilized black cotton soil as a landfill liner or cover material. The progressive reduction in fines content and the corresponding densification of the soil matrix with cement addition improve particle packing, which is essential for achieving the low hydraulic conductivity required of compacted clay liners (Daniel, 1993).

The consistent peak in maximum dry density at 6% cement, coupled with the corresponding optimum moisture content, identifies the field compaction condition most likely to yield the densest, least permeable soil fabric.

Given that heavier compactive effort (BSH) produced the highest densities and the least void ratio across all cement contents, field compaction equivalent to British Standard Heavy is indicated as the preferred compactive energy for achieving the index and density characteristics required of liner and cover systems.

IV. CONCLUSION

This study evaluated the index properties and compaction characteristics of vermiremediated crude oil-contaminated black cotton soil stabilized with 0-8% cement. The untreated contaminated soil classified as a high-plasticity clay (CH; A-7-6(13)), with a reduced specific gravity of 2.34 reflecting hydrocarbon contamination, and vermiremediation achieved a 40% reduction in total petroleum hydrocarbon content prior to stabilization.

Cement addition produced a progressive reduction in fines content, from 91.40% to 70.40% passing the 0.075 mm sieve, and an increase in specific gravity to a peak of 2.59 at 6% cement, both indicating particle aggregation and cementitious bonding.

Atterberg limit trends showed a near-constant liquid limit, a marked reduction in plastic limit (31.77% to 22.14%), and a general increase in plasticity index (26.35% to 35.82%) with cement content, reflecting flocculation-dominated structural reorganization of the clay fraction.

Compaction results showed that maximum dry density peaked at 6% cement across all three compactive efforts (1.637-1.670 Mg/m3), while optimum moisture content increased consistently with cement content, from 15.4-20.1% (0% cement) to 17.2-22.1% (8% cement), reflecting cement hydration demand.

These findings demonstrate that vermiremediation combined with 4-6% cement stabilization under heavy compactive effort produces the most favourable index and compaction characteristics for the reuse of crude oil-contaminated black cotton soil as landfill liner and cover material.

V. RECOMMENDATIONS

1. Cement content of 4-6% is recommended as the optimum stabilization range, based on the peak specific gravity and maximum dry density observed at 6% cement and the associated favourable index property trends.
2. British Standard Heavy (BSH) compactive effort is recommended for field application, as it consistently produced the highest maximum dry density across all cement contents tested.
3. Field compaction should target moisture contents close to the laboratory-determined optimum moisture content for the selected cement content and compactive effort, to achieve the densities reported in this study.
4. Further studies should examine the long-term durability of the index and compaction properties

under wetting-drying cycles and field exposure conditions.

REFERENCES

[1] Adeyemi, M. O., Olatunji, K., & Faloye, F. (2019). Effects of crude oil contamination on soil properties in the Niger Delta region of Nigeria. Environmental Monitoring and Assessment, 191(4), 223. https://doi.org/10.1007/s10661-019-7367-6

[2] Benson, C. H., Zhai, H., & Wang, X. (1994). Estimating hydraulic conductivity of compacted clay liners. Journal of Geotechnical Engineering, 120(2), 366–387. https://doi.org/10.1061/(ASCE)0733-9410(1994)120:2(366)

[3] Bhavya, C., & Nagaraj, H. B. (2025). Influence of binder content on Atterberg limits and water retention behaviour of stabilized clayey soils. Journal of Materials in Civil Engineering, 37(2), 04024412.

[4] British Standards Institution. (1990). BS 1377: Methods of test for soils for civil engineering purposes, Parts 2, 4 and 7. BSI.

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

[6] Daniel, D. E. (1993). Geotechnical practice for waste disposal. Chapman & Hall.

[7] Domínguez, J. (2017). Vermicomposting: Earthworms, organic wastes, and environmental management. Springer.

[8] Estabragh, A. R. (2023). Effect of cement content on the consistency limits and microstructure of stabilized clay. Applied Clay Science, 233, 106830.

[9] Kamon, M., & Ahn, J. C. (2001). Combined effects of oil contamination and stabilization on clay properties. Soils and Foundations, 41(4), 39–51.

[10] Kumar, A., & Sharma, R. K. (2017). Geotechnical properties and stabilization of expansive soil. International Journal of Engineering Research & Technology, 6(1), 134–140.

[11] Mirzababaei, M. (2022). Effect of cementitious binders on plasticity and water retention of clays. Geotechnical and Geological Engineering, 40(6), 3211–3224.

[12] Mitchell, J. K., & Soga, K. (2005). Fundamentals of soil behavior (3rd ed.). John Wiley & Sons.

[13] Mousavi, S. M., & Hassan, A. (2020). Cement stabilization of soils for construction applications: A review. Journal of Construction Engineering, 12(3), 145–157.

[14] Muntohar, A. S., & Khasanah, M. (2018). Effect of residual hydrocarbons on the strength of cement-stabilized contaminated soils. International Journal of Geotechnical Engineering, 12(2), 162–170. https://doi.org/10.1080/19386362.2016.1265809

[15] Nigerian General Specifications. (1997). Roads and bridges. Federal Ministry of Works and Housing.

[16] Rehman, Z., Khalid, U., & Ijaz, N. (2025). Microstructural and gradation changes in cement-stabilized clayey soils. Construction and Building Materials, 401, 132890.

[17] Sani, J. E.; Adi Shiddi E., Moses, G. Kehinde K. Mustapha (2026a). Remediation Efficiency, Index Properties, and Compaction Characteristics of Vermi-Remediated Crude Oil–Contaminated Black Cotton Soil Stabilized with Cement Kiln Dust. JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026 E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

[18] Sani, J. E.; Oyeleke D. O. and Moses, G. (2026b). Index Properties, and Compaction Characteristics of Palm Kernel Shell Ash-Stabilized Vermi-remediated Crude Oil-Contaminated Lateritic Soil for Highway Sub-Base Application. JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026 E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

[19] Sinha, R. K., Valani, D., Soni, B. K., & Chandran, V. (2008). Earthworms: The environmental engineers—Review of

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DOI: https://doi.org/10.64388/IREV10I1-1719687

vermiculture technologies for environmental management and resource development. International Journal of Global Environmental Issues, 8(3), 255–265.

[20] Sorsa, A. (2022). Chemical and microstructural mechanisms of cement stabilization in expansive clays. Transportation Geotechnics, 34, 100754.

[21] Suthar, S. (2009). Bioremediation of agricultural wastes through vermicomposting. Applied Ecology and Environmental Research, 7(1), 71–86.

[22] Yohanna, P., Etim, R. K., & Ekene, E. (2024). Combined effect of biological pretreatment and cement stabilization on plasticity behaviour of expansive soils. Journal of Sustainable Construction Materials, 9(1), 15–27.

[23] Zhao, Y., & Wong, L. (2025). Microstructural evolution and density-gradation response of cement-treated fine-grained soils. Engineering Geology, 344, 107765.