

## Corn Cob Ash-Modified Black Cotton Soil as Liner and Cover Material in Municipal Solid Waste Containment Facilities

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### Abstract

Black cotton soil (BCS) is a widely distributed expansive clay with poor engineering behaviour, characterised by high volume change, susceptibility to cracking and low strength, which renders it unsuitable in its natural state for infrastructure applications. Stabilisation with agro-industrial by-products offers a cost-effective and environmentally sustainable alternative to conventional chemical admixtures. This study evaluates the geotechnical suitability of corn cob ash (CCA)-modified BCS for use as compacted liner and cover material in municipal solid waste containment facilities. The natural BCS and CCA blends (0, 4, 8, 12 and 16% by dry weight) were subjected to classification tests, standard compaction at three energy levels (British Standard Light — BSL; West African Standard — WAS; British Standard Heavy — BSH), unconfined compressive strength (UCS) at four moulding water contents (OMC – 2%, OMC, OMC + 2%, OMC + 4%), volumetric shrinkage strain (VSS), long-term hydraulic conductivity ( $k$ ) permeated with municipal solid waste leachate. All tests followed BS 1377 (1990) and BS 1924 (1990) protocols. The natural BCS was classified as A-7-6 (13) (AASHTO) and CH (USCS). CCA addition reduced plasticity and modified compaction parameters. At 16% CCA compacted with BSH energy and within a moulding water content range of 13.5–15.5%, UCS values exceeded 200 kN/m<sup>2</sup>, VSS values fell below 4%, and hydraulic conductivity remained at or below  $1 \times 10^{-7}$  cm/s satisfying all three liner design thresholds simultaneously. Black cotton soil blended with 16% CCA and compacted with not less than BSH compactive energy fulfils the principal design parameter requirements for use as liner and cover material in municipal waste containment facilities, offering a viable, low-cost, and ecologically responsible construction alternative in regions where CCA is abundantly available.

**KEYWORDS:** Black cotton soil (BCS); Corn cob ash (CCA); Moulding water content (MWC); Optimum moisture content (OMC); Unconfined compressive strength (UCS); Volumetric shrinkage strain (VSS); Waste containment; Hydraulic conductivity.

### 1. INTRODUCTION

Black cotton soils are a well-known category of expansive clays distributed widely across semi-arid tropical and temperate regions where annual evaporation exceeds precipitation (Ikeagwuani et al., 2019). Their characteristic colours range from light grey to dark grey and black, with montmorillonite as the dominant clay mineral (Eberemu et al., 2019). In their dry state, these soils are hard and exhibit relatively high bearing capacity; however, upon wetting,

they swell substantially, and in dry conditions they develop deep and wide desiccation cracks up to 1.5 m deep and 0.9 m wide making them highly problematic for engineering construction (Prasad and Ahalya, 2023; Nigatha and Neduri, 2022).

The engineering limitations of black cotton soil necessitate stabilisation or modification before it can be reliably deployed in critical infrastructure applications. Ground improvement techniques aimed at enhancing shear strength, reducing shrink-swell potential and improving hydraulic properties have been the focus of extensive research. Among these, the incorporation of agro-industrial by-products is gaining increasing prominence on account of their non-toxic character, local availability and cost-saving potential compared with conventional chemical stabilisers such as cement and lime (Oriola et al., 2017; Osinubi and Stephen, 2005).

Nigeria produces approximately 12.7 million metric tonnes of corn annually (FAO, 2022), generating large volumes of corn cob as an agricultural residue. Corn cob ash (CCA), produced by controlled combustion of corn cobs at 550–750 °C for approximately five hours, contains pozzolanic oxides — including SiO<sub>2</sub> (27.87%), K<sub>2</sub>O (27.08%), CaO (12.47%) and Al<sub>2</sub>O<sub>3</sub> (9.09%) — that can engage in cementitious reactions with clay minerals. Prior studies have demonstrated the potential of CCA as a supplementary cementitious material in concrete (Aulakhet et al., 2018; Olafusi et al., 2017; Kamau and Ahmed, 2017). Its incorporation into expansive soils as a combined cementitious and biosorbent admixture therefore merits systematic investigation, particularly in the context of waste containment applications.

The main line of defence against the external migration of methane gas and leachate in a landfill is the liner and cover system (Yaashikaa *et al.*, 2022). A rational approach to the development of a liner system is the use of a performance standard criterion (Tavana *et al.*, 2021). Specific design criteria are developed on a site-specific basis, and a performance standard delineates the anticipated performance of a lining system (Heerten, 2022). Clay was the most prevalent liner material used in landfills until around 1982 (Daramola *et al.*, 2024). A hydraulic conductivity of approximately 10<sup>-9</sup> m/sec or less is indicative of proper clay liners.

Municipal solid waste landfills rely on low-permeability compacted clay liners and cover systems to contain leachate and prevent contamination of surrounding soil and groundwater (Alghamdi et al., 2021; Fan et al., 2022; Kenue et al., 2023). The performance of these liner systems depends on achieving simultaneously: hydraulic conductivity  $k \leq 1 \times 10^{-7}$  cm/s, volumetric shrinkage strain  $VSS \leq 4\%$ , and unconfined compressive strength  $UCS \geq 200$  kN/m<sup>2</sup> (Daniel and Wu, 1993; Tay et al., 2001).

Despite the abundance of both black cotton soil and corn cob ash in northern Nigeria, their combined use as a liner material has not been systematically characterised. This study therefore aims to: (i) determine the index, compaction and strength properties of CCA-modified BCS at incremental treatment levels (0–16% CCA) under three compactive energies; (ii) evaluate volumetric shrinkage behaviour and long-term hydraulic conductivity under simulated leachate permeation; and (iii) assess whether any CCA–BCS combination satisfies all published liner and cover design criteria simultaneously.

## 2. MATERIALS AND METHODS

### 2.1 Materials

#### 2.1.1 Black Cotton Soil (BCS)

Black cotton soil was obtained from a borrow pit at Gamadadi, Maiduguri, Borno State, Nigeria (coordinates: 11.5841° N, 10.3202°E) at a depth exceeding 0.5 m below ground level, to avoid contamination by topsoil and organic matter. Disturbed bulk samples were transported to the Civil Engineering Geotechnical Laboratory of the Nigerian Defence Academy (NDA), Kaduna, for testing and characterisation.

#### 2.1.2 Corn Cob Ash (CCA)

Corn cobs were collected from a plantation in the Maraban Jos area of Kaduna State. They were transported to the incinerator at Yusuf Dan Tsoho Hospital (opposite Kaduna Polytechnic, Tudun Wada, Kaduna) and burnt to ash at a controlled temperature range of 550–750 °C for five hours. The resulting ash was thereafter transported to the NDA Civil Engineering Geotechnical Laboratory for characterisation and use. The specific gravity of the CCA was determined to be 2.05. The oxide compositions of both the BCS and CCA, determined by X-ray fluorescence (XRF) analysis, are presented in Tables 1 and 2, respectively.



**Table 1: Oxide Composition of Black Cotton Soil (BCS)**

Oxide	Concentration (%)
SiO <sub>2</sub>	58.278
V <sub>2</sub> O <sub>5</sub>	0.118
Cr <sub>2</sub> O <sub>3</sub>	0.035
MnO	0.258
Fe <sub>2</sub> O <sub>3</sub>	11.403
CoO	0.045
NiO	0.004
CuO	0.044
Nb <sub>2</sub> O <sub>5</sub>	0.020
SO <sub>3</sub>	0.272
CaO	2.709
K <sub>2</sub> O	3.177
BaO	0.063
Al <sub>2</sub> O <sub>3</sub>	20.268
Ta <sub>2</sub> O <sub>5</sub>	0.019
TiO <sub>2</sub>	2.053
ZnO	0.008
Ag <sub>2</sub> O	0.076
Cl	0.803
ZrO <sub>2</sub>	0.323
PbO	0.022

**Table 2: Oxide Composition of Corn Cob Ash (CCA)**

Oxide	CCA (%)
SiO <sub>2</sub>	27.871
CaO	12.468
Al <sub>2</sub> O <sub>3</sub>	9.093
Fe <sub>2</sub> O <sub>3</sub>	7.386
MgO	1.316
MnO	0.130
K <sub>2</sub> O	27.080
SO <sub>3</sub>	1.333
P <sub>2</sub> O <sub>5</sub>	3.234
TiO <sub>2</sub>	1.186
CuO	0.106



## 2.2 Methods

### 2.2.1 Classification of Soil Sample

Index property tests were conducted in accordance with BS 1377 Part 2 (1990) and BS 1924 (1990). Tests performed on the natural soil included: natural moisture content (NMC), particle size distribution, liquid limit (LL), plastic limit (PL) and specific gravity (Gs). The soil was classified using both the Unified Soil Classification System (USCS; ASTM, 1992) and the American Association of State Highway and Transportation Officials (AASHTO, 1986) system.

### 2.2.2 Compaction Tests

Compaction specimens were prepared and tested in accordance with BS 1377 (1990) and BS 1924 (1990). Three compactive efforts were employed: British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH), applied to both untreated and CCA-treated BCS across treatment levels of 0, 4, 8, 12 and 16% CCA by dry weight.

#### 2.2.2.1 British Standard Light (BSL)

Approximately 2.5 kg of air-dried sample passing the 20 mm BS test sieve was thoroughly mixed with water at 7–16% moisture content and compacted into a standard 1000 cm<sup>3</sup> mould in three equal layers, each receiving 27 blows from a 2.5 kg rammer dropping freely through 300 mm. The collar was removed, the specimen trimmed level, and the weight of the mould and compacted soil recorded. A representative sub-sample was taken for moisture content determination, and the remainder broken down, rewetted and recompactd at incrementally higher moisture contents. This sequence was repeated at a minimum of four moisture contents bracketing the optimum, enabling determination of the maximum dry density (MDD) and optimum moisture content (OMC).

#### 2.2.2.2 British Standard Heavy (BSH)

BSH compaction employed a 4.5 kg rammer dropping freely through 450 mm to compact the specimen in five equal layers within a 1000 cm<sup>3</sup> mould, with 27 blows per layer. All other procedural steps were identical to those of the BSL test.

#### 2.2.2.3 West African Standard (WAS)

The WAS compactive effort uses the same rammer mass (4.5 kg) and drop height (450 mm) as BSH but reduces the number of blows per layer to 10, resulting in an intermediate compactive energy. All other procedural steps were identical to those of the BSH test.

### 2.2.3 Unconfined Compressive Strength (UCS)

Unconfined compressive strength tests were conducted in accordance with BS 1377 (1990) on natural and CCA-treated BCS specimens (0, 4, 8, 12 and 16% CCA) compacted at BSL, WAS and BSH energy levels. Specimens were compacted into 1000 cm<sup>3</sup> moulds at OMC and then extruded and trimmed to dimensions of 38.1 mm diameter and 76.2 mm length. For each compactive effort and CCA level, duplicate specimens were prepared at four moulding water contents: OMC – 2%, OMC, OMC + 2% and OMC + 4%. Compacted specimens were cured for 48 hours in sealed, desiccation-protective plastic bags prior to testing. During testing, specimens were loaded axially at a constant strain rate of 0.10 mm/min using a compression apparatus, with simultaneous recording of axial force and deformation at regular intervals until failure. UCS was taken as the deviator stress at the peak of the stress–strain curve.

### 2.2.4 Volumetric Shrinkage Strain (VSS)

Volumetric shrinkage upon desiccation was evaluated using cylindrical specimens extruded directly from the compaction mould (a total of 60 specimens: 20 per energy level across BSL, WAS and BSH). For each energy level and each CCA content (0, 4, 8, 12 and 16%), one specimen was prepared at each of the four moulding water contents (OMC – 2%, OMC, OMC + 2%, OMC + 4%), yielding four specimens per CCA level per energy level. Extruded specimens were placed on a laboratory bench and allowed to dry under ambient conditions. Measurements of mass, diameter and height were recorded at five-day intervals from Day 1 to Day 30, enabling computation of volumetric shrinkage as a function of drying duration and CCA content.

## 3. RESULTS AND DISCUSSION

### 3.1 Index Properties

The index properties of the natural BCS are summarised in Table 3. The soil has a liquid limit of 47%, a plastic limit of 28.39% and a plasticity index of 18.61%, placing it in the high-plasticity clay (CH) category of the USCS (ASTM, 1992) and the A-7-6 (13) group of the AASHTO (1986) classification system. The fines content of 78.85% and the dominant clay mineral (montmorillonite) are consistent with the expansive character of black cotton soils reported widely in the Nigerian literature (Eberemu et al., 2019; Osinubi, 1999).



**Table 3: Index Properties of the Natural Black Cotton Soil (BCS)**

Property	Value
Natural Moisture Content (%)	18.7
Percentage Passing No. 200 Sieve (%)	78.85
Liquid Limit (%)	47.00
Plastic Limit (%)	28.39
Plasticity Index (%)	18.61
Specific Gravity (Gs)	2.47
AASHTO Classification	A-7-6 (13)
USCS Classification	CH (High-plasticity Clay)
Maximum Dry Density — BSL (g/cm <sup>3</sup> )	1.68
Maximum Dry Density — WAS (g/cm <sup>3</sup> )	1.74
Maximum Dry Density — BSH (g/cm <sup>3</sup> )	1.80
Optimum Moisture Content — BSL (%)	18.41
Optimum Moisture Content — WAS (%)	17.28
Optimum Moisture Content — BSH (%)	16.26
Dominant Colour	Greyish Black
Dominant Clay Mineral	Montmorillonite

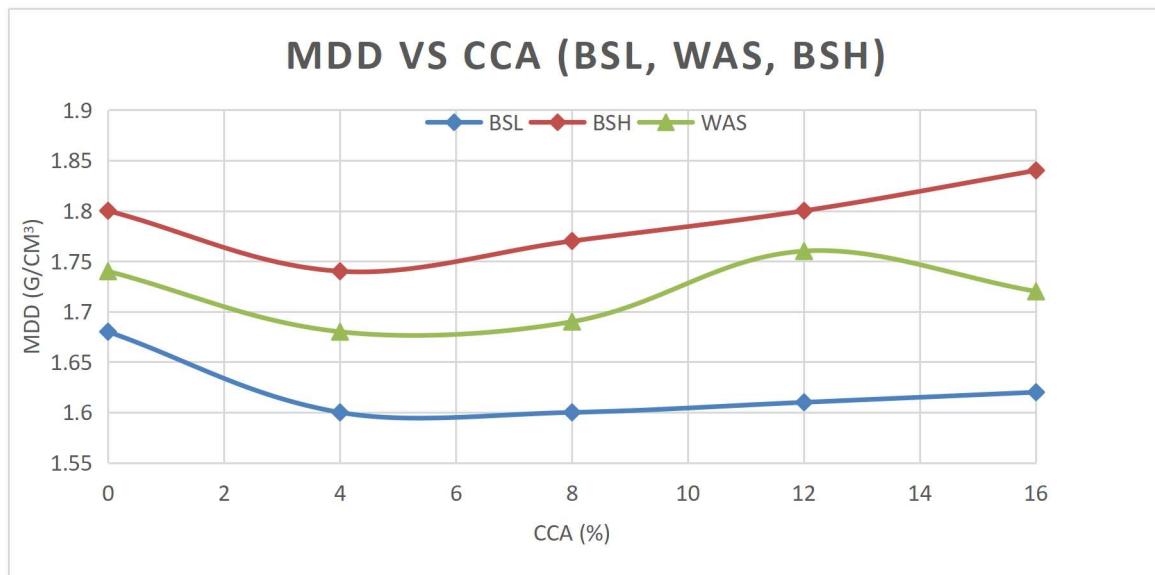
### 3.2 Compaction Characteristics

#### 3.2.1 Maximum Dry Density (MDD)

The variation of MDD with CCA content under the three compactive efforts is presented in Fig. 1. Under BSL compaction, MDD decreased from 1.68 g/cm<sup>3</sup> at 0% CCA to a minimum of 1.60 g/cm<sup>3</sup> at 8% CCA before recovering to 1.62 g/cm<sup>3</sup> at 16% CCA. The initial reduction is attributed to the relatively low calcium content of CCA, which limits early cementitious reaction and results in a less workable matrix at lower additive levels.

Under WAS compaction, MDD decreased from 1.74 g/cm<sup>3</sup> (0% CCA) to 1.69 g/cm<sup>3</sup> at 8% CCA before recovering to a peak of 1.76 g/cm<sup>3</sup> at 12% CCA. Similarly, under BSH compaction, MDD decreased from 1.80 g/cm<sup>3</sup> (0% CCA) to 1.77 g/cm<sup>3</sup> at 8% CCA before rising to a peak of 1.84 g/cm<sup>3</sup> at 16% CCA. The reduction in MDD at intermediate CCA concentrations is attributable to the occupation of void space by the lower-density CCA particles and the associated flocculation and agglomeration of clay particles induced by cation exchange reactions (Etim et al., 2018). The subsequent recovery at higher CCA contents reflects the increased pozzolanic reaction products that densify the soil matrix.



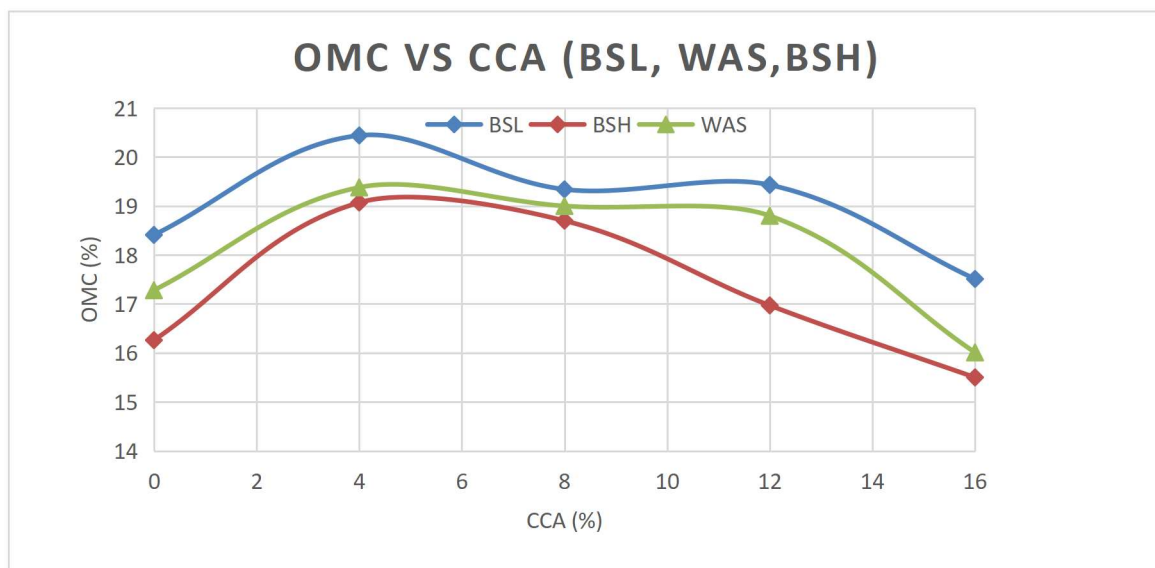


**Fig. 1: Variation of maximum dry density (MDD) of CCA-modified BCS with CCA content for BSL, WAS and BSH compactive efforts.**

**3.2.2 Optimum Moisture Content (OMC)**

The variation of OMC with CCA content is shown in Fig. 3.2. For all three compactive efforts, OMC increased from the natural state to a peak at 4% CCA before declining with further CCA addition. Specifically, OMC increased from 18.41% (natural) to 20.44% at 4% CCA and subsequently decreased to 17.51% at 16% CCA for BSL; from 17.28% to 19.38% at 4% CCA then to 16.01% at 16% CCA for WAS; and from 16.26% to 19.07% at 4% CCA then to 15.50% at 16% CCA for BSH.

The initial increase in OMC with CCA content is consistent with findings reported by Akinmade (2008) and Ochepe (2008) for similar agro-industrial stabilisers in black cotton soils. The additional water demand is attributed to two concurrent processes: (i) greater water requirement for dissociation of the CCA, releasing Ca<sup>2+</sup> and OH<sup>-</sup> ions necessary for cation exchange reactions; and (ii) increased total surface area associated with the higher additive content, requiring more water to lubricate the soil-CCA matrix. The subsequent decline in OMC at higher CCA contents reflects the progressive densification and reduction in inter-particle voids. The consistent reduction in OMC with increasing compactive effort is consistent with Osinubi (1999), who observed that higher energy more effectively breaks down flocculated aggregates, destroys shear planes and closes large pores.



**Fig. 2: Variation of optimum moisture content (OMC) of CCA-modified BCS with CCA content for BSL, WAS and BSH compactive efforts.**

### 3.3 Unconfined Compressive Strength (UCS)

The design requirement for compacted soil liners and cover systems is  $UCS \geq 200 \text{ kN/m}^2$  (Daniel and Wu, 1993). The relevant design limits are presented in Table 4. UCS results for BSL, WAS and BSH compactive efforts are shown in Figs 3, 4 and 5, respectively.

**Table 4: Liner and Cover Material Design Parameter Limits**

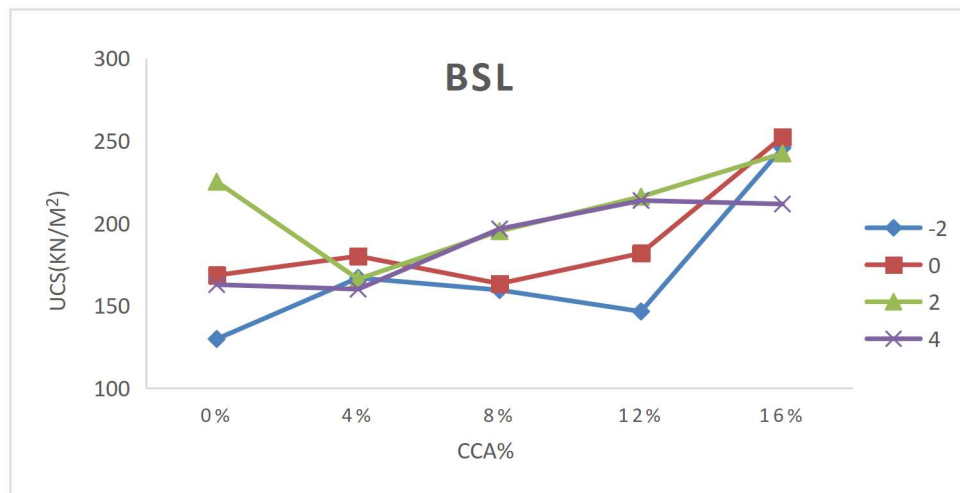
Parameter	Design Limit
Hydraulic Conductivity, k	$\leq 1.0 \times 10^{-7} \text{ cm/s}$
Volumetric Shrinkage Strain (VSS)	$\leq 4\%$
Unconfined Compressive Strength (UCS)	$\geq 200 \text{ kN/m}^2$

Under BSL compaction, UCS generally increased with CCA addition from 0 to 16% across all four moulding water contents, with the exception of a slight reduction at 16% CCA for OMC + 4% moulding water content. The minimum UCS recorded was 129.59 kN/m<sup>2</sup> (0% CCA, OMC - 2%) and the maximum was 252.40 kN/m<sup>2</sup> (16% CCA, OMC). Although the minimum value falls below the 200 kN/m<sup>2</sup> threshold, specimens prepared at or above OMC at 16% CCA exceeded the design limit, suggesting that appropriate moisture control during compaction is critical when using BSL energy.

Under WAS compaction, UCS values increased from 0 to 8% CCA for specimens at OMC - 2%, OMC and OMC + 4% moulding water contents, before declining at 12–16% CCA. For the OMC + 2% specimens, the peak was observed at 12% CCA. The minimum and maximum UCS values for WAS were 187.86 kN/m<sup>2</sup> (8% CCA, OMC - 2%) and 299.43 kN/m<sup>2</sup> (8% CCA, OMC), respectively.

Under BSH compaction, UCS values at OMC - 2% and OMC + 2% decreased from 0 to 4% CCA before recovering to peak values at 8% CCA, then declining again at 12–16% CCA. The minimum and maximum UCS for BSH were 245.19 kN/m<sup>2</sup> (16% CCA, OMC - 2%) and 337.71 kN/m<sup>2</sup> (8% CCA, OMC + 2%), respectively. Importantly, all BSH specimens at 16% CCA exceeded 200 kN/m<sup>2</sup>, indicating consistent fulfilment of the strength criterion at the highest treatment level under BSH energy.

The general improvement in UCS with CCA addition is attributed to internal geochemical alteration, modification of the diffuse double-layer ionic concentration, and consequent rearrangement of the soil particle fabric following stabilisation. These mechanisms are well established for clay soils treated with alkaline pozzolanic admixtures (Daniel and Wu, 1993).



**Fig. 3: Variation of UCS with CCA content at four moulding water contents — BSL compactive effort.**



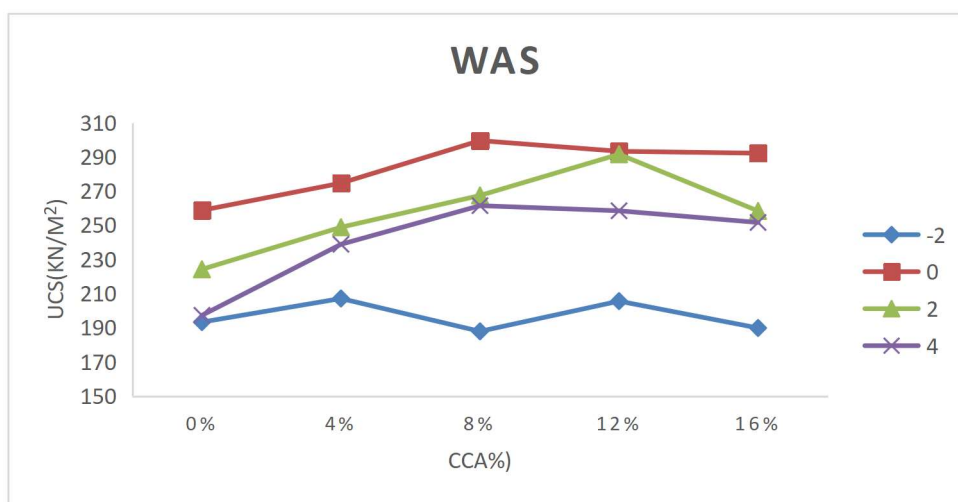


Fig. 4: Variation of UCS with CCA content at four moulding water contents — WAS compactive effort.

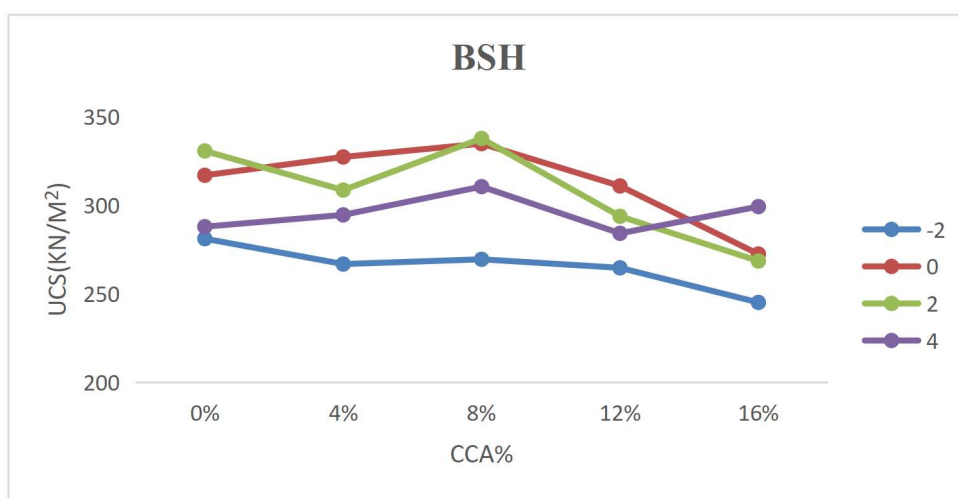


Fig. 5: Variation of UCS with CCA content at four moulding water contents — BSH compactive effort.

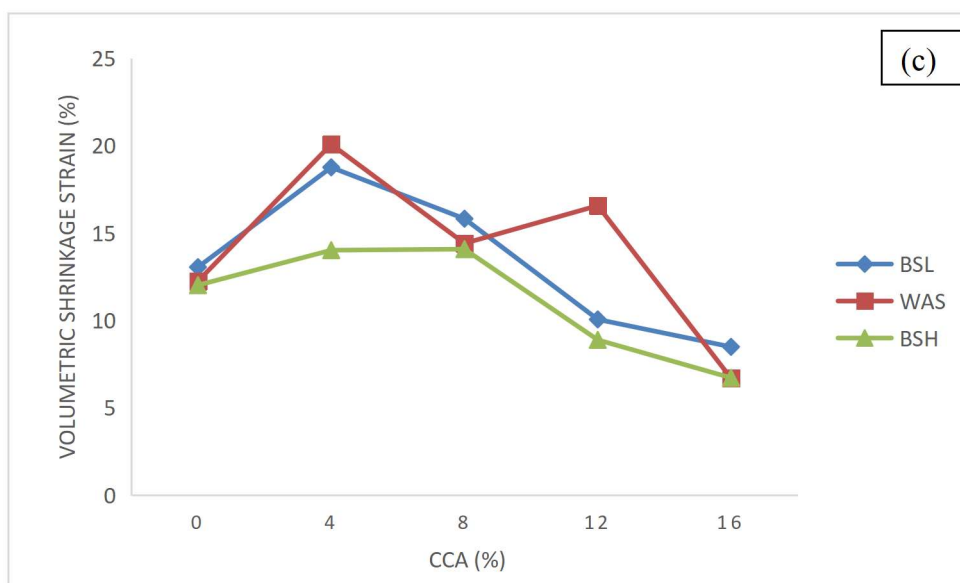
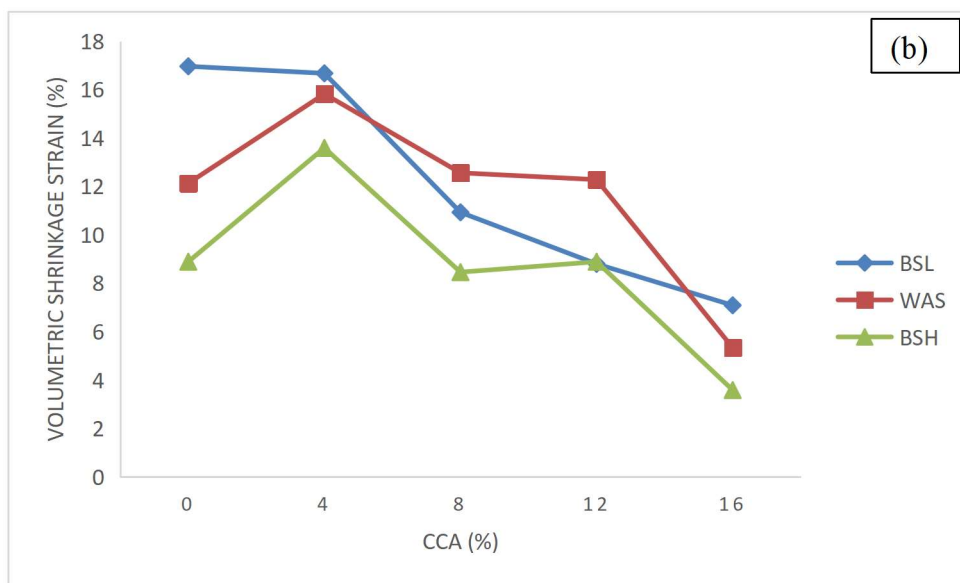
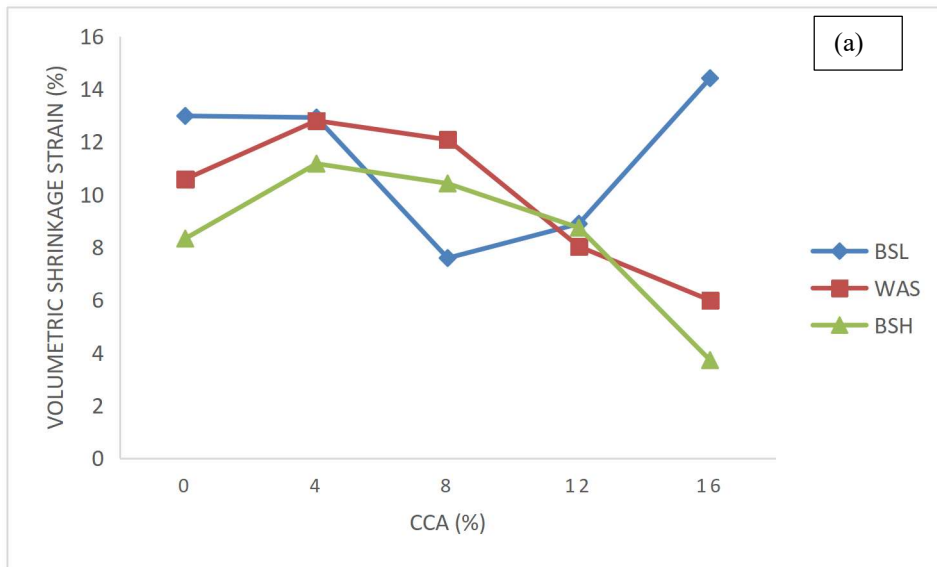
### 3.4 Volumetric Shrinkage Strain (VSS)

#### 3.4.1 Effect of CCA Content on VSS

The variation of VSS with CCA content at the four moulding water contents, compacted using BSL, WAS and BSH energies, is presented in Figs 6(a)–(d). In general, VSS decreased with increasing CCA content from 0 to 16% for all compactive efforts, with the exception of a localised increase at 4% CCA. This transient increase is attributed to the elevated OMC at 4% CCA treatment, which results in a greater initial water content and, consequently, a larger volume of pore water available to be expelled during desiccation — leading to higher shrinkage. At 16% CCA, the lowest VSS values were consistently recorded across all compactive efforts and moulding water contents.

The permissible VSS limit of less than 4% for hydraulic structures (Tay et al., 2001) was achieved only in specimens compacted at OMC – 2% and OMC under BSH compactive effort at 16% CCA. All other combinations of CCA content, compactive effort and moulding water content yielded VSS values exceeding 4%, confirming that simultaneous satisfaction of the strength and shrinkage criteria requires the combined use of the highest CCA content and highest compactive energy.





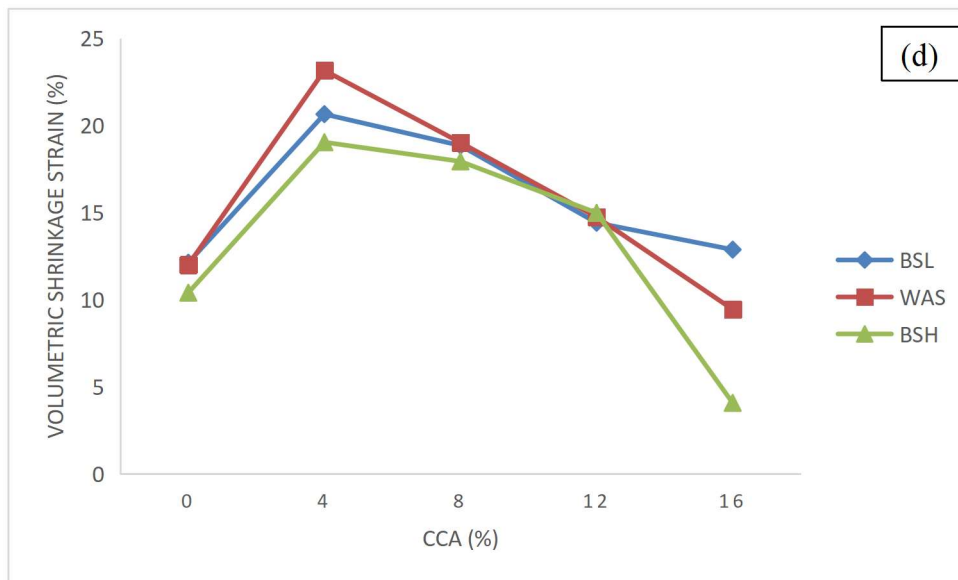
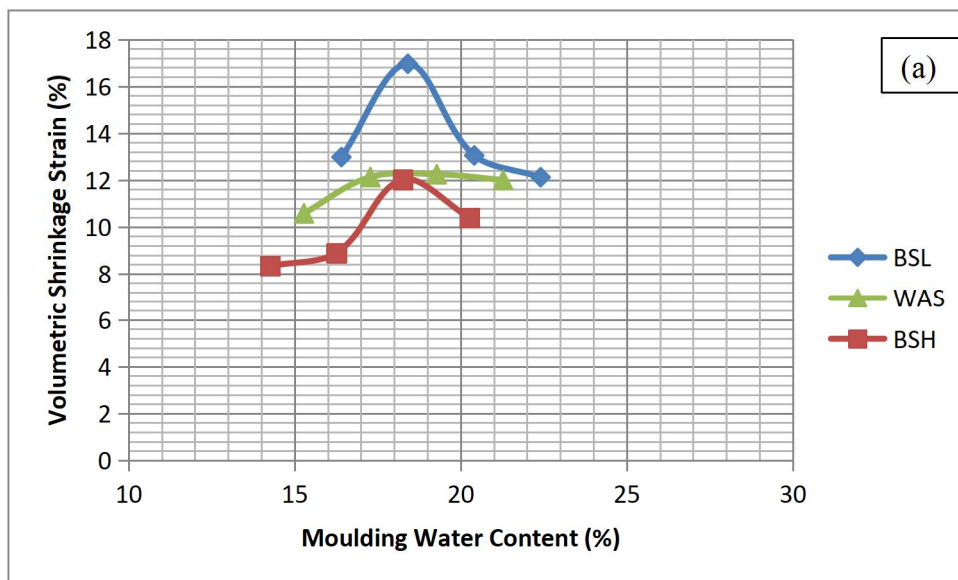
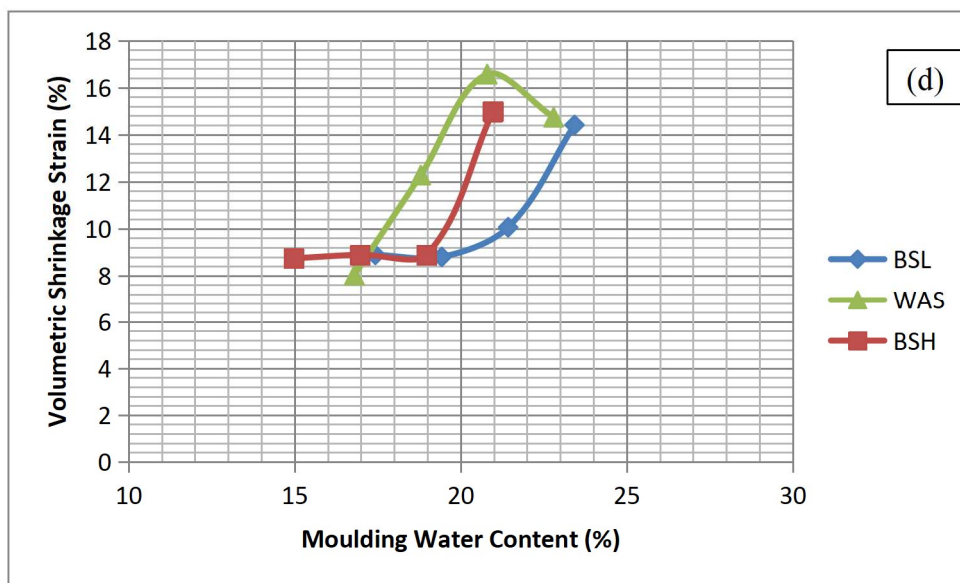
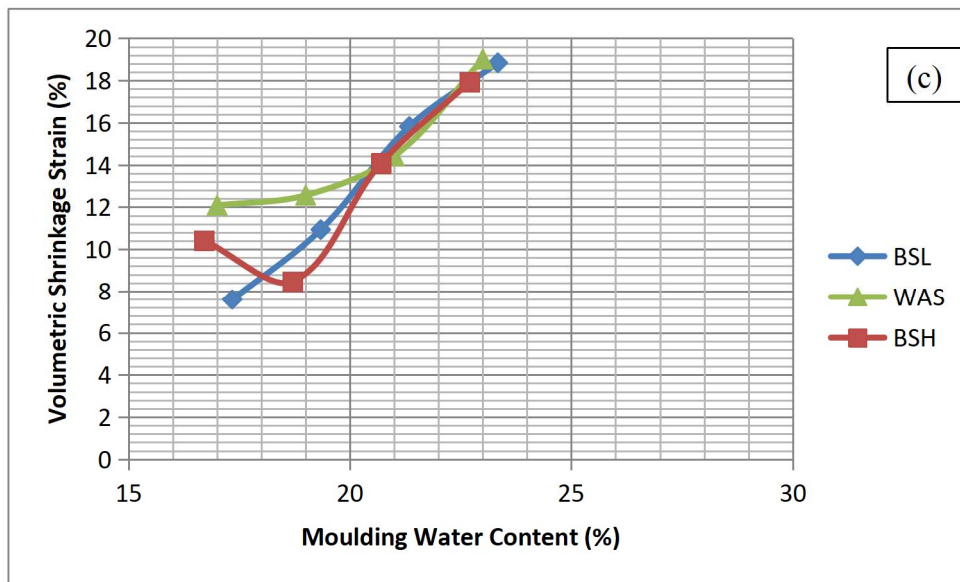
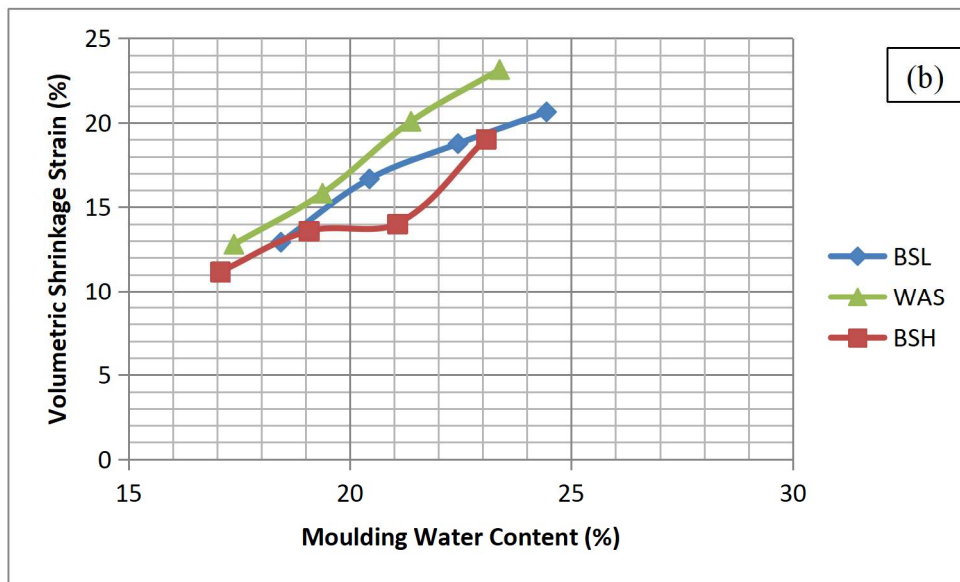


Fig. 6(a-d): Variation of VSS with CCA content at (a) OMC – 2%, (b) OMC, (c) OMC + 2% and (d) OMC + 4%.

3.4.2 Effect of Moulding Water Content on VSS

The variation of VSS with moulding water content for natural BCS and CCA-treated specimens (0, 4, 8, 12 and 16% CCA) at all compactive efforts is illustrated in Figs 7(a)–(e). VSS generally increased with moulding water content, with a slight reduction observed at the highest moulding water content for both natural and treated soils. This behaviour is consistent with the observations of Daniel and Wu (1993) and Albrecht and Benson (2001): specimens compacted at higher moulding water contents contain more pore water, which generates stronger capillary menisci upon drying, driving greater volumetric contraction as water is expelled. The specimens at 16% CCA compacted with BSH energy at OMC – 2% and OMC achieved VSS values below the 4% threshold, confirming that both the treatment level and compactive energy must be simultaneously optimised to satisfy the VSS design criterion.





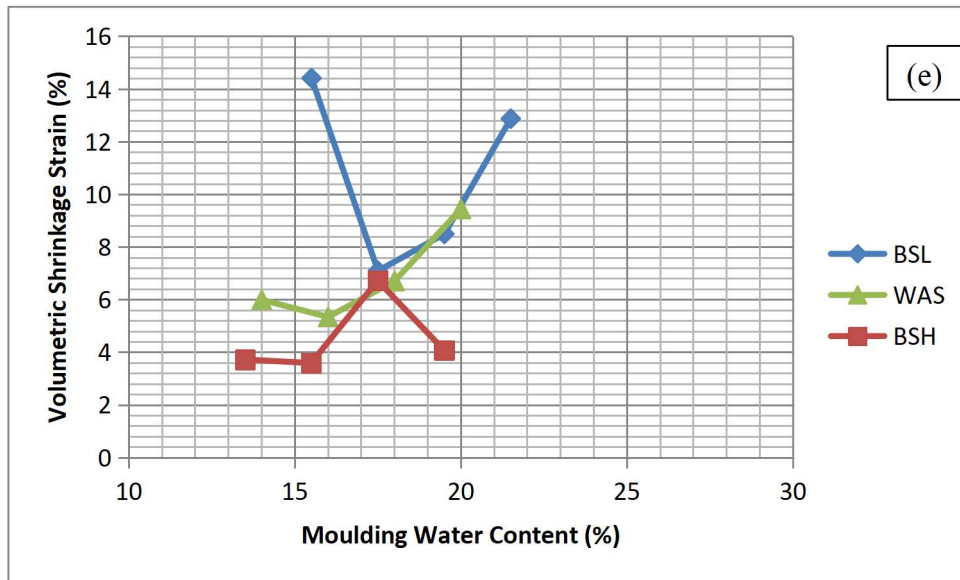


Fig. 7(a–e): Variation of VSS with moulding water content for (a) 0%, (b) 4%, (c) 8%, (d) 12% and (e) 16% CCA.

### 3.5 Hydraulic Conductivity (k)

#### 3.5.1 Long-Term Hydraulic Conductivity under Leachate Permeation

The variation of hydraulic conductivity with permeation time under municipal solid waste leachate is presented in Fig. 8. For the natural BCS, the initial hydraulic conductivity was  $8.40 \times 10^{-10}$  cm/s, which increased to  $2.29 \times 10^{-8}$  cm/s at the end of the permeation period — an increase by a factor of approximately 27. This increase reflects the chemical interaction between the leachate and the clay fabric, which disrupts the diffuse double layer and promotes particle deflocculation.

For CCA-treated specimens, the initial hydraulic conductivity values were  $8.38 \times 10^{-10}$ ,  $1.08 \times 10^{-9}$ ,  $1.89 \times 10^{-9}$  and  $3.16 \times 10^{-9}$  cm/s for 4, 8, 12 and 16% CCA, respectively. At the end of permeation, these increased to  $1.37 \times 10^{-8}$ ,  $3.51 \times 10^{-8}$ ,  $7.84 \times 10^{-8}$  and  $2.09 \times 10^{-8}$  cm/s, representing multiplication factors of 16.35, 325, 414.81 and 66.14 for 4, 8, 12 and 16% CCA, respectively. All final hydraulic conductivity values remained below the design threshold of  $1 \times 10^{-7}$  cm/s, with the sole exception of the 41-day value at 16% CCA ( $1.29 \times 10^{-7}$  cm/s), which was marginally above the threshold. These findings are consistent with published results for similar agro-industrial stabilised soil liners (Oluremi, 2015; Osim, 2017).

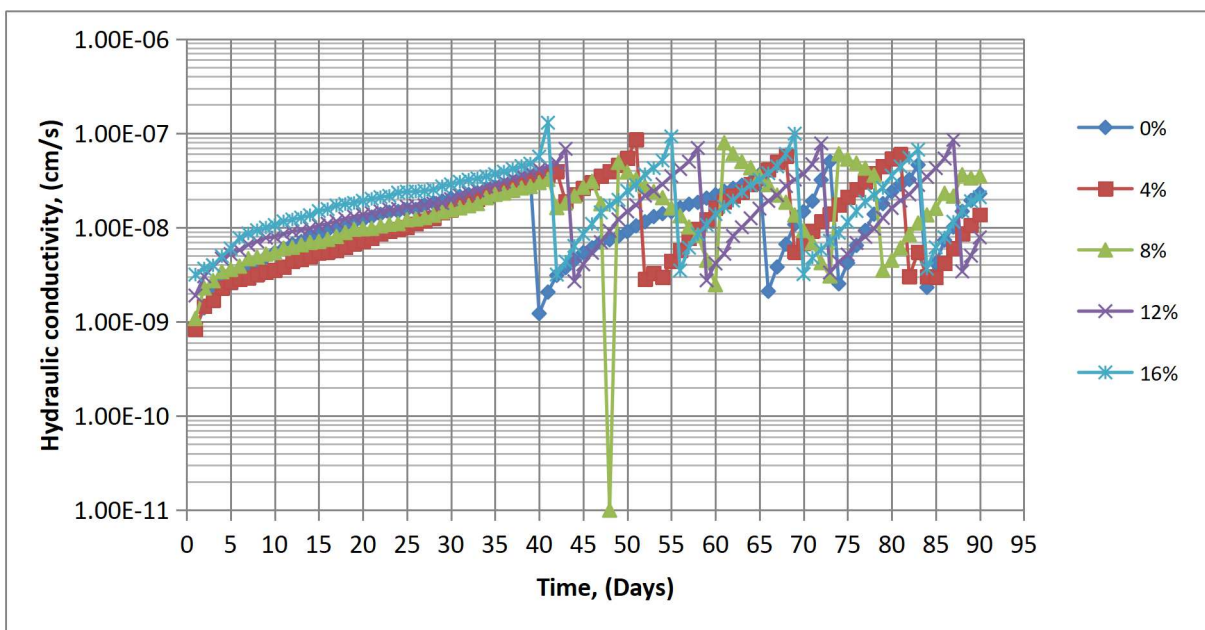


Fig. 8: Variation of hydraulic conductivity of BCS–CCA blends with permeation time (leachate permeation).



#### 4. CONCLUSION

This study investigated the geotechnical performance of corn cob ash (CCA)-modified black cotton soil (BCS) as liner and cover material for municipal solid waste containment facilities. The following conclusions are drawn from the experimental results:

1. The natural black cotton soil was classified as A-7-6 (13) under the AASHTO (1986) system and as CH (high-plasticity clay) under the USCS (ASTM, 1992), confirming its expansive nature and the need for stabilisation prior to use in waste containment applications.
2. CCA addition reduced the liquid limit and plasticity index of BCS, indicating modification of the clay–water interaction through cation exchange. The MDD initially decreased at intermediate CCA contents — reaching minimum values of 1.60, 1.68 and 1.74 Mg/m<sup>3</sup> at 4% CCA for BSL, WAS and BSH, respectively — before recovering at higher CCA contents. The OMC exhibited a corresponding initial increase to peak values at 4% CCA (20.44%, 19.38% and 19.07% for BSL, WAS and BSH, respectively), thereafter declining with additional CCA content.
3. UCS results demonstrated progressive strength improvement with CCA addition. The minimum UCS values across the three compactive efforts were 129.59 kN/m<sup>2</sup> (BSL, 0% CCA, OMC – 2%), 187.86 kN/m<sup>2</sup> (WAS, 8% CCA, OMC – 2%) and 245.19 kN/m<sup>2</sup> (BSH, 16% CCA, OMC – 2%), while the corresponding maxima were 252.40 kN/m<sup>2</sup> (BSL, 16% CCA, OMC), 299.43 kN/m<sup>2</sup> (WAS, 8% CCA, OMC) and 337.71 kN/m<sup>2</sup> (BSH, 8% CCA, OMC + 2%). The design threshold of UCS  $\geq$  200 kN/m<sup>2</sup> was met by all BSH specimens at 16% CCA irrespective of moulding water content.
4. The VSS criterion ( $<$  4%) was satisfied exclusively by specimens prepared at 16% CCA, compacted with BSH energy, at moulding water contents of OMC – 2% and OMC. All other CCA–energy–moisture combinations yielded VSS values exceeding the permissible limit.
5. Long-term hydraulic conductivity under leachate permeation remained at or below  $1 \times 10^{-7}$  cm/s for all CCA treatment levels except for one data point (41 days, 16% CCA, marginally above threshold), indicating satisfactory hydraulic barrier performance consistent with published results for similar stabilised soil liner systems.
6. Overall, black cotton soil modified with 16% CCA and compacted using not less than British Standard Heavy (BSH) compactive energy, at a moulding water content between 13.5% and 15.5%, simultaneously satisfies the UCS, VSS and hydraulic conductivity requirements for liner and cover material in municipal waste containment facilities. CCA represents a viable, low-cost and locally available agro-industrial stabiliser for expansive soils in northern Nigeria and similar semi-arid regions.

#### REFERENCES

- AASHTO (1986). Standard Specifications for Transport Materials and Methods of Sampling and Testing (14th ed.). American Association of State Highway and Transportation Officials, Washington, D.C.
- Akinmade, O. B. (2008). The Effects of Locust Bean Waste Ash on the Geotechnical Properties of Black Cotton Soil. Unpublished M.Sc. Thesis, Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria.
- Albrecht, B. A., and Benson, C. H. (2001). Effect of desiccation on compacted natural clays. *Journal of Geotechnical and Geoenvironmental Engineering*, 127(1), 67–75.
- Alghamdi, A. G., Aly, A. A., and Ibrahim, H. M. (2021). Assessing the environmental impacts of municipal solid waste landfill leachate on groundwater and soil contamination in western Saudi Arabia. *Arabian Journal of Geosciences*, 14(5), 350.
- Amadi, A.A. (2008). Hydraulic and Contaminant Transport Performance of Compacted Lateritic Soil– Bentonite Mixtures Proposed as Waste Containment Barrier. Unpublished Ph.D Thesis. Department of Civil Engineering, Ahmadu Bello University Zaria.
- ASTM (1992). Annual Book of Standards, Vol. 04.08. American Society for Testing and Materials, Philadelphia, PA.
- Aulakhet, D. S., Singh, J., and Kumar, S. (2018). The effect of utilising rice husk ash on some properties of concrete — a review. *Current World Environment*, 13(2), 224–231.
- BS 1377 (1990). Methods of Testing Soils for Civil Engineering Purposes. British Standards Institution, London.
- BS 1924 (1990). Methods of Tests for Stabilised Soils. British Standards Institution, London.
- Cotton, T. E., Davis, M. M., and Shackelford, C. D. (1998). Effects of test duration and specimen length on diffusion testing of unconfined specimens. *Geotechnical Testing Journal*, 21(2), 78–94.
- Daniel, D. E., and Wu, Y. K. (1993). Compacted clay liners and covers for arid sites. *Journal of Geotechnical Engineering*, 119(2), 223–237.
- Daramola, S. O., Hingston, E. D. C., and Demlie, M. (2024). A review of lateritic soils and their use as landfill



- liners. *Environmental Earth Sciences*, 83(3), 118.
- Eberemu, A.O. (2008). Evaluation of bagasse ash treated lateritic soil as a suitable material for waste landfill barrier. Unpublished Ph.D dissertation. Department of civil Engineering Ahmadu Bello University, Zaria.
- Eberemu, A. O., Osinubi, K. J., Ijimdiya, T. S., and Sani, J. E. (2019). Cement kiln dust–locust bean waste ash blend stabilisation of tropical black clay for road construction. *Geotechnical and Geological Engineering*, 37, 3455–3470.
- Etim, R. K., Attah, I. C., Yohanna, P., and Eshiet, S. J. (2018). Effect of periwinkle shell ash on the geotechnical properties of compacted lateritic soil for use as a road construction material. In: Book of Abstracts, 1st International Conference, Faculty of Engineering, University of Nigeria, Nsukka, p. 99.
- Fan, X., Xu, H., Jin, G., Lv, Y., Wu, S., and Wu, T. (2022). Regional differences in the influence of intermediate cover permeability on perched leachate in landfills. *Urban Climate*, 42, 101094.
- Food and Agriculture Organization of the United Nations (FAO) (2022). FAOSTAT — Crop Production Data. Retrieved from: <http://www.fao.org/faostat>
- Heerten, G. (2022). Geosynthetic clay liner performance in geotechnical applications. In *Clay geosynthetic barriers* (pp. 3-19). CRC Press.
- Ijimdiya, T.S. (2010). Evaluation of Bagasse Ash Treated Black Cotton Soil as Hydraulic Barrier in Waste Containment System. Unpublished PhD dissertation. Department of Civil Engineering, Ahmadu Bello University, Zaria.
- Ijimdiya, T.S. and Osinubi, K. J. (2011) “.Attenuative Capacity of Compacted Black Cotton Soil treated with Bagasse Ash.” *Electronic Journal of Geotechnical Engineering*, Vol. 16, Bund. D, 419-429. Illuri, H. K. and Nataatmadja, A. (2007) Reduction of Shrink-swell potential with EPS inclusion. In Ameratunga, Jay and Taylor, Brett and Patten, Mathew, Eds, Proceedings 10<sup>th</sup> Australia New Zealand Conference on Geomechanics 2007: Common Ground, Page pp. 90-95, Brisbane.
- Ikeagwuani, C. C., Obeta, I. N., and Agunwamba, J. C. (2019). Stabilisation of black cotton soil subgrade using sawdust ash and lime. *Soils and Foundations*, 59(1), 162–175. <https://doi.org/10.1016/j.sandf.2018.10.004>
- Kamau, J., and Ahmed, A. (2017). A review of the use of corncob ash as a supplementary cementitious material. *European Journal of Engineering Research and Science*, 2(8), 1–6.
- Kenue, A. W., Sana, E., Adhikary, A., Pal, S., and Hussain, M. (2023). Assessment of landfill leachate and its surface and subsurface migration: experimental and numerical investigations. *Journal of Hazardous, Toxic, and Radioactive Waste*, 27(4), 05023003.
- Moses, G., & Afolayan, J.O. (2011). Compacted foundry sand treated with cement kiln dust as hydraulic barrier material. *Electronic Journal of Geotechnical Engineering*, 16(Bund. A), 337-355.
- Moses, G. (2012). Hydraulic and Contaminant Transport Performance of Compacted Bagasse Ash Treated Foundry Sand for Use in Waste Containment Facility An Unpublished PhD dissertation presented to the Postgraduate School, Ahmadu Bello University, Zaria.
- Nigatha, D., and Neduri, P. (2022). Efficiency of cement and lime in stabilising black cotton soil. *Materials Today: Proceedings*, 68(5), 1588–1593.
- Ochepo, J. (2008). The Effect of Elapsed Time on the Geotechnical Properties of Black Cotton Soils Stabilised with Lime–Bagasse Ash Admixture. Unpublished M.Sc. Thesis, Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria.
- Olafusi, O. S., Adewuyi, A. P., Sadiq, O. M., Adisa, A. F., and Abiola, O. S. (2017). Rheological and mechanical characteristics of self-compacting concrete containing corncob ash. *Journal of Engineering Research*, 22(1), 72–85.
- Oluremi, J. R. (2015). Evaluation of Waste Wood Ash-Treated Lateritic Soil for Use in Municipal Solid Waste Containment Application. Unpublished Ph.D. Thesis, Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria.
- Oriola, F. O. P., Moses, G., and Sani, J. E. (2017). Stabilisation of lateritic soil with cement kiln dust for road pavement base material based on defined curing temperature conditions. *Indian Journal of Engineering*, 14(37), 219–228.
- Osim, A. R. (2017). Compacted Cement Kiln Dust-Treated Black Cotton Soil as Suitable Liner and Cover Material in Waste Containment Facilities. Unpublished Ph.D. Dissertation, Ahmadu Bello University, Zaria, Nigeria.
- Osinubi, K. J. (1999). Evaluation of admixture stabilisation of Nigerian black cotton soil. *Nigerian Society of Engineers Technical Transactions*, 34(3), 88–96.
- Osinubi, K. J., and Stephen, T. A. (2005). Economic utilisation of an agro-industrial waste — bagasse ash. In: Proceedings of the 4th Nigerian Materials Congress (NIMACON 2005), Zaria, Nigeria, 17–19 November, pp. 36–40.



- Prasad, K. S. R., and Ahalya, A. (2023). Stabilisation of black cotton soil with waste plastic and admixtures. IOP Conference Series: Earth and Environmental Science, 1130, Article 012040.
- Shackelford, C. D. (1989). Diffusion of contaminants through waste containment barriers. Transportation Research Record, 1219, 169–182. Transportation Research Board, National Research Council, Washington, D.C.
- Shackelford, C. D., and Daniel, D. E. (1991). Diffusion in saturated soil. II: Results for compacted clay. Journal of Geotechnical Engineering, ASCE, 117(3), 485–506.
- Tavana, M., Mousavi, H., Nasr, A. K., and Mina, H. (2021). A fuzzy weighted influence non-linear gauge system with application to advanced technology assessment at NASA. *Expert Systems with Applications*, 182, 115274.
- Tay, Y. Y., Stewart, D. I., and Cousens, T. W. (2001). Shrinkage and desiccation cracking in bentonite–sand landfill liners. *Engineering Geology*, 60(1–4), 263–274.
- Yaashikaa, P. R., Kumar, P. S., Nhung, T. C., Hemavathy, R. V., Jawahar, M. J., Neshanthini, J. P., and Rangasamy, G. (2022). A review on landfill system for municipal solid wastes: Insight into leachate, gas emissions, environmental and economic analysis. *Chemosphere*, 309, 136627.

