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Investigation Into the Effect of Admixed Cement and Rice Husk Ash on Hydraulic Conductivity, Shrinkage and Strength Properties of Black Cotton Soil

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Abstract

Black cotton soil (BCS) is problematic for liner construction due to its high plasticity, swelling potential, and permeability. This study investigates the stabilization of BCS using cement and rice husk ash (RHA) to enhance its engineering properties for use as a compacted clay liner in waste containment and water retention structures. BCS samples were stabilized with cement at 1%, 2%, and 3% combined with RHA at 2%, 4%, and 6%. The treated soils were subjected to standard compaction, unconfined compressive strength (UCS), volumetric shrinkage and hydraulic conductivity. The results indicate that stabilization significantly improved the geotechnical properties of BCS. The optimum mix of 3% cement + 6% RHA lowered the optimum moisture content from 19.2% to 14.5% and increased the maximum dry density from 1.61 to 1.86 Mg/m^3, indicating improved compaction characteristics. UCS at 28 days increased from 148 kN/m^2 to 365 kN/m^2, satisfying the minimum strength requirement for liner materials. Hydraulic conductivity decreased by 92%, from 2.97×10^{-6} to 2.23×10^{-7} cm/s, meeting the permeability criteria for low-to-moderate hazard liners. The findings demonstrate that 3% cement + 6% RHA stabilization effectively refines the pore structure and enhances the strength and impermeability of BCS, making it viable for liner applications. This approach also provides an environmentally sustainable method for utilizing RHA while reducing cement consumption.

Keywords: Black Cotton Soil; Hydraulic Conductivity; UCS, Volumetric Shrinkage; Rice Husk Ash

1.0 INTRODUCTION

Liners are critical components of waste containment systems, designed to prevent leachate migration into groundwater and surrounding soils. To function effectively, they must have low hydraulic conductivity, high strength, and long-term durability [1]. Proper management of solid waste is a challenge faced by environmental protection agencies in developing countries of the world [2].

Landfills, although the least among the waste management options/hierarchy [3] play a vital role in the management of solid waste and it prevents the pollution of the environment, soil and water sources provided proper bottom and cover linings are provided [4 -5]. The selection of suitable materials for liner and cover is an important aspect of landfill design to minimize the migration of leachate and gases into the surrounding environment. In order to build a cost-effective landfill, there is need to use locally available materials as liners and cover [6].

Black cotton soils, prevalent in parts of Nigeria, pose significant challenges in geotechnical engineering due to their high plasticity, swelling potential, and low strength [7-8], making them unsuitable as natural liner materials for waste containment systems. Traditional liner materials like compacted clay are often scarce, expensive, or environmentally taxing to source [9]. While cement stabilization is effective but costly and carbon-intensive, alternative locally available agricultural wastes like rice husk ash (RHA) remains underutilized for waste containment applications.

2.0 LITERATURE REVIEW

In Nigeria, black cotton soil, which is expansive clay, is typically found in low lying areas of North Eastern States of Gombe, Borno, Yobe, Adamawa, Taraba, and Bauchi [10]. Soil stabilization is the permanent physical and chemical alteration of soils to enhance their physical properties [11]. It includes compaction, pre-consolidation, drainage, and many such processes. However, the term stabilization is generally restricted to the process which alters the soil material itself for improvement of its properties. Omisande [12] investigated and improved the engineering properties of the black cotton soils of Ilaro and its environs. The soil-fly ash mixtures were prepared by mixing 0%,10%,20%,30%, 40% and 50% of fly ash (by weight). All these mixtures were tested in the laboratory for their index properties, compaction characteristics and California Bearing Ratios. From the test results, it was identified that addition of fly ash decreases plasticity and improves strength characteristics. Addition of 30-40% attains higher CBR values and improved swell characteristics. The study concludes that fly ash has a good potential to be used as an additive for improving the engineering properties of black cotton soils. The research recommended 30% of fly ash content for improving the engineering properties of BCS and to make it suitable in many civil applications.

Annafi [13], studied the influence of mixing time on the strength qualities of lime and iron ore tailings on black cotton soil as a subgrade material. The soil was stabilized with 0, 2, 4, 6, 8, and 10% lime and 0, 2, 4, 6, 8, and 10% Iron ore trailing content. Atterberg limits, compaction, unconfined compressive strength (UCS), California bearing ratio (CBR) tests were performed to investigate the effect. Statistical analysis was carried out by MINI-TAB software. There was a decrease in liquid limit of the mixes as the lime and IOT content increased according to the findings. After mixing, the liquid limit of all the treated Black Cotton Soil increased in an hour. The plastic limit (PL) of the soil dropped as additives content increased. Between 0 and 2 hours after mixing, the unconfined compressive strength and California bearing ratio values rose as the additives content increased. For all lime content evaluated, peak values were observed for the 8 per cent lime and 8 per cent Iron Ore Trailing treatment.

Paul [14] stabilized black cotton soil by the use of iron ore tailings and cement. British standard light compaction for various percentages of iron ore tailings and cement was conducted (0-10%), the optimum moisture content values of 21.2, 20.8, 20.5, 20, 20.3, and 20.2 percent were observed. Higher cement concentrations and compactive efforts followed the same pattern. Using software, regression models, Regression analysis reveals that the independent factors studied have a significant impact on the dependent variables. The amounts of cement and IOT contributions to the improvements were determined using analysis of variance. As a result, for soil rehabilitation or geotechnical engineering applications, black cotton soil treated with a 4 percent cement 10 percent IOT blend and compacted with British Standard Heavy energy produce the optimum strength.

Pushpakumara and Mendis [15] noted that the unconfined compressive strength increased to 121.7 when using a mixing percentage of 10% RHA and 20% lime during a curing period of 28 days. This study showed that RHA can be successfully recycled as a soil stabilizer, to avoid environmental pollution produced by open dumping of RHA. Moreover, using RHA as soil stabilizer would reduce the CO2 emissions from other soil stabilizers like cement because of the CO2 emissions due to the use of cement also reducing the cost of using cement. It was noted that using rice husk ash and lime as soil reinforcing materials benefits dams and road sections under high tensile loads. Also, the stabilization of soil with cement, RHA, and plastic trash. They used the Grey-Taguchi analysis, which showed that the approach enhanced the soil's characteristics [16] – [17].

Iorliam et al. [18] examined the improvement of clay using calcium carbide waste (CCW) for clay liners. Clay was mixed with 0%, 4%, 8%,12% and 16% of CCW. The liquid limit for natural clay decreased from 47.20% to 45.95% at 16% CCW additions, while the plastic limit of the clay increased from 31% to 35.59% at 16% additions. Plasticity index and shrinkage limit of natural clay decreased from 16.20 % to 10.26 % and 13.57 % to 6.42 % respectively, at 16% CCW additions. Maximum dry density of natural sample increased from 1.65 to 2.01 Mg/m³, and the optimum moisture content decreased from 18.10% to 17.71%. Hydraulic conductivity of natural sample decreased from 8.771× 10-8 cm/sec to a minimum value of 3.13 × 10-8 cm/sec at 16% CCW additions. UCS values increased with incremental CCW content with peak UCS values of 286.4, 295 and 365 kN/m2 recorded at 16 % CCW content after 7, 14 and 28-days curing period respectively. Resistance to loss in strength (durability) value of natural sample increase from 50 kN/m² to 295 kN/m² at 16% CCW additions. Void ratio and coefficient of volume compressibility of natural sample decreased from 0.24 to 0.12 and 0.10 to 0.009 respectively at 16% CCW addition. The results suggest that CCW influences soil properties, improving compaction, UCS, and durability as well as decreasing permeability as CCW content increased up to 16%.

3.0 MATERIALS AND METHOD

The black cotton soil used was obtained from Yamaltu-Deba Local Government Area of Gombe state. The location lies approximately on latitude 100 16'N and longitude110 21'E. In terms of extent of deposit, black cotton clays were not restricted to the area of study, but are widely spread throughout the North–eastern part of Nigeria. A disturbed sample of the clay was dug after removing the top soil and collected for laboratory analysis. Some amount of the sample was sealed in a polythene bag for determination of natural moisture content. In the laboratory, the soil was air dried, pulverized and sieved with British Standard Sieve No. 4 which is of 4.75 mm aperture as required for the tests. The water for the research work was clean and portable water in accordance with [19] and obtained from the tap at Abubakar Tafawa Balewa University, Bauchi. Clean and portable water is of great importance in the stabilization process because the presence of impurities in water can affect the cementitious process and reduce the compressive strength and durability of the stabilized soil. Ordinary Portland cement used was obtained from the open market and its, properties conform to specifications [20]. Rice husk ash was obtained from rice milling industry at sabn-kaura, Bauchi. The RHA was finely ground with a grinding machine to achieve a finer particle size, and sieved to an average particle size using150 µm. The x-ray florescence of the soil was determined using Philips PW 1606 X-ray florescence spectrometer at the National Geosciences Laboratories, Kaduna.

3.1 Methods

The laboratory test was performed on the soil in order to determine its engineering properties was in accordance with [21 - 22]. The following tests were performed:

(i) Moisture content

(ii) Particle size distribution

(iii) Atterberg limits (Liquid limit and Plastic limit)

(iv) Compaction test (BSL)

(v) Volumetrijkc shrinkage test (VS)

(vi) Unconfined Compressive Strength (UCS)

3.1.1 Moisture content determination

Moisture content is defined as the amount of water that exists within the pore space of the soil grains. Sample of the fresh soil was placed in a container of known mass and recorded as M1. The soil plus the container was weighed to the nearest 0.01 g and recorded as M2, after which was placed in an oven set at a temperature range of l05 to ll0°C for a period of 24 hours to dry, after drying, the container plus the dry soil was weighed and recorded as M3. The moisture content (W) was calculated using Equation (1)

$$W = \frac{M_2 - M_3}{M_3 - M_1} \times 100 \quad \dots (1)$$

Where;

M_1 = mass of container (g)

M_2 = mass of container + wet soil (g)

M_3 = mass of container + dry soil (g)

The above procedures were repeated for about three times in order to calculate the moisture content of the natural soil.

3.1.2 Particle size distribution

Sieving method was used to separate coarse grain sizes such as gravel and sand particles in to different sizes ranges with the aid of series of sieves of standard aperture opening. The sedimentation procedure is use for soils like silt and clay particles which are very small in sizes the measurements are made either by;

a. Sampling a suspension of soil particle in water by means of special pipette method or

b. Determining the density of the suspension using a special hydrometer (hydrometer method).

3.1.3 Atterberg limits

The test includes the determination of the liquid limits, plastic limits and the plasticity index for the natural soil and the stabilized soils. They were conducted in accordance with test 1 [21], for the natural soil and [22] for the stabilized soils at the geotechnical laboratory of Civil Engineering, ATBU.

The plasticity index was computed in accordance with BS l377: part 2: 1990. Plasticity index is the difference between the Liquid limit and the Plastic limit, and is express mathematically below in Equation 2.

$$I_p = W_l - W_p \quad \dots (2)$$

Where;

I_p = plasticity index (%)

W_l= liquid limit (%)

W_p= plastic limit (%)

Linear shrinkage test was conducted in accordance with BS [22]. In this test, 125 g of soil sample that was pass 425 µm BS sieve size and was mixed with water in order to obtain a homogeneous mixture, the paste was then placed in the lubricated shrinkage moulds and vibrated gently in order to expel air pockets from the mixture. It was then placed in an oven at a temperature of l05°C to 1l0"C for 24 hours. On cooling, the length of the sample was measured with a scale rule and the linear shrinkage (Ls) was calculated from the expression in Equation (3).

$$Ls = \left(1 - \frac{lenghtafterdrying}{initiallenght}\right) \times 100(\%) \quad \dots (3)$$

The length of the mould is l40 mm.

3.1.4 Compaction test

The compaction test standard proctor (SP) was conducted in accordance with [21 – 22] for the natural and modified soil respectively. The soil was broken and mixed with water for compaction; the procedure was repeated for five times from which the optimum moisture content (OMC) and maximum dry density (MDD) was determined by plotting a graph of dry density versus moisture content. The procedures were repeated for the soil using requisite levels of modified blend. The Equations (4) and (5) were used to calculate the bulk and dry densities respectively

$$\rho_b = \frac{M_2 - M_1}{v} \quad \ldots (4)$$

$$\rho_d = \frac{100 \,.\, \rho_b}{100 + w} \quad \ldots (5)$$

Where;

ρ_b = Bulk density (g/cm^3)

M_1 = mass of empty mould (g)

M_2 = mass of mould + wet soil (g)

W = moisture content (%)

ρ_d= dry density

3.1.5 Unconfined compressive strength (UCS)

The Equation 6 was employed to determine the unconfined compressive strength (UCS) of each of the abovementioned blends in cylindrical shape of 120 mm x 100 mm after being produced at MDD and OMC and crushed with the aid of compression machine in accordance to BS [21].

$$qu = P\,(1- \varepsilon)/A \quad \ldots (6)$$

where:

qu = Unconfined compressive strength (kN/m^2 or kPa)

P = Load that crushes cylindrical specimen to failure (kN)

ε = calculated strain from ratio of difference between length of cylindrical specimen before failure and length after failure to original length of cylindrical specimen before failure to

A = area of cylindrical specimen before failure (mm^2)

3.1.6 Determination of hydraulic conductivity (K)

The hydraulic conductivity test was conducted using distilled water and stabilised black cotton clay with kaolin and sand. The test was performed using the falling head procedure in accordance with [23 - 24]. The soil specimen for this experiment was air-dried in the laboratory and pulverised to a size small enough to pass BS sieve No. 4 (4.76 mm aperture). A weight of 3 kg of the soil was measured and compacted at moulding water contents of -2 %, 0, and +2 % relative to OMCs derived from the moisture-density relationship for the compaction energy. The compacted samples were soaked in distilled water for 24 hours to allow for full saturation before the commencement of the test. It was computed using the relation from Equation 7.

$$k=2.303\,\frac{al}{At}\,\log_{10}\frac{h1}{h2} \quad (7)$$

where;

k = Hydraulic conductivity (m/s)

a = Area of standpipe tube (m^2)

l = Thickness of the specimen along the flow path (m)

A = Cross-sectional area of the specimen (m^2)

t = elapsed time (s)

h_1 = Height of water above datum in the standpipe at time t_1 (m)

h_2 = Height of water above datum in the standpipe at time t_2 (m)

The hydraulic conductivity values were reported as the arithmetic mean of the last three computed measurements of hydraulic conductivity.

4.0 RESULTS AND DISCUSSION

4.1 Preamble

This chapter presents the results of tests carried out on BCS, RHA and cement during the experimental investigation.

4.2 Black Cotton Soil

4.2.1 Index properties of black cotton soil

The summary of the properties of the BCS is presented in Table 1.

Property	Value
Natural Moisture Content (%)	18.5
Liquid limit (%)	66.4
Plastic limit (%)	32.7
Plasticity index (%)	33.7
Volumetric shrinkage (%)	11.5
Activity	1.0
Specific gravity	2.32
Percentage Passing No. 200 sieve	83
Percentage Sand (0.075 - 4.76) (%)	17.9
Percentage gravel (< 4.76mm) (%)	0
Maximum Dry Density (MDD) Mg/m^3	1.61
Optimum Moisture Content (OMC) %	22.8
7 days UCS kN/m^2	108
28 days UCS kN/m^2	245
Hydraulic conductivity	2.97×10^{-6} cm/s
Colour	Black Grey
Dominant clay mineral	Montmorillonite
AASHTO Classification	A-7-5
UCSC Classification	CH

Based on results presented in Table 1, montmorillonite dominance in the BCS will be vulnerable to chemical attack from landfill leachate, which can increase permeability over time if not treated. The BCS may degrade chemically. The PI 33.6%, Activity 1.0, LL 66.4% values confirm high swelling and shrinkage with moisture changes. This causes heave during wet seasons and cracking during dry seasons. The hydraulic conductivity (k) in BCS of 2.97 × 10-6 cm/s is 30 times above the U.S. EPA requirement of ≤ 1 × 10-7 cm/s for compacted clay liners in municipal solid waste landfills which implies that the soil will allow excessive leachate migration. However, the high montmorillonite content means it will respond well to pozzolanic stabilization [25]. UCS 245 kN/m2 at 28 days is insufficient for a liner that must resist overburden stress and waste load without shear failure. These results of OMC at 22.8% will make field compaction difficult, especially in wet conditions.

4.2.2 Physical and chemical properties of black cotton soil

The oxide composition of the BCS and RHA using X-ray Fluorescence (XRF) is presented in Table 2.

Table 2: XRF of BCS and RHA

Oxide	BCS (%)	RHA (%)
SiO_2	55.3	84.6
Al_2O_3	12.1	2.3
Fe_2O_3	9.2	0.7
CaO	2.83	4.5
MgO	2.76	0.7
K_2O	0.43	1.8
Na_2O	0.72	0.1
TiO_2	1.4	-
LOI	12.9	4.6
Sum of SiO_2, Al_2O_3 and Fe_2O_3	76.6	87.6

In Table 2, The sum of SiO2, Al2O3 and Fe2O3 of 76.6% for BCS indicates a clay-dominated soil. In black cotton soil, high Al2O3 in the octahedral sheet and low interlayer charge in montmorillonite allow water intercalation, causing swelling and high plasticity. The iron oxides present contribute to the high cation exchange capacity and dark colour of BCS. The RHA with SiO2 is 84.6% shows that it is a good pozzolan. The silica is mostly amorphous due to controlled burning, so it reacts with Ca $(OH)_2$ from cement hydration to form C-S-H gel [26 – 27]. RHA itself has little cementitious value, but it's highly reactive with lime from cement to produce secondary C-S-H that fills pores and reduces permeability.

4.3 Performance Evaluation Test Results

4.3.1 Compaction Characteristics

The result of the OMC of the BCS and the admixed BCS are presented in Table 3 while the analysis of variance (ANOVA) for OMC is presented in Table 4.

Table 3: OMC and MDD Result

A: Cement %	Response 1 OMC (%)	Response 2 MDD (Mg/m^3)

Control	22.8	1.61
1C 2R	20.5	1.74
1C4R	19.0	1.77
2C 4R	17.5	1.79
1C 6R	18.0	1.80
2C 4R	17.5	1.79
2C 2R	19.0	1.76
2C 6R	14.0	1.82
2C 4R	17.5	1.79
3C 2R	16.0	1.81
2C 4R	17.5	1.79
2C 4R	17.5	1.79
3C 4R	16.0	1.84
3C 6R	14.5	1.86

The reduction in OMC with cement and RHA addition is attributed to the immediate cation exchange and flocculation reactions, which reduce the diffuse double layer and lower water demand. The lowest OMC of 14.0% at 2% cement + 6% RHA indicates optimal pozzolanic activity at this combination. The identical OMC values at the centre points confirm the reliability of the experimental procedure. The MDD increased from 1.61 Mg/m³ for untreated BCS to 1.86 Mg/m³ at 3% cement + 6% RHA, representing a 15.5% improvement. This increase is due to flocculation and pozzolanic reactions that reduce plasticity and fill voids with cementitious gels. The consistent MDD of 1.79 Mg/m3 at the centre points confirms good experimental control. The trend indicates that cement and RHA act synergistically, with the greatest density achieved at the highest dosage level within the studied range. The increase in MDD with cement and RHA addition is consistent with findings by [28], who reported that pozzolanic reactions between cement, RHA, and clay reduce void volume and increase dry density. Similarly, Sabat [29] observed improved compaction characteristics in Black Cotton Soil treated with RHA and lime due to flocculation and cementitious gel formation.

Table 4: ANOVA for OMC

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	33.67	2	16.83	32.74	< 0.0001
A-Cement	20.17	1	20.17	39.23	< 0.0001
B-RHA	13.50	1	13.50	26.26	0.0004
Residual	5.14	10	0.5141		
Lack of Fit	5.14	6	0.8568		
Pure Error	0.0000	4	0.0000		
Cor Total	38.81	12			

In Table 4, the Model F-value of 32.74 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.05 indicate model terms are significant. A, B are significant model terms.

Table 5: Fit Statistics for OMC

Parameter	Value
Std. Dev	0.7170
Mean	17.27
C.V (%)	4.15
R^2	0.8675
Adjusted R^2	0.8410
Predicted R^2	0.7328
Adeq Precision	19.3551

Mean of 17.27% shows an average OMC across all experimental runs. The C.V of 4.15% measures relative variability. C.V. < 10% usually means the model has good reproducibility. R^2 of 0.8675 showed the proportion of total variation in OMC explained by the model. 86.75% of the variation in OMC is explained by cement, RHA, and their interactions. Above 0.8 is considered a good fit for geotechnical data. Adjusted R^2 was 0.8410. Predicted R^2 of 0.7328 measures how model predicts new data points. Predicted R^2 is within 0.2 of Adjusted R^2. The model has reasonable predictive power and not overfitted. Adeq Precision is signal-to-noise ratio. 19.36 > 4. A ratio > 4 is desirable. This means the model has a strong signal and can navigate the design space and can be used for optimization. The model equation for the OMC is given in Equation (8). ANOVA for MDD and Fit statistics of Admixed BCS is shown in Tables 6 and 7.

$$OMC = 23.9359 - 1.83333\,A - 0.75\,B \qquad \text{… (8)}$$

Table 6: ANOVA for MDD

Source	Mean Square	F-value	p-value
Model	0.0030	966.62	< 0.0001
A-Cement	0.0067	2133.33	< 0.0001
B-RHA	0.0048	1541.33	< 0.0001
AB	0.0000	8.00	0.0222
A^2	0.0006	183.79	< 0.0001
Residual	3.125E-06		
Lack of Fit	6.250E-06		
Pure Error	0.0000		
Cor Total			

In Table 6, the Model F-value of 966.62 implies the model is significant. P-values less than 0.05 indicate model terms are significant. In this case A, B, AB, A^2 were the significant model terms.

Table 7: Fit Statistics for MDD

Parameter	Value
Std. Dev	0.0018
Mean	1.80
C.V (%)	0.0984
R^2	0.9979
Adjusted R^2	0.9969
Predicted R^2	0.9860
Adeq Precision	112.4973

Table 7 showed that the Predicted R^2 of 0.9860 is in reasonable agreement with the Adjusted R^2 of 0.9969; i.e. the difference is less than 0.2. Adeq Precision of 112.497 indicates an adequate signal. The model equation for MDD is shown in Equation 9

$$MDD = 1.71 - 0.015\, A + 0.0167\, B + 0.013\, A^2 \qquad \dots (9)$$

4.3.2 Result of Volumetric Shrinkage (VS) of BCS

The result of VS is presented in Table 8, the analysis of variance in Table 9.

Table 8: Result of VS of BCS

Run	Response 3 VS %	Response 5 UCS at 28 days kN/m^2	Response 6 K cm/s
Control	11.5	245	2.97×10^{-6}
1C 2R	9.7	260	1.41×10^{-6}
1C4R	8.3	285	8.9×10^{-7}
2C 4R	5.5	310	6.5×10^{-7}
1C 6R	8.7	300	5.2×10^{-7}
2C 4R	5.5	310	6.5×10^{-7}
2C 2R	6.4	285	1.2×10^{-6}
2C 6R	5.9	335	3.8×10^{-7}
2C 4R	5.5	310	6.5×10^{-7}
3C 2R	4.8	320	5.8×10^{-7}
2C 4R	5.5	310	6.5×10^{-7}
2C 4R	5.5	310	6.5×10^{-7}
3C 4R	4.2	345	3.2×10^{-7}
3C 6R	4.5	365	2.23×10^{-7}

Table 9: ANOVA for VS

Source	Mean Square	F-value	p-value
Model	6.85	635.44	< 0.0001
A-Cement	29.04	2694.91	< 0.0001
B-RHA	0.5400	50.11	0.0002
AB	0.1225	11.37	0.0119
A^2	1.60	148.85	< 0.0001
B^2	1.21	112.35	< 0.0001
Residual	0.0108		
Lack of Fit	0.0251		
Pure Error	0.0000		

In Table 9, the Model F-value of 635.44 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.05 indicate model terms are significant. A, B, AB, A^2, B^2 were the significant model terms. The Fit statistics is shown in Table 10.

Table 10: Fit Statistics for VS

Parameter	Value
Std. Dev	0.0018
Mean	1.80
C.V (%)	0.0984
R^2	0.9978
Adjusted R^2	0.9962
Predicted R^2	0.9777
Adeq Precision	78.5145

The Predicted R^2 of 0.9777 is in reasonable agreement with the Adjusted R^2 of 0.9962; i.e. the difference is less than 0.2. Adeq Precision measures the signal to noise ratio. A ratio of 78.515 indicates an adequate signal. The model equation for VS is shown in Equation 10.

$$VS = 16.9 - 5.6A - 1.65B + 0.762\,A^2 + 0.17\,B^2 \quad ..\ (10)$$

Table 11: Actual and Predicted Values for Volumetric Shrinkage

Run Order	Actual Value	Predicted Value
1	9.70	9.60
2	8.30	8.46
3	5.50	5.50
4	8.70	8.65

5	5.50	5.50
6	6.40	6.46
7	5.90	5.86
8	5.50	5.50
9	4.80	4.85
10	5.50	5.50
11	5.50	5.50
12	4.20	4.06
13	4.50	4.60

Figure 1 shows 3D response surface for the interaction between cement, rice husk ash and their interaction with volumetric shrinkage.

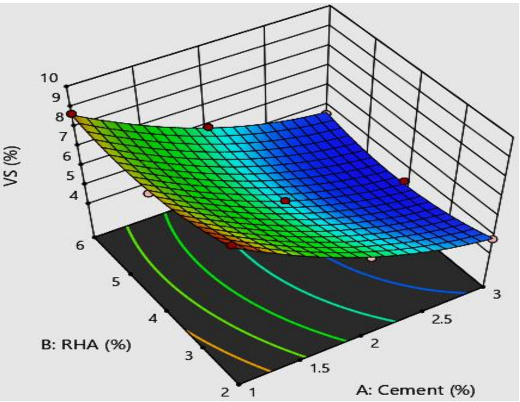

Figure 1: 3-D Response Graph for Effect of Cement and RHA on VS

4.3.3 Result of UCS at 28 days

The result of Unconfined Compressive Strength is presented in Table 12, the ANOVA in Table 13 and the Fit statistics in Table 14.

Table 12: Result of UCS at 28 Days

Run	Factor 1 A: Cement %	Factor 2 B: RHA %	Response 5 UCS at 28 days kN/m^2
Control	0	0	245
1	1	2	260
2	1	4	285
3	2	4	310
4	1	6	300
5	2	4	310
6	2	2	285

7	2	6	335
8	2	4	310
9	3	2	320
10	2	4	310
11	2	4	310
12	3	4	345
13	3	6	365

In Table 22, the 28-day UCS increased from 245 kN/m² for untreated soil to 365 kN/m² at 3% cement + 6% RHA, a 49% gain. Strength increased for all mixes between 7 and 28 days, confirming ongoing pozzolanic reaction between RHA and calcium hydroxide. Unlike at 7 days, the highest dosage of 3% cement + 6% RHA gave the maximum strength, indicating that sufficient curing time allows excess RHA to participate in cementitious reactions.

Table 13: ANOVA for UCS at 28 Days

Source	Mean Square	F-value	p-value
Model	4370.83	661.99	< 0.0001
A-Cement	5704.17	863.93	< 0.0001
B-RHA	3037.50	460.05	< 0.0001
Residual	6.60		
Lack of Fit	11.00		
Pure Error	0.0000		

The Model F-value of 661.99 implies the model is significant. The p-values less than 0.05 indicate model terms are significant. In this case A, B are significant terms.

Table 14: Fit Statistics for UCS at 28 Days

Parameter	Value
Std. Dev	2.57
Mean	311.15
C.V (%)	0.8258
R^2	0.9925
Adjusted R^2	0.9910
Predicted R^2	0.9856
Adeq Precision	86.4139

The Fit statistics in Table 14 showed the Predicted R^2 of 0.9856 is in reasonable agreement with the Adjusted R^2 of 0.9910. Adeq Precision measures the signal to noise ratio. Ratio of 86.414 indicates an adequate signal. The model equation for UCS at 28 days is shown in Equation 11. Figure 2 shows a 3D response surface for the interaction between cement and rice husk ash and their influence on UCS at 28 days.

$UCS\ 28\,d\ =\ 204\ +\ 30.8 * A\ +\ 11\ *\ B$... (11)

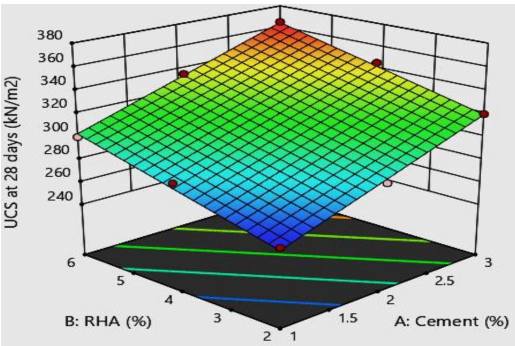

Figure 2: Effect of Cement and RHA on UCS at 28 Days

4.3.4 Hydraulic conductivity (K)

The result for hydraulic conductivity is presented in Table 15, the ANOVA in Table 16 and the Fit-statistics in Table 17.

Table 15: Result of Hydraulic Conductivity

Run	Factor 1 A: Cement %	Factor 2 B: RHA %	Response 6 K cm/s
Control	0	0	2.97×10^{-6}
1	1	2	1.41×10^{-6}
2	1	4	8.9×10^{-7}
3	2	4	6.5×10^{-7}
4	1	6	5.2×10^{-7}
5	2	4	6.5×10^{-7}
6	2	2	1.2×10^{-6}
7	2	6	3.8×10^{-7}
8	2	4	6.5×10^{-7}
9	3	2	5.8×10^{-7}
10	2	4	6.5×10^{-7}
11	2	4	6.5×10^{-7}
12	3	4	3.2×10^{-7}
13	3	6	2.23×10^{-7}

Hydraulic conductivity decreased from 2.97×10^{-6} cm/s for untreated BCS to 2.23×10^{-7} cm/s at 3% cement + 6% RHA, a 92% reduction. The decrease is due to flocculation of clay particles and pore filling by cementitious gels formed from cement hydration and pozzolanic reaction of RHA. The lowest K values were observed at 2 - 3% cement + 4 - 6% RHA, indicating optimum pore blockage. The reduced permeability will limit water ingress and reduce swelling potential in the field. The control of 2.97×10^{-6} cm/s was too high. Untreated BCS is not suitable, 1% Cement + 2% RHA gave 1.41×10^{-6} cm/s was marginal but too permeable for most specs. 2% C + 4% RHA was 6.5×10^{-7} cm/s was good for some compacted clay liners. The acceptable mix for liner specifications were: 2% C + 6% RHA which gave 3.8×10^{-7} cm/s, 3% C + 4% RHA gave 3.2×10^{-7} cm/s and 3% C + 6% RHA gave 2.23×10^{-7} cm/s but still above 1×10^{-7} cm/s.

Table 16: ANOVA for the Linear Model for K ($\times 10^{-7}$ cm/s)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	130.01	5	26.00	117.32	< 0.0001
A-Cement	48.00	1	48.00	216.56	< 0.0001
B-RHA	71.21	1	71.21	321.28	< 0.0001
AB	7.10	1	7.10	32.04	0.0008
A^2	1.55	1	1.55	6.97	0.0334
B^2	3.35	1	3.35	15.13	0.0060
Residual	1.55	7	0.2216		
Lack of Fit	1.55	3	0.5172		
Pure Error	0.0000	4	0.0000		
Cor Total	131.56	12			

In Table 16, the Model F-value of 117×10^{-7} cm/s implies the model is significant. P-values less than 0.05 indicate model terms are significant. A, B, AB, A^2, B^2 were the significant model terms.

Table 17: Fit Statistics for K

Parameter	Value
Std. Dev	0.4708
Mean	6.75
C.V (%)	6.98
R^2	0.9882
Adjusted R^2	0.9798
Predicted R^2	0.8867
Adeq Precision	39.2287

The Predicted R^2 of 0.8867 as shown in Table 17 is in reasonable agreement with the Adjusted R^2 of 0.9798; i.e. the difference is less than 0.2. Adeq Precision measures the signal to noise ratio. A ratio of 39.229 indicates an adequate signal. The model equation for hydraulic conductivity is shown in Equation 12.

$$K = 25.9 - 2.5A - 5.259B + 0.67AB - 0.748\,A^2 + 0.275B^2 \qquad \dots (12)$$

The 3D surface graph of the interaction between cement and RHA and its influence on hydraulic conductivity is presented in Figure 3.

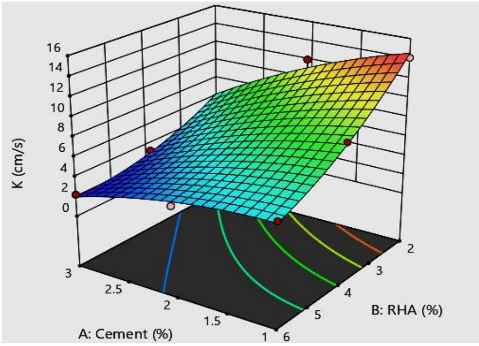

Figure 3: Effect of Cement and RHA on Hydraulic Conductivity

4.4 Optimisation of Mixtures by Numerical Method

The goals set for responses in numerical optimisation are presented in Table 18 and the solutions of optimal values for factors and responses are shown in ramp plot in Figure 4.

Table 18: Goals for Numerical Optimization

Name	Goal	Lower Limit	Upper Limit
A: Cement	is in range	1	3
B: RHA	is in range	2	6
OMC	minimize	14	20.5
MDD	maximize	1.74	1.86
VS	minimize	4.2	9.7
UCS at 28 days	maximize	260	365
K	minimize	2.23	14.1

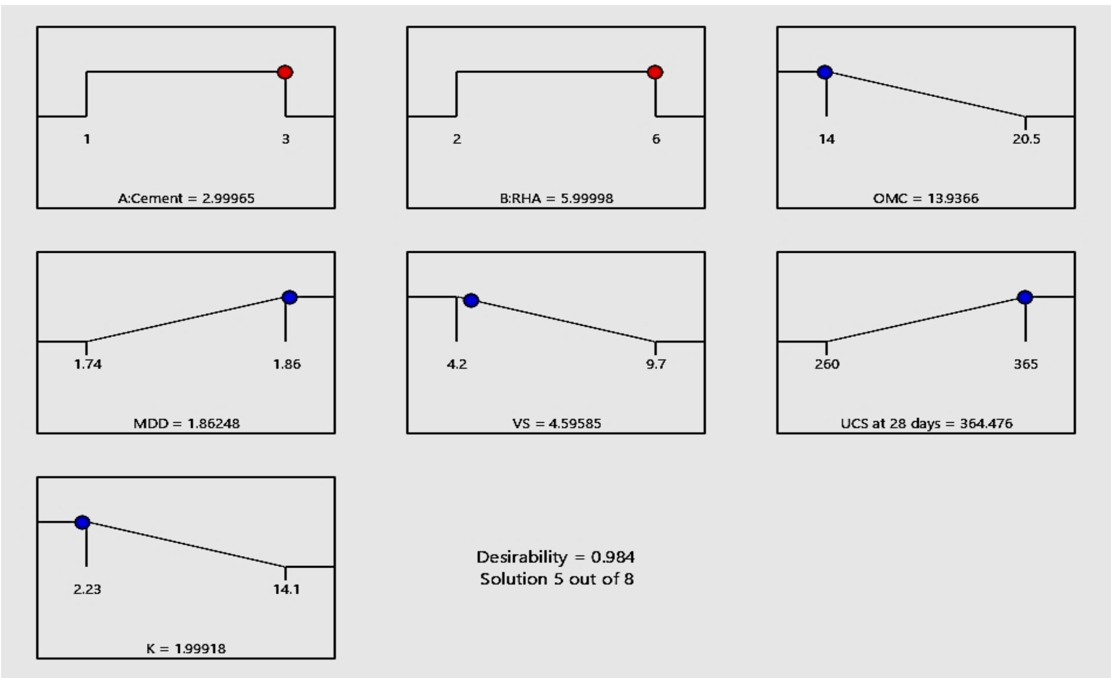

Figure 4: Ramp Plot Showing the Optimal Values for Factors and Responses

5.0 CONCLUSION

This study evaluated the stabilization of black cotton soil (BCS) using cement and rice husk ash (RHA) for liner applications in waste containment systems. The conclusions drawn are as follows:

i. Combined effects on geotechnical properties: The addition of cement and RHA significantly improved the geotechnical properties of BCS. Compaction characteristics improved, with optimum moisture content decreasing from 19.2% to 14.5% and maximum dry density increasing from 1.61 to 1.86 Mg/m^3 at the optimum mix. Unconfined compressive strength increased from 148 kN/m^2 to 365 kN/m^2 at 28 days, while hydraulic conductivity reduced by 92% from 2.97×10^{-6} to 2.23×10^{-7} cm/s. The improvements are attributed to pore filling and binding by calcium silicate hydrate (C-S-H) gel formed through pozzolanic reactions.

ii. Optimal mix proportions for liner criteria: The mix of 3% cement + 6% RHA was identified as optimal. It achieved a UCS of 365 kN/m^2, exceeding the 200 kN/m^2 minimum for compacted clay liners, and a hydraulic conductivity of 2.23 $\times 10^{-7}$ cm/s, which meets the requirements for low-to-moderate hazard waste containment, agricultural ponds, and canal linings.

iii. Regression models for prediction and design: Regression models were developed to predict OMC, MDD, UCS and hydraulic conductivity as functions of cement content, RHA content, and curing time. The models showed good correlation with experimental data and can be used to estimate strength and permeability for mix designs within the tested range. This provides a practical tool for engineers to select mix proportions that meet specified liner performance criteria without extensive laboratory testing.

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