

Optimization of Geotechnical Enhanced Lateritic Soil Stabilized with Bentonite and Ceramic Dust for Landfill Liner Application



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ABSTRACT: The suitability of native lateritic soil for landfill liner applications is often limited by its inherent geotechnical properties. This study focuses on the optimization of a ternary blend comprising lateritic soil, bentonite, and ceramic dust to simultaneously achieve low hydraulic conductivity ($K \leq 1 \times 10^{-9}$ m/s), high unconfined compressive strength ($UCS \geq 200$ kN/m²), and low volumetric shrinkage ($V_{sh} \leq 4\%$). A robust methodological framework was employed, utilizing Response Surface Methodology (RSM) with a Central Composite Design (CCD). The experimental program systematically evaluated four key factors: bentonite content (0–12%), ceramic dust content (0–10%), molding moisture content (13–23%), and three distinct compaction energies—British Standard Heavy (BSH), British Standard Light (BSL), and West African Standard (WAS). A total of 45 mixture combinations were prepared and tested for hydraulic conductivity, unconfined compressive strength, and volumetric shrinkage after a 28-day curing period. The resulting dataset was analyzed using Minitab software to develop second-order polynomial models, which were validated through ANOVA ($p < 0.05$), high coefficients of determination ($R^2 > 0.93$), and non-significant lack-of-fit tests. The analysis revealed significant main effects and interactions, such as the effect of bentonite and moisture on hydraulic conductivity and ceramic dust with moisture on strength. Multi-objective optimization was performed using the desirability function approach. The findings confirm that while specific mixtures like 12% bentonite with 10% ceramic dust under BSH compaction met all regulatory criteria, the RSM-identified optimum (2.79% bentonite, 5% ceramic dust at 18% moisture) achieved excellent permeability and strength but exhibited excessive shrinkage (6.61%). This study demonstrates the critical role of a systematic, multi-variable optimization methodology in identifying the trade-offs necessary for formulating a viable, sustainable landfill liner material.

KEYWORDS: Bentonite, Ceramic Dust, Landfill Liner, Lateritic Soil, Optimization, Response Surface Methodology.

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I. INTRODUCTION

Municipal Solid Waste (MSW) generation has increased exponentially in developing regions due to rapid urbanization and population growth. In Minna, Niger State, Nigeria, inadequate waste management infrastructure poses significant threats to environmental quality and groundwater resources. The decomposition of this waste produces leachate which is a contaminated liquid that can migrate from unlined or poorly lined landfills into underlying aquifers, causing severe groundwater pollution and public health risks (Ahmad and Ali, 2023). Environmental protection agencies worldwide have established stringent regulations for engineered landfill liners as critical barriers in waste containment facilities. These liners must satisfy specific geotechnical performance criteria: low hydraulic conductivity ($K \leq 1 \times 10^{-9}$ m/s) to minimize leachate migration (Chandra et al., 2020), adequate unconfined compressive strength ($UCS \geq 200$ kN/m²) to maintain structural integrity under overburden pressures, and low volumetric shrinkage ($V_{sh} \leq 4\%$) to prevent desiccation

cracking that could compromise barrier performance (USEPA, 1994; CGRM, 2007).

Research has focused on stabilizing marginal soils with additives to enhance their geotechnical properties for liner applications. For instance, while bentonite is widely used to reduce hydraulic conductivity, studies by Chen and Wang (2023) confirm that its addition often compromises the soil's unconfined compressive strength. Conversely, pozzolanic additives like ceramic dust have been shown to counteract this weakness; research by Amadi et al. (2024); Qays and Jathwa (2021), found that they enhance strength and durability through improved particle bonding, making the liner more resistant to environmental stresses. Other studies have explored synergistic combinations to achieve a balanced performance. For instance, the study by Olaolu et al. (2024) demonstrated that snail shell ash with granulated blast furnace slag shows effective improvement to compaction and compressibility characteristics of local bentonite for base liners. Similarly, Chandra et al. (2020) established the feasibility of using Indian fly ash-bentonite composites as a

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sustainable alternative to traditional sand-bentonite mixes which achieve satisfactory adsorption and hydraulic performance. Lateritic soil, a locally abundant material, is often considered for liner construction. However, its inherent clay mineralogy, predominantly kaolinite, often results in insufficient impermeability and problematic shrinkage-swelling behavior which rendering it un-suitable for direct application (Rizal et al. 2022; Mehmet et al. 2022; Dumbleton 1963). Consequently, research has focused on stabilizing such soils with additives to enhance their properties.

The core problem investigated is the non-suitability of native lateritic soil in the study area with the essential geotechnical requirements for landfill liners, a shortfall consistent with findings from other regions (Hrithik et al. 2023). While bentonite has been widely recognized for its capacity to drastically reduce hydraulic conductivity (Chen and Wang, 2023) and ceramic dust has more recently been identified for its pozzolanic potential to enhance strength and durability (Amin et al. 2023; Amadi et al. 2024), a significant knowledge gap exists regarding their synergistic effects in a ternary blend (Olaolu et al., 2024; Chandra et al., 2020). The precise formulation needed to achieve a balanced optimization of hydraulic conductivity, compressive strength, and shrinkage resistance in a laterite-bentonite-ceramic dust composite has not been yet established. To address this, Response Surface Methodology (RSM) was employed. Which is a robust statistical and mathematical technique used for developing, improving and optimizing processes which is particularly useful for modeling and analyzing problems where multiple variables influence a set of performance responses (Ahmad and Ali 2023; Osuolale and Akinwumi, 2022; Amadi and Eberemu,

2012). Its efficacy in optimizing the geotechnical properties of soil-additive mixtures has been demonstrated in recent studies; for instance, it has been successfully applied to model the compaction and compressibility characteristics of stabilized bentonite (Olaolu et al. 2024) and to evaluate the synergistic effects of multiple additives on soil behavior (Gideon and Amadi, 2024). In this study, RSM facilitated the design of experiments and the development of predictive models to identify the optimal blend ratio of laterite, bentonite, and ceramic dust that concurrently minimizes hydraulic conductivity and volumetric shrinkage while maximizing unconfined compressive strength. The primary objective was to define the optimum combination of these materials to produce a sustainable, effective and compliant landfill liner material.

II. MATERIALS AND METHODS

Lateritic soil was sourced from a borrow pit in Minna, Niger State, Nigeria (9°37'N, 6°33'E) at depths of 1.0 to 1.5 m, which was air-dried, pulverized, and sieved through a 4.75 mm sieve to remove gravel-sized particles. Ceramic dust, obtained as waste from tile polishing at the West African Ceramic Company in Kogi State, was oven-dried at 105°C for 24 hours and sieved through a 75 µm sieve. Commercial sodium bentonite procured from Kaduna State was sourced as air-dried powder passing the 75 µm sieve and stored in airtight containers. Representative samples underwent physical, geotechnical, and mineralogical characterization following BS 1377 (1990) procedures, the samples are shown in Figure 1 (a-c).



Figure 1 Constituent materials (a) Pulverized lateritic soil (b) Bentonite (c) Ceramic Dust

A. Materials Preparation and Testing Procedures.

Pulverized lateritic soil was amended with varying proportions of bentonite (0%, 6%, 12%) and ceramic dust (0%, 5%, 10%) at moisture contents of 13%, 18%, and 23%. A control sample without additives served as reference. The additives ranges were selected based on prior studies (Qays and Jathwa, 2021; Amin et al., 2023; Noolu et al. 2024). A Central Composite Design (CCD) under Response Surface Methodology was implemented using Minitab Version 19 statistical software, considering four numerical factors: bentonite content (0–12%), ceramic dust content (0–10%), moisture content (13–23%) by weight of lateritic soil and compaction energies coded as 1 (BSH), 2 (WAS), and 3 (BSL).

The design comprised of 16 factorial points (full factorial combinations at ± 1 levels), 8 axial points (axial distance $\alpha = 2.0$ from center), and 21 center points for pure error estimation. Laboratory procedures were meticulously executed using three distinct compaction energies: British Standard Heavy (BSH) and British Standard Light (BSL) conforming to BS 1377 (1990), and West African Standard (WAS) adhering to Osinubi and Nwaiwu (2006) and Norazlan et al. (2019). Three response variables were measured for each experimental run: hydraulic conductivity (K) in m/s (target $\leq 1 \times 10^{-9}$ m/s), unconfined compressive strength (UCS) in kN/m² (target ≥ 200 kN/m²), and volumetric shrinkage (Vsh) in percentage (target $\leq 4\%$), as illustrated in Table 1.

Table 1 Strategic Elaboration of Experimental Materials and Methods

Component	Description & Strategic Purpose	Standards & Specifications
Base Material (Pulverized Lateritic Soil)	The primary soil matrix under investigation chosen for its relevance in geotechnical applications.	
Additives & Treatment	Bentonite (0%, 6%, 12%): Added to reduce hydraulic conductivity (K) by filling pores and swelling. Ceramic Dust (0%, 5%, 10%): A waste material used as a pozzolanic agent to potentially improve strength (UCS) and alter shrinkage characteristics. The ranges were strategically selected based on prior literature to identify an optimal dosage.	Proportions based on prior studies Qays and Jathwa, 2021; Amin <i>et al.</i> , 2023; Noolu <i>et al.</i> 2024
Experimental Design	Central Composite Design (CCD) under RSM: A statistically rigorous design used to efficiently study the interactive effects of multiple variables (bentonite, ceramic dust, moisture content, compaction energy) with a minimal number of experimental runs (45 specimens). This model allows for the development of predictive equations for the responses (K, UCS, Vsh).	Response Surface Methodology (RSM)
Compaction Energies	British Standard Heavy (BSH - Code 1) & Light (BSL - Code 3): Represent high and low compaction efforts, simulating different field conditions and their impact on soil density and structure. West African Standard (WAS - Code 2): A regional standard, ensuring the research's local applicability Mixing & Compaction: Treated soils were manually mixed for homogeneity and dynamically compacted into specific molds	BSH & BSL: BS 1377 1990, WAS: Osinubi and Nwaiwu 2006; Norazlan <i>et al.</i> , 2019
Specimen Preparation and Curing:	All specimens were sealed and cured for 28 days in a fog room. This critical step allows for full hydration, pozzolanic reactions, and stable fabric development, ensuring results reflect medium-to-long-term performance.	BS 1377 1990 and BS 1924 1990

Table 2 Summary of Laboratory Testing Procedures and Analytical Framework

Testing Parameter	Methodological Procedure	Strategic Purpose
Hydraulic Conductivity (K)	Method: Falling-head permeameter. Calculation: Equation (1).	To quantify the effectiveness of the bentonite-amended soil as a barrier layer by measuring its ability to impede water flow
Unconfined Compressive Strength (UCS)	Method: Axial loading of cylindrical specimens at a controlled strain rate until failure. Calculation: Equation (2) from maximum load.	To evaluate the improvement in load bearing capacity and stiffness for potential use in liners
Volumetric Shrinkage (Vsh)	Method: Measuring volume change from the saturated state to the oven-dried state. Calculation: Equation (3).	To assess the volume stability and potential for cracking upon drying, a critical property for liners.
Data Analysis & Optimization	Method: Response Surface Methodology (RSM) using the CCD model to analyze the dataset (K, UCS, Vsh for all 45 runs).	To statistically determine the complex interactions between factors and to identify the optimal combination that minimizes K and Vsh while maximizing UCS.

The compaction process involved manually mixing the treated soils and dynamically compacting them in permeability molds for hydraulic conductivity (K), while for UCS and Vsh tests, the mixtures were compacted into

cylindrical molds (38×76 mm). All freshly prepared specimens were then sealed and cured for 28 days in a controlled fog room (23–25°C, 95% RH) as per (BS 1377 1990; BS 1924 1990) to ensure pozzolanic reactions ceramic

dust through consistent hydration. Testing for K, the specimens were saturated via gradual back-pressure until pore pressure parameter $B \geq 0.95$, then tested in a falling-head permeameter under a hydraulic gradient of approximately 20, with readings taken at intervals for 24-hour until steady state flow was achieved (coefficient of variation $< 5\%$ for three consecutive readings); K-values were calculated using Equation (1). For unconfined compressive strength testing, specimens were axially loaded in a motorized tri-axial machine with a 2 kN proving ring at a constant strain rate of 1.0 mm/min until failure or 20% axial strain, with UCS determined from the maximum load using Equations (2), finally for volumetric shrinkage, saturated specimens were measured with a digital caliper (0.01 mm precision) to determine initial volume, the samples were air-dried at $105 \pm 5^\circ\text{C}$ to constant mass (24 – 48 hours) and re-measured to determine final volume, with Vsh calculated using Equation (3). The entire dataset generated from these tests for K, UCS, and Vsh were then integrated into the RSM analysis by utilizing the CCD model to statistically optimize and interpret the complex interactive effects of the additive proportions, moisture content, and compaction energy on the measured geotechnical properties (K, UCS, and Vsh) as illustrated in Table 2 while materials preparation and testing procedures from samples collections to optimization are illustrated in Figure 2.

For hydraulic conductivity,

$$K = \frac{a}{A} \cdot \frac{L}{t} \ln \frac{h_1}{h_2} \tag{1}$$

where:

- k = Hydraulic conductivity (m/s)
- a = Cross-sectional area of the standpipe (m²)
- L = Length of the soil sample (m)
- A = Cross-sectional area of the soil sample (m²)
- t = Time interval for the head to fall from h_1 to h_2 (seconds)
- h_1 = Initial head (m) h_2 = Final head (m)

$$UCS = \frac{P}{A} \tag{2}$$

Where P= axial load at failure

A = corrected area = $A_o/(1-E)$

where, A_o = is the initial cross-sectional area of the specimen

E = axial strain = $\Delta L/L_o$

ΔL = Change in Length L_o = Original Length

$$V_{sh}(\%) = \left(\frac{V_o - V_d}{V_o} \right) \times 100 \tag{3}$$

Where, V_o = Initial volume V_d = Final volume

B. Response Surface Methodology (RSM)

Response Surface Methodology (RSM) is a mathematical statistical technique for experimental design and process optimization. It helps engineers minimize experimental trials while optimizing input variables. In Minitab, RSM employs designs like CCD or Box-Behnken Design (BBD) to model relationships between variables and responses. The software fits quadratic regression models, generates response surfaces/contour plots, and identifies significant factors for designing mix composition, a total of 45 mixtures at moisture content of 13 – 23% as output was used in specimen’s preparation and testing for K, UCS, and Vsh for optimization (Zhang et al., 2021).

Experimental data were analyzed using Minitab Version 19, where second-order polynomial models were fitted to each response variable to establish relationships between the coded independent variables and measured responses. This model adequacy was evaluated through ANOVA at 95% confidence level, examining R^2 , adjusted R^2 , predicted R^2 , lack-of-fit tests, and residual plots. Simultaneous optimization of the three responses was performed using the desirability function approach of Derringer and Suich (1980), with composite desirability calculated as the geometric mean of individual desirabilities to identify the optimal factor combination.

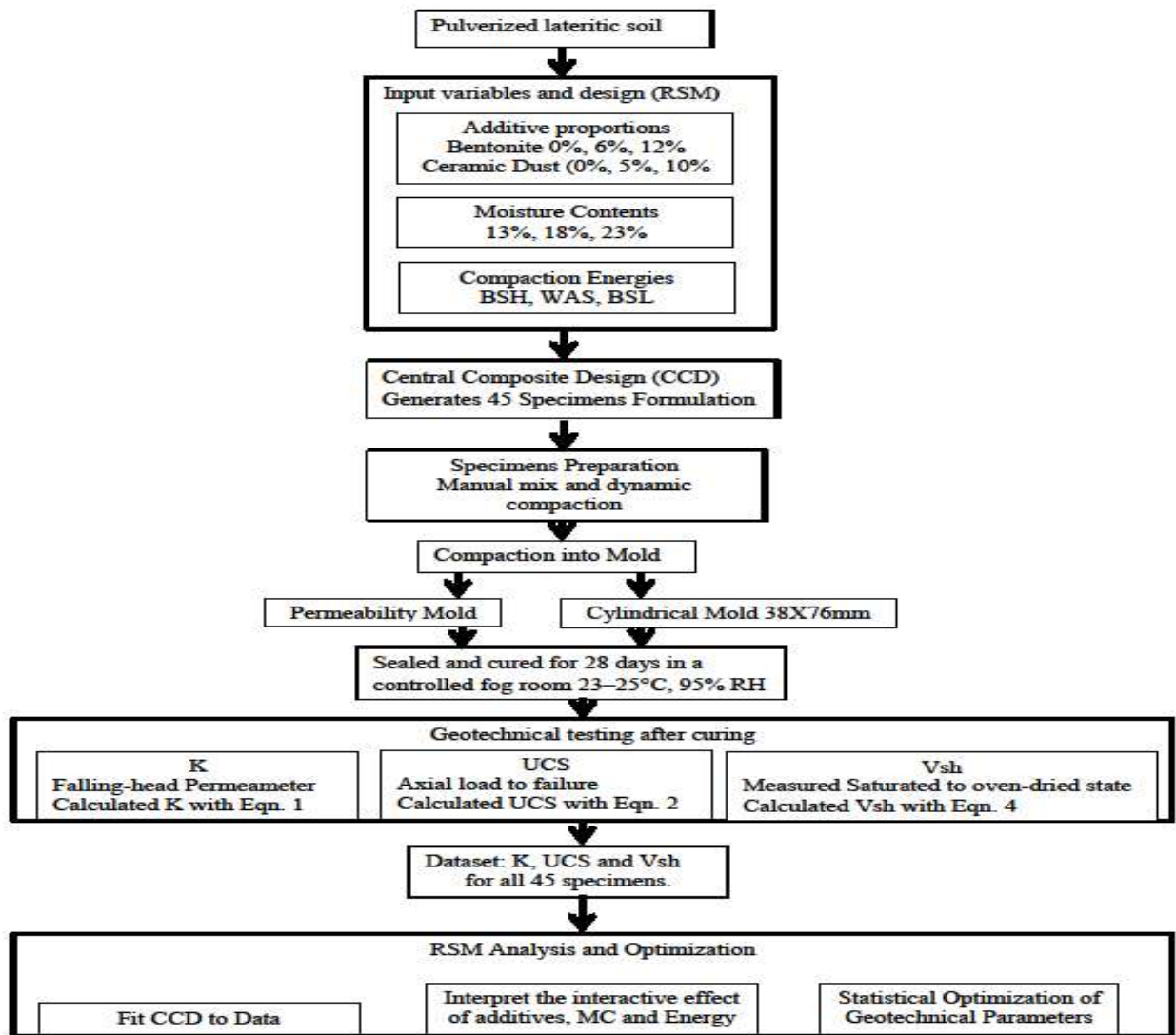


Figure 2 Flow chart showing Material Preparations and Methodology

III. RESULTS AND DISCUSSION

A. Characterization of study soil mixtures

The particle size analysis (Shown in Figure 3) revealed the lateritic soil composed of 60.65% sand (≤ 2.0 mm) and 1.99% fines. Classification tests in Table 3 present a liquid limit of 44% and plasticity index of 4%, categorizing the soil as A-2-5 (AASHTO) and ML (USCS). Compaction tests per BS 1377 (1990) and BS 1924 (1990) yielded: compaction parameters for BSH as: OMC=15.0%, MDD=1.59 g/cm³,

WAS as: OMC=17.2%, MDD=1.54 g/cm³, BSL: OMC=19.5%, MDD=1.44 g/cm³. The XRD analysis identified key mineral constituents: Laterite: Niobium-Nickel (23%), Nacrite (13%), 2-methylfuran (12%), Tridymite HP (5%), Hematite (26%), Aluminum oxide (14%) and silica (SiO₂) (5%). Bentonite: Montmorillonite (70%), Albite (28%), Vermiculite (3%), Copper(I) cyanide complex (1%) and Ceramic dust: Quartz (53%), Labradorite (40%), Violarite (6%), Cristobalite low (1%).

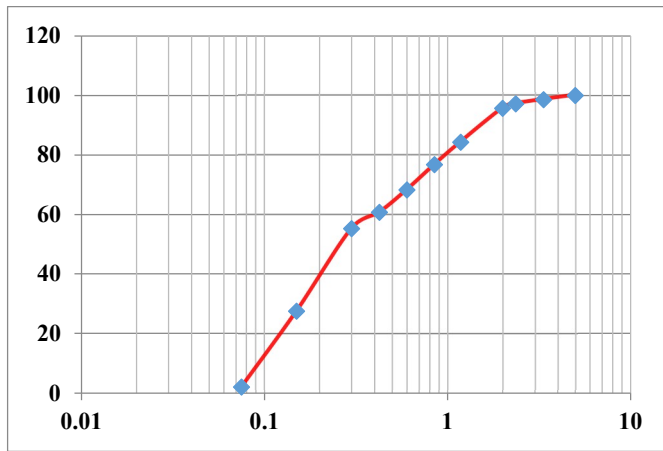


Figure 3 Particle Size Distribution Curve of Lateritic Soil

Table 3 Physical Properties of the Lateritic Soil, CD and Bentonite

Property	Quantity
Percentage Passing BS No. 200 Sieve	1.99
Natural Moisture Content, %	20.50
Liquid Limit, %	44.00
Plastic Limit, %	40.00
Plasticity Index, %	4.00
Specific gravity	1.84
Color	Reddish Brown
AASHTO Classification	A-2- 5
USCS	ML
Liquid Limit of Bentonite	332
Plasticity Index of Bentonite	242
Liquid Limit of Ceramic Dust	34
Plasticity Index of Ceramic Dust	9

B. Hydraulic Conductivity Performance of the Mixtures for Landfill Liner Applications

Hydraulic conductivity tests results for BSH, WAS, and BSL compaction is shown in Figures. 4 - 6. Compliance summaries by energy method appear in Table 4. From the data reported in Figure 4, BSH achieved 33.3% compliance (5/15 runs), with successful mixtures as (Runs 7, 11, 20, 36 and 38) recording $K=9.3 \times 10^{-10} - 6.2 \times 10^{-10}$ m/s at 18 – 23% MC representing a significant improvement over the control (Run 32: $K=3.6 \times 10^{-9}$ m/s), this proved that bentonite's swelling reduces K. Ten BSH runs including Runs 1, 5, 8, 25, 27, 30, 31, 32, 39 and 43 failed to yield acceptable K ($K=4.4 \times 10^{-9} - 1.5 \times 10^{-9}$ m/s within 13–23% MC range). Figures 5 & 6 revealed that mixtures compacted with WAS and BSL demonstrated 20% compliance (3/15 runs each), as detailed in Figures 6 – 8 WAS compliant runs (4, 26 and 42) achieved $k = 9.6 \times 10^{-10} - 9.1 \times 10^{-10}$ m/s at 18–23% MC, recording k of more than one order of magnitude Reduction than the control specimen (Run 18: $K=3.8 \times 10^{-9}$ m/s). Twelve WAS runs (2, 12, 13, 15, 18, 19, 33, 35, 37, 40, 41 and 45) failed to achieve the Target k ($K=2.5 \times 10^{-8} - 1.5 \times 10^{-9}$ m/s) within 13–23% MC range. Similarly, BSL's successful runs (6, 10 and 16) showed $K=1.0 \times 10^{-9} -$

9.6×10^{-10} m/s at 18–23% MC range were better than the control (Run 9: $K=2.8 \times 10^{-8}$ m/s). Twelve BSL runs (3, 9, 14, 17, 21, 24, 28, 29, 34 and 44) failed ($K=3.7 \times 10^{-8} - 1.6 \times 10^{-9}$ m/s) despite similar MC ranges.

All compaction methods achieved $K \leq 1 \times 10^{-9}$ m/s, with BSH showing highest compliance (33.3% against WAS/BSL's 20%). It is important to note that, successful runs occurred exclusively at 18-23% moisture content, confirming optimal hydration for particle bonding and swelling potential of bentonite's. BSH's superior performance demonstrates that high-energy compaction has a critical role in creating dense, low-permeability soil structure. All these highlight the dual importance of moisture and compaction energy control in low permeability liners.

Table 4 Hydraulic Conductivity Compliance Assessment by Compaction Energy

Compaction Energy	Total Runs	Runs Meeting $K \leq 1 \times 10^{-9}$	Compliance Rate
BSH	15	5	33.3%
BSL	15	3	20.0%
WAS	15	3	20.0%

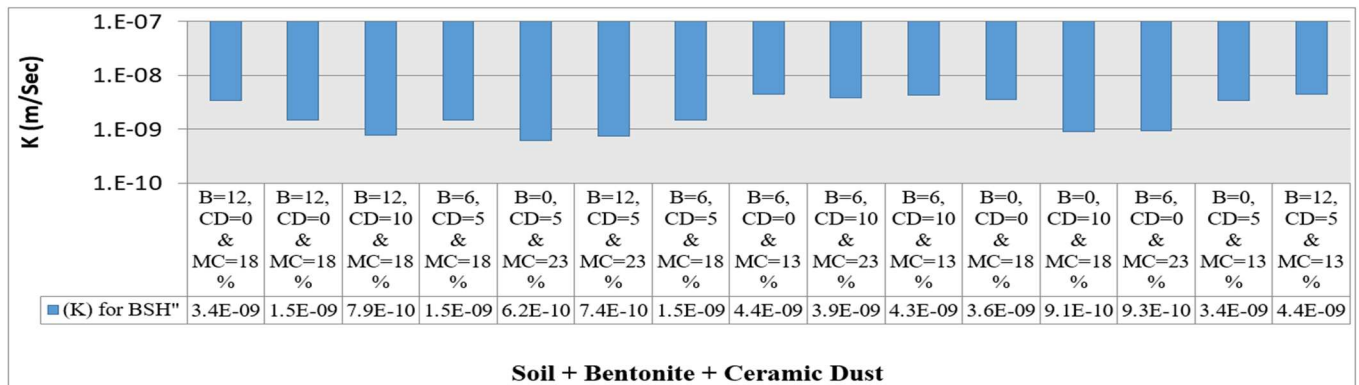


Figure 4: Hydraulic Conductivity Results for Mixtures Compacted with BSH

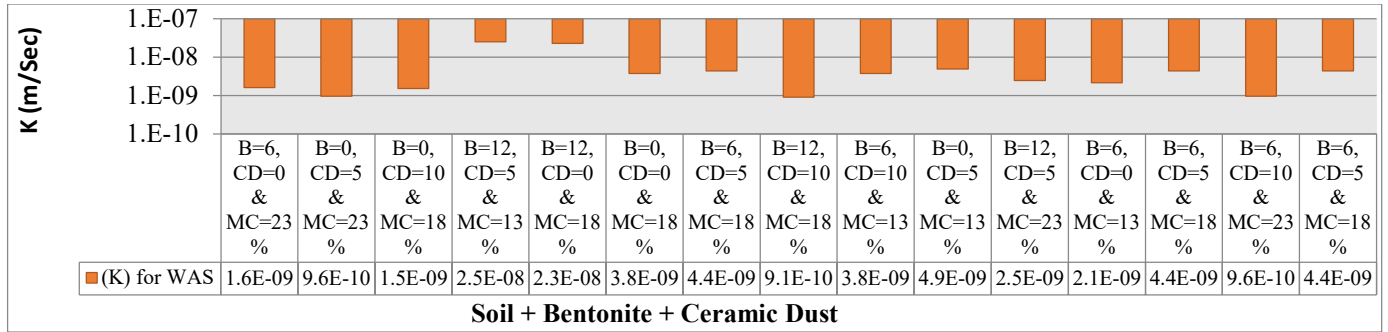


Figure 5 Hydraulic Conductivity Results for Mixtures Compacted with WAS

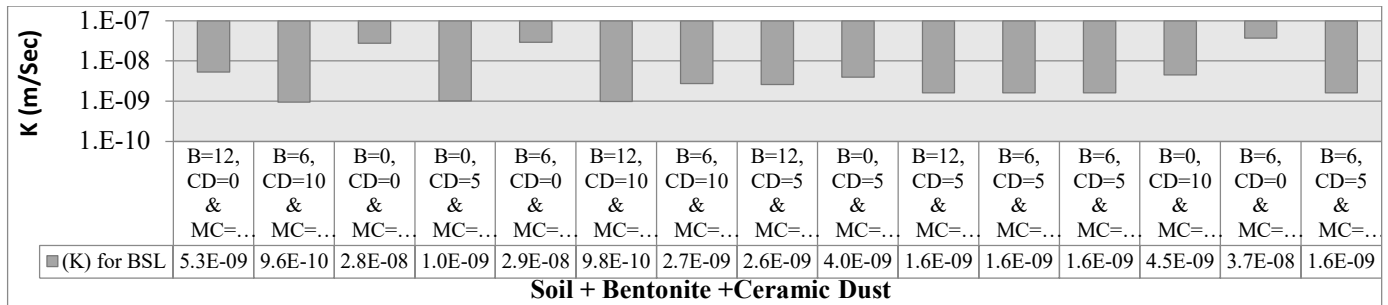


Figure 6 Hydraulic Conductivity Results for Mixtures Compacted with BSL

C. Unconfined Compressive Strength (UCS) Performance of the Mixtures.

Figures 7 - 9 show UCS results for BSH, WAS, and BSL compaction, with compliance patterns by energy method detailed in Table 5, revealing distinct strength characteristics across compaction efforts.

Table 5 UCS Compliance Assessment by Compaction Energy

Compaction Energy	Total Runs	Runs Meeting UCS ≥ 200 kN/m ²	Compliance Rate
BSH	15	9	60%
BSL	15	8	53.3%
WAS	15	5	33.3%

The mixtures compacted with WAS achieved 53.3% compliance (8/15 runs had UCS ≥200 kN/m²), with successful mixtures as (Orders 13, 19, 26, 33, 35, 40, 41 and 45) reaching UCS values of 202.5-347.7 kN/m² at 13-18% moisture contents. Seven runs namely (Orders 2, 4, 12, 15, 18, 37 and 42 and control specimen) with UCS values ranging from 66.7 -184.0 kN/m² at higher moisture (18-23%) Failed to meet the specification requirement of UCS ≥200 kN/m², including the control (Order 18: 121.8 kN/m²). Figure 8, demonstrates WAS's intermediate strength performance, reinforcing the pattern of optimal UCS at lower moisture contents (13-18%) across compaction methods.

Table 5 revealed that 60% of mixtures compacted with BSH energy achieved the threshold UCS value (i.e., 9/15 runs UCS ≥200 kN/m²), with successful mixtures (Orders 5, 7, 8, 25, 27, 31, 36, 39 and 43) reaching 201.1-381.8 kN/m² at 13-18% moisture. However, six BSH runs (Orders 1, 11, 20, 30, 32, 38 and the control specimen with UCS ranging from 56.3-169.5 kN/m² at moisture content of 18-23% failed to meet the target value of UCS ≥200 kN/m² Figure 7, illustrates the results of BSH's strength performance, although the magnitude diminished at higher moisture contents. The data in Figure 7 confirms moisture content's critical role in strength development and pozzolanic reactions of ceramic dust with optimal values occurring at 13-18% moisture under BSH compaction.

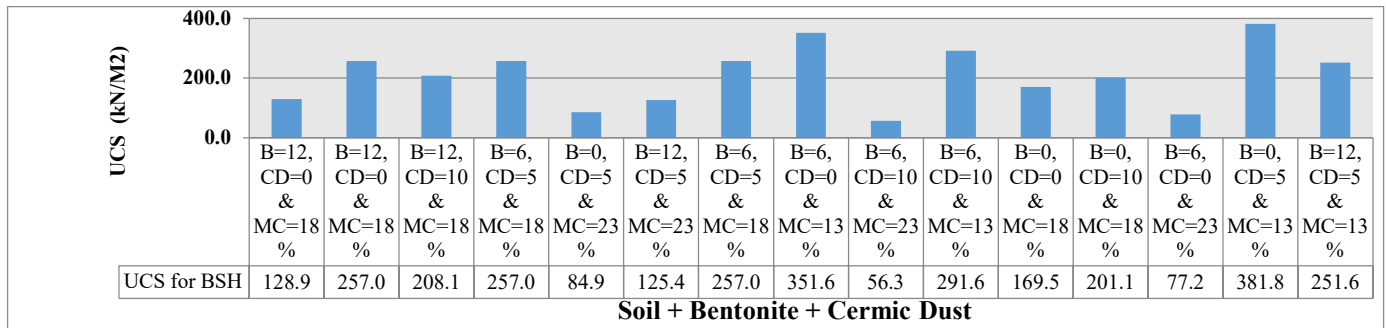


Figure 7 Unconfined Compression Strength of Mixtures Compacted with BSH Energy

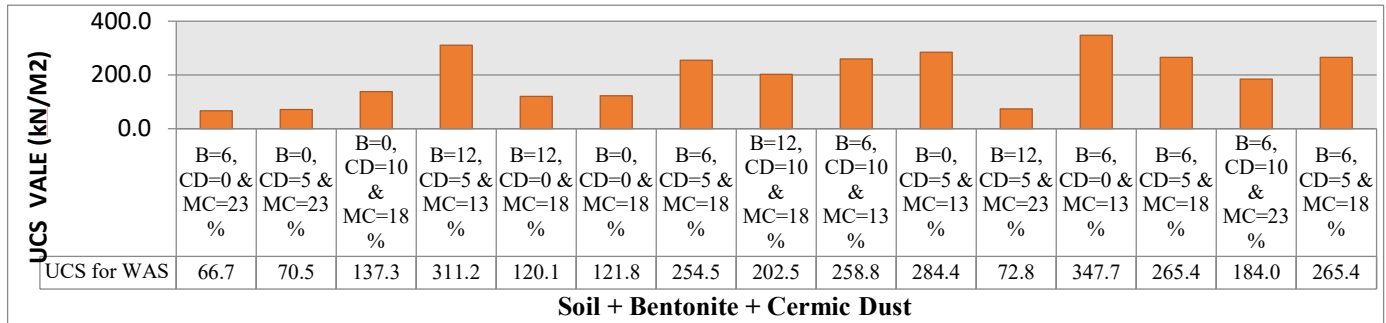


Figure 8 Unconfined Compression Strength of the Mixtures Compacted with WAS Energy

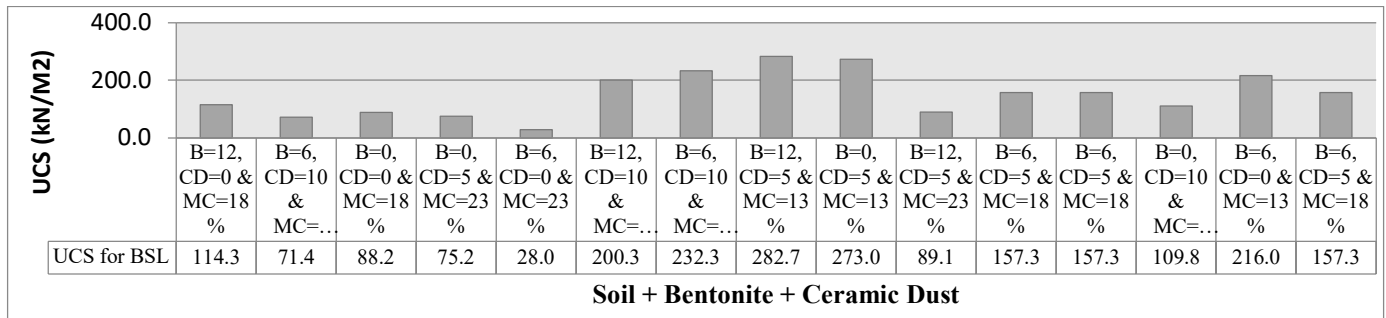


Figure 9 Unconfined Compression Strength of the Mixtures Compacted with BSL Energy

Similarly, 33.3% of mixtures compacted with BSL effort met the specification requirement (i.e., 5/15 runs Attained UCS ≥ 200 kN/m²), with successful mixtures as (Orders 16, 17, 21, 22 and 34) achieving 200.3 - 282.7 kN/m² at 13-18% moisture. However, ten BSL Orders 3, 6, 9, 10, 14, 23, 24, 28, 29 and 44 and the control sample with 28.0-157.3 kN/m² at higher moisture (18-23%) failed to meet the UCS threshold value of UCS ≥ 200 kN/m² confirming BSL's inferior strength gain and the critical moisture-strength relationship as illustrated in Figure 9.

Generally, optimal strength performance occurred between 13-18% moisture which is the favorable for pozzolanic reactions of ceramic dust, while higher Moisture content (18-23%) caused failures. Compliance rates reflects compaction energy in the following order : BSH (60%) > WAS (53.3%) > BSL (33.3%). These outcomes confirm UCS requirements depend on precise moisture and compaction energy control.

D. Volumetric Shrinkage Behaviour of Soil Mixtures.

Figures 10 – 12, present Vsh results for BSH, WAS, and BSL compaction methods, with compliance rates

summarized in Table 6, showing distinct shrinkage behaviors across different energy levels.

Table 6 V_{sh} Compliance Assessment by Compaction Energy

Compaction Energy	Total Runs	Runs Meeting (V _{sh} ≤ 4%)	Compliance Rate
BSH	15	6	60%
BSL	15	5	33.3%
WAS	15	5	33.3%

Six BSH runs met the V_{sh} ≤ 4% criterion namely, (Run 7: 3.2%, Run 27: 3.0%, Run 31: 2.3%, Run 36: 3.8%, Run 39: 3.2%, and Run 43: 3.2%) at 13-18% MC, recording lower shrinkage strains than the control (Run 32: 4.9%). However, nine runs including orders 1, 5, 8, 11, 20, 25, 30, 32 and 38 failed to meet the acceptable volumetric strain V_{sh} ranging from 4.2 to 7.2% at higher moisture (18-23% MC), (Figure.10). Expectedly, mixtures prepared at lower moisture contents (13-18%) yielded acceptable volumetric shrinkage values, while higher moisture (18-23%) led to

excessive shrinkage, highlighting the relationship between moisture content and volumetric stability in compacted soils (Olaolu et al., 2024).

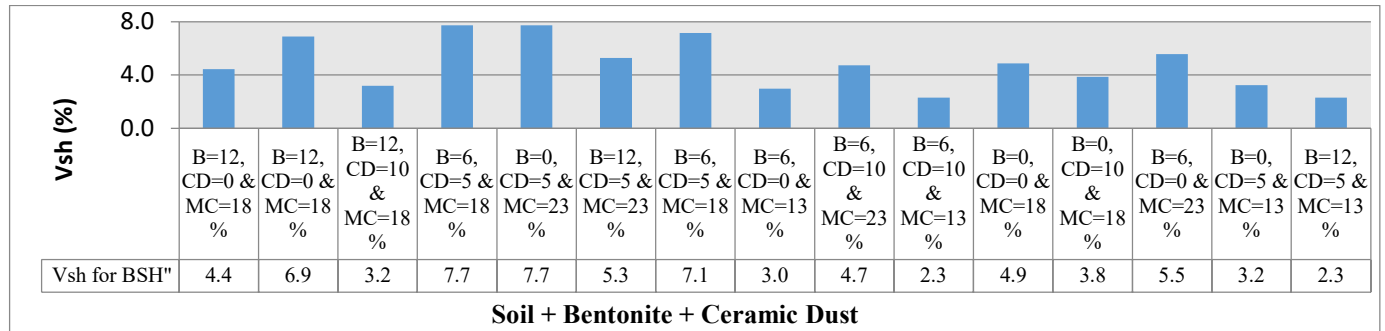


Figure 10: Volumetric shrinkage Results of the Mixture Compacted with BSH Energy

Similarly, Five WAS runs achieved volumetric shrinkage values that comply with regulatory specification ($V_{sh} \leq 4\%$) (Amadi et al., 2024; Amin et al., 2023; Ahmad and Ali, 2023). These include Run 13 (2.8%), 26 (3.3%), 33 (2.8%), 35 (3.0%), and 40 (3.2%) at 13-18% MC, resulting in lower shrinkage strains compared to the control mixture (Run 18: 6.4%). However, ten runs including 2, 4, 12, 15, 18, 19, 37, 41, 42 and 45 with V_{sh} 4.6 – 8.0% at mc range

of 18 – 23% exceeded the specified shrinkage values (Fig. 11). These results confirm the consistent pattern observed in the BSH compaction methods, where lower moisture contents (13-18%) produced acceptable shrinkage characteristics while higher moisture led to excessive shrinkage, reinforcing the critical moisture- V_{sh} relationship in liner material development.

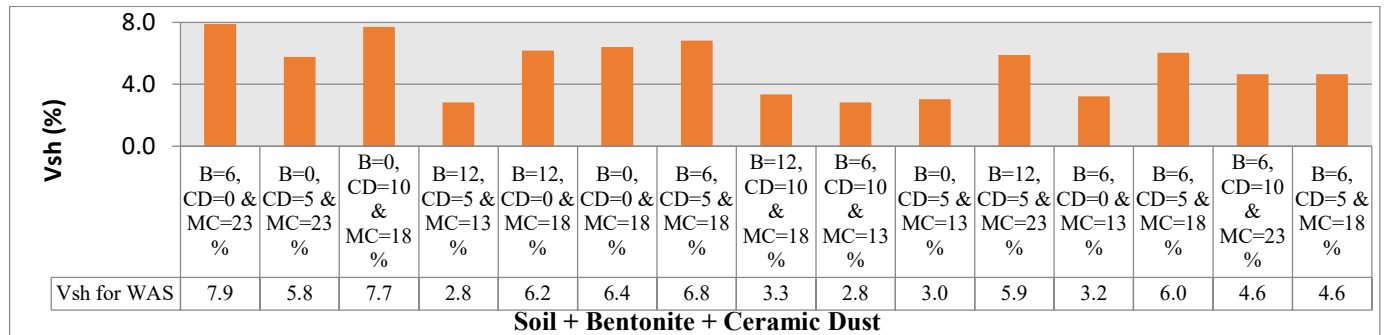


Figure 11 Volumetric shrinkage Results of the Mixtures Compacted with WAS Energy

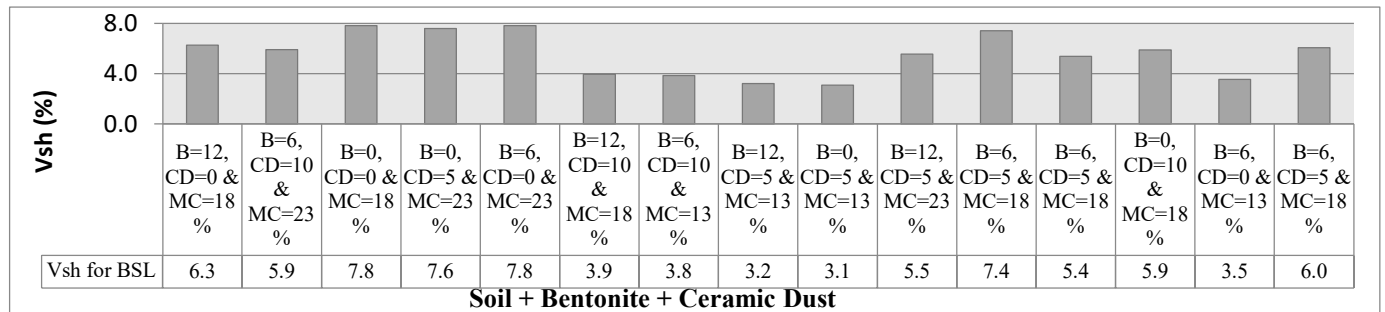


Figure 12 Volumetric shrinkage Results of Mixtures Compacted with BSL Energy

Regarding mixtures compacted with BSL energy, five BSL runs met specification requirement viz (Run 16:3.9%, 17:3.8%, 21:3.2%, 22:3.1%, 34:3.5%) at 13-18% MC range. Similar to WAS compaction, the control mixture yielded V_{sh} in excess of the acceptable value (Run 9: 7.8%). Ten runs Created at mc range of 13 - 23 consisting of orders 3, 6, 9, 10, 14, 23, 24, 28, 29 and 44 failed due to higher volumetric shrinkage strains ($V_{sh} = 5.4 - 8.5\%$) as shown in

Figure 12. The results confirm lower moisture (13-18%) minimizes shrinkage, while higher moisture increases V_{sh} which is consistent across all compaction methods (Amadi et al., 2024). Though BSH demonstrated minimal V_{sh} compared to WAS/BSL, it is important to note that the successful runs occurred at 13-18% moisture. While this moisture condition favored minimal V_{sh} and enhanced

UCS, it is at variance with the MC range (18-23%) that yielded favourable k values as reported in Tables 4.

E. Soil Mixtures and Compaction Conditions that Satisfied Landfill Liner Requirements.

For reference, result of the various parameters for the control specimens of the three compaction methods are presented in Table 7, BSH Compaction method proved most effective in improving the suitability of the soil for use as liner in waste landfills with Run 7 (12%B+10%CD+18%MC) achieving $K=7.9 \times 10^{-10}$ m/s, $V_{sh}=2.7\%$, $UCS=208.1$ kN/m² and Run 36 (0%B+10%CD) yielding ($K=9.1 \times 10^{-10}$ m/s, $V_{sh}=3.5\%$, $UCS=201.1$ kN/m²) both satisfying the standard requirements (Garba et al.,2020) and surpassing the BSH control specimens (Table 8).

Meanwhile WAS yielded only Run 26 (12%B+10%CD) that proved effective in terms of the landfill liner geotechnical criteria recording ($K=9.1 \times 10^{-10}$ m/s, $V_{sh}=3.1\%$, $UCS=202.5$ kN/m²). Lastly, for mixtures compacted with BSL, only the mixture containing 12%B+10%CD (Run 16) met the specified criteria ($K=9.8 \times 10^{-10}$ m/s, $V_{sh}=3.8\%$, $UCS=200.3$ kN/m²), see Table 6. In all the optimum mixtures, the regulatory requirements for three geotechnical criteria namely k, UCS and V_{sh} were simultaneously achieved albeit marginally especially for mixtures compacted with BSL method.

Table 7 Control Run Orders Across Energy Methods

Compaction Energy	Run Order	Mix Composition	K (m/sec)	UCS (kN/m ²)	Vsh (%)
BSH	32	B=0, CD=0 & MC=18%	3.6×10^{-9}	169.5	4.7
WAS	18	B=0, CD=0 & MC=18%	3.8×10^{-9}	121.8	5.9
BSL	9	B=0, CD=0 & MC=18%	2.8×10^{-8}	88.2	7.5

Table 8 Run Orders that Comply with Landfill Liner Requirements for Different Energy Methods

Compaction Energy	Run Order	Mix Composition	K (m/sec)	UCS (kN/m ²)	Vsh (%)
BSH	7	B=12, CD=10 & MC=18%	7.9×10^{-10}	208.1	2.7
	36	B=0, CD=10 & MC=18%	9.1×10^{-10}	201.1	3.5
WAS	26	B=12, CD=10 & MC=18%	9.1×10^{-10}	202.5	3.1
BSL	16	B=12, CD=10 & MC=18%	9.8×10^{-10}	200.3	3.8

F. Optimization of the Study Mixtures for Landfill Liner Requirements

Optimum mixture that meets the key liner requirements which was identified by the optimization procedure contains 2.79% bentonite. The mixture recorded hydraulic conductivity ($K=1 \times 10^{-9}$ m/s) and UCS (213.6 kN/m²) and volumetric shrinkage V_{sh} of 6.61% which slightly exceeded

the $V_{sh} \leq 4\%$ standard (Table 9). Despite this deviation, the composite desirability of 1.0 confirms optimal performance. While the blend excels in permeability and strength, minor adjustments may be needed in order to achieve the acceptable V_{sh} strain.

Table 9 Optimization Results for K, UCS and V_{sh} Criteria

Parameters						
Response	Goal	Lower	Target	Upper	Weight	Importance
K (m/Sec.)	Maximum	0	1.0E-9	1.0E-9	1	1
UCS Kn/m ²	Maximum	27.9559	200	200	1	1
Vsh (%)	Maximum	2.2819	4	4	1	1
Response	Multiple Fit	Response SE Fit	Prediction 95% CI	95% PI		
K (m/Sec.)	0	0	-1.0E-9, 1.0E-9	-1.0E-9, 1.0E-9		
UCS Kn/m ²	213.6	14	(185.2, 242.0)	(118.7, 308.5)		
Vsh (%)	6.612	0.301	(6.001, 7.224)	(4.571, 8.653)		
Solution						
Solution	B (%)	CD (%)	MC (%)	UCS(KN/m2) Fit	K(m/Sec) Fit	Vsh(%) Fit
1	2.79	5	18	213.606	1.0E-9	6.6122

Table 10 Summary of RSM Model Statistics

Response	R ²	Adjusted R ²	Predicted R ²	Model p-value	Lack-of-Fit p-value
K	0.942	0.918	0.885	<0.001	0.124
UCS	0.956	0.935	0.902	<0.001	0.087
Vsh	0.938	0.912	0.879	<0.001	0.146

RSM Model Statistics in Table 10 illustrate Second-order polynomial models fitted to each response variable were validated through ANOVA, which confirmed model significance ($p < 0.05$) for all responses with high coefficients of determination indicating excellent model fit, while non-significant lack-of-fit ($p > 0.05$) and high predicted R² values confirmed adequate model fit without systematic error and strong predictive capability for new observations. ANOVA further revealed significant main effects ($p < 0.05$) for all factors on each response, along with significant two-way interactions including Bentonite \times Moisture Content for K ($p = 0.003$), Ceramic Dust \times Moisture Content for UCS ($p = 0.008$), Bentonite \times Ceramic Dust for Vsh ($p = 0.012$), and Moisture Content \times Compaction Energy for all responses ($p < 0.05$). The significance of these interaction terms confirms that factor effects are interdependent, justifying the use of Response Surface Methodology over one-factor-at-a-time approaches for this optimization study.

IV. CONCLUSION

Choice of material for use as compacted landfill liner is a critical component in the construction of a waste containment facility. The objectives of this study were to evaluate the impact of different compositions of bentonite and CD mixtures on the geotechnical design properties of lateritic soil namely k, UCS and Vsh as well as to determine ideal Combinations of Bentonite and Ceramic Dust required to enhance the soil for use as landfill liner material. The following conclusions were drawn from the investigation. The incorporation of bentonite along with CD significantly improved the design parameters with notable improvements observed in mixtures compacted with BSH efforts. The optimum mixture determined through optimization procedure yield 2.79% bentonite and 5%CD do not produce 100% composite desirability. The mixtures failed to reaches a balance amongst the geotechnical parameters (Vsh $> 4\%$) which minimizes performance and in addition requires careful optimization of mixture proportions and compaction conditions for K, UCS and Vsh.

Mixture selection for field performance and cost-effectiveness for projects requiring guaranteed compliance with all regulatory requirements, the 12% bentonite + 10% ceramic dust mixture compacted at 18% moisture under BSH energy is recommended. Where ceramic dust available in high quantity, 0% bentonite + 10% ceramic dust under BSH compaction offers a viable alternative with slightly lower performance margins, for strict compliance moisture

content should be maintained within $\pm 1\%$ of target, additive proportions within $\pm 0.5\%$, and compaction energy consistently applied.

AUTHOR CONTRIBUTIONS

GARBA, S: Conceptualization, Research Execution - experiments, data collection, Writing original draft. **AMADI, A. A:** Supervision, review & editing. **ADEJUMO, T. E:** Supervision & Optimization. **ABUBAKAR M:** RSM mixture composition design & Supervision.

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