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EXPERIMENTAL INVESTIGATION OF RICE HUSK ASH AND METAKAOLIN AS STABILIZING AGENTS FOR BLACK COTTON SOIL IN SUB-BASE CONSTRUCTION

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ABSTRACT

The study demonstrates the potential of rice husk ash (RHA) and metakaolin (Mk) as stabilizing agents for black cotton soil (BCS), particularly for use as sub-base material. BCS material when encountered may not be suitable or adequate for use as subbase material due to poor strength, therefore the need for its stabilization. Soil stabilization can change one or more soil properties to improve the technical properties and performance of a soil. For this reason, there is need for effective utilization of different stabilizers to improve the geotechnical properties of the BCS. A central composite design (CCD) was employed to optimize the proportions of RHA and Mk for maximum improvement of geotechnical properties of BCS. The BCS was classified as A-7-6 and CH according to the American Association of State Highway and Transportation Officials (AASHTO) and the unified soil classification system. The OMC was 9.8%, MDD was 1.69 Mg/m^3. The soil has specific gravity of 2.19, Natural moisture content of 0.71%, LL of 44.9% and PL of 25.8%. Addition of RHA and Mk significantly improved the unconfined compressive strength (UCS) and California bearing ratio (CBR). The optimal stabilization mixture of 15% RHA and 5% Mk was found to significantly improve the soil's geotechnical properties, making it suitable for subbase applications. The increase in UCS and CBR values shows that RHA and Mk act as pozzolans and also as filler in black cotton soil. These findings have important implications for the construction industry, where stabilized black cotton soil can be used as a reliable and sustainable subbase material. Models for prediction of unconfined compressive strength (UCS) and Californian bearing ratio (CBR) were developed. The use of CCD proved to be an effective tool in optimizing the stabilization process, and the results demonstrate the potential of RHA and Mk as sustainable additives for improving the geotechnical properties of black cotton soil.

KEYWORDS: Rice Husk Ash, Metakaolin, Black Cotton Soil, Stabilization, Central Composite Design

I.INTRODUCTION

Black cotton soil, also known as expansive clay soil is a soil type with unique properties that pose significant challenges for construction and infrastructure development. It is characterized by high plasticity, expansive behavior and pronounced shrinkage and swelling behavior due to changes in humidity [1]. BCS found in North-East, Nigeria [2] has inherent properties which result in soil instability, foundation settlement and damage to infrastructure, making it a particularly problematic soil type for engineering applications [3].

The expansive nature places sufficient stress on structures, driveways, sidewalks, basement floors, plumbing, and even foundations to cause damage. With extensive soils found all over the world, the challenge facing civil engineers is felt anywhere in the world. Expansive soils, if not properly treated, can become a natural hazard and cause serious damage to structures. To date, problems related to this type of soil have resulted in billions of dollars in losses in repairs and rehabilitation [4].

The use of pozzolanic materials such as metakaolin and RHA has gained attention as a potential solution to improve the technical properties of problematic soils such as BCS. Pozzolan has the potential to reduce swelling and cracking of extensive floors. Reducing the plasticity and shrinkage swelling potential of fine-grained soils is also a common goal or goal [2]. The improved soil material is generally found to be stronger and more durable. However, like fly ash, rice husk ash, metakaolin, etc., they are used in civil engineering since they have pozzolanic properties [5].

Metakaolin is a highly reactive aluminosilicate material obtained by calcining kaolin clay at high temperatures and exhibits pozzolanic properties that help form cementitious compounds when mixed with cement [6]. Metakaolin is not entirely natural, nor is it a by-product of an industrial process. Metakaolin is derived from a naturally occurring mineral (kaolin) and is specifically manufactured for cementitious applications; this is refined kaolin clay that is fired (calcined) under well-controlled conditions to produce an amorphous aluminosilicate. It is reactive in concrete and is obtained by calcining the kaolinitic clay at very high firing temperatures of around 600–800 °C [2, 7]. The calcination of kaolinitic clay is shown in Equation (1):

$$\underset{\text{Kaolin}}{Al_2Si_2O_5(OH)_4} \xrightarrow[\text{Heat}]{600^\circ C - 800^\circ C} \underset{\text{Metakaolin}}{Al_2O_3.2SiO_2 + 2H_2O} \quad \dots (1)$$

The effect of metakaolin (MK) on the geotechnical properties of extensive soils means that the use of different percentages of metakaolin results in reduced swelling and increased shear strength.

According to previous studies, there is very little information on the use of metakaolin (MK) as a soil stabilizer, so further test work is needed to cover all expected parameters [8, 9].

RHA, a by-product of rice milling, also has pozzolanic properties [10, 11] and can contribute to improved soil stabilization when used appropriately. The soil stabilization using RHA in terms of strength can be explained using the pozzolanic reactions. The pozzolanic reactions took place in soil mixtures between calcium hydroxide ($Ca(OH)_2$) in RHA and silicate oxide (SiO_2). Therefore, chemical binders such as metakaolin, cement and lime form $Ca(OH)_2$ when they react with water in the soil. In soil amendment, this should be used in conjunction with RHA to increase the efficiency of RHA. In the presence of water, a mixture of RHA and lime, CaO dissolves and releases calcium ions (Ca_{2+}).

The amorphous silica in RHA reacts with Ca_{2+} (cations) to produce the cementitious product calcium silicate hydrate (CSH). When mixed with Ordinary Portland Cement (OPC) and RHA, the amorphous silica in RHA reacts with additional lime content in the cement, which can be as high as 60%. The pozzolanic reaction to form CSH gel. The output from the pozzolanic reactions in form of gel cover and bond the soil particles, which result to an increase in the durability and strength of soil mixtures. The gels gradually crystallize, which also results in further results in improvement in soil strength [12].

Soil modification in terms of physical properties such as plasticity index and water content can be analyzed based on the non-plastic properties and structure of RHA. The extra layers and honeycomb voids in the RHA structure result in RHA's high water absorbency [13]. When RHA is mixed with soil, this ability reduces the water content of the stabilized soil. Part of the hydration process can also lead to a reduction in water content. The water absorption and non-plastic nature of RHA can result in a reduction in the plasticity index of soil mixes [12]. Regarding the compaction characteristics, the high water absorption capability of RHA will lead to an increase in the optimum moisture content (OMC) of the soil mixtures. By comparison, as the RHA content increases due to the lightweight of RHA, the maximum dry density (MDD) of the stabilized soil will be decreased, compared to (MDD) metakaolin, cement, and lime [14]. Typically, geotechnical properties of improved soil by increase of RHA content.

The benefits of using agricultural or industrial by-products for the purpose of soil stabilization have increased as they are inexpensive and easily available in addition, there is also environmental benefits as it decreases the environmental impact coming from production of these materials, which otherwise should be disposed on a landfill [15]. While individual studies have examined the effects of either metakaolin or RHA on soil stabilization, comprehensive investigation of their combined potential, particularly across multiple RHA types, remains very limited. This research gap underscores the need to systematically investigate the synergistic effects of using different RHA types in combination with metakaolin to stabilize black cotton soil. The results of this study have the potential to offer sustainable solutions to improve the technical properties of black cotton soil, thereby contributing to more effective foundation design, construction practices and infrastructure development.

II.METHODOLOGY

2.1 Materials

Soil samples used for the study were collected using the disturbed bulk sampling method from a drill pit at a depth of 1.0 to 1.5 m at the Hadejia Western Bypass in Hadejia, Jigawa State, Nigeria (latitude 12º 26'51.92093 N and longitude 10º 0'55.24406 E).

The rice seed samples were collected from JARDA (Jigawa State Agricultural and Rural Development Agency), and dehusked at 3 Brothers Rice Mill

The raw material for metakaolin production is kaolin clay sourced from Alkaleri, Alkaleri Local Government Area in Bauchi State.

2.2 Methods

The study was carried out in two phases. Phase one determined the soil index properties without adding the additives, and index properties by adding additives, which were, particle size distribution, Atterberg limit test, specific gravity, bulk density, dry density, moisture content test. Phase two is, oxide composition of binders, compaction British Standard Light (BSL); British Standard Heavy (BSH): and West African Standard (WAS), Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR), SEM, XRD. Tests were carried out in accordance with BS 1377:1990. In the case of the stabilization tests. In the second phase, depending on the dry weight of the soil, **III.** different proportions of RHAs and MK are added todetermine the engineering properties of when to use RHA and MK as a stabilizer. In tests on stabilized/treated soils, the effectiveness and strength properties of BCS was improved by varying the percentage of RHA as given by RSM. The soil was replaced by dry weight of RHS and MK, to improve the technical properties of the soil. Similar tests were performed on the treated soil [16].

2.3 Experimental Design

The binding materials are mixed with the Black cotton soil at the following levels: 8, 11.5, 15% RHA and 1, 3, 5% Mk. The responses are Unconfined Compressive Strength and California Bearing Ratio.

III.RESULTS AND DISCUSSION

3.1 Properties of Black Cotton Soil

Table 1 presents the summary of the properties of the Black Cotton Soil.

Table 1: Summary of Properties of Black Cotton Soil

Property	Value
Natural moisture content (%)	0.71
Liquid limit (%)	44.9
Plastic limit (%)	25.8
Plasticity index (%)	19.1
Volumetric shrinkage (%)	8.98
Activity	1.4
Specific gravity	2.19
Percentage PASSING No. 200 sieve	87.7
Percentage (Fines) < 0.075 - 4.76mm (%)	87.7
Percentage Sand (0.075 - 4.76) (%)	12.3
Percentage gravel (< 4.76mm) (%)	0
Maximum Dry Density (MDD) Mg/m³	1.69
Optimum Moisture Content (OMC) %	9.8
Strength properties	
7 days UCS kN/m^3	245
7 + 7 days UCS kN/m^3	95
14 days UCS kN/m^3	253
28 days UCS kN/m^3	362
Colour	Black
Dominant clay mineral	Montmorillonite
AASHTO Classification	A - 7 - 6
Clay Soil (AASHTO)	Fair to poor
UCSC Classification	CH

3.2 Result of OMC against MDD

Table 2 showed the result of OMC and MDD using BSL, WAS and BSH.

Table 2: Summary of Results of OMC and MDD

Run	RHA (%)	MK (%)	BSL OMC (%)	MDD mg/m^3	WAS OMC (%)	MDD mg/m^3	BSH OMC (%)	MDD mg/m^3
1	8	5	17	1.65	17	1.72	16.5	1.79
2	15	3	17.5	2.02	17.5	2.08	17	2.08
3	11.5	3	16	1.76	15.5	1.86	15	1.87
4	11.5	1	15.5	1.72	16.5	1.86	16.5	1.82
5	11.5	3	16	1.76	15.5	1.86	15	1.87
6	11.5	3	16	1.76	15.5	1.86	15	1.87
7	11.5	3	16	1.76	15.5	1.86	15	1.87
8	8	1	15.5	1.82	16	1.86	14.5	1.92
9	11.5	3	16	1.76	15.5	1.86	15	1.87
10	11.5	5	18.5	1.81	18.5	1.87	18.5	1.84
11	15	1	17	1.94	17	2.0	16.5	2.02
12	8	3	16.5	1.78	16.5	1.82	15.5	1.86
13	15	5	19.5	1.8	19.5	2.0	18.5	2.04

The results shown in Table 2 revealed that at different mix of RHA and Mk, OMC and MDD were achieved. Using BSL method, the lowest MDD of 1.65 mg/m^3 at OMC of 17% was achieved with 8% RHA and 5% Mk. The lowest MDD 1.72 mg/m^3 at OMC of 17% was also achieved with 8% RHA and 5% Mk using WAS. Lastly, using BSH method, the lowest MDD of 1.79 mg/m^3 at OMC of 16.5% was achieved with 8% RHA and 5% Mk.

3.3 Analysis of Unconfined Compressive Strength

The results of UCS at 28 days using British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH), are presented in Table 3 while the ANOVA and Fit statistics are presented in Table 4 – 6 and Table 7 respectively.

Table 3: Result of Unconfined Compressive Strength

Run	Factor 1 A:RHA %	Factor 2 B:Mk %	Response 1 UCS (BSL) N/mm^2	Response 2 UCS (WAS) N/mm^2	Response 3 UCS (BSH) N/mm^2
1	15	5	1440	1680	1920
2	15	3	1280	1600	1760
3	11.5	3	960	1200	1360
4	15	1	1200	1360	1600
5	8	1	600	740	1100
6	11.5	3	960	1200	1360
7	8	5	640	800	960
8	11.5	1	800	1040	1120
9	8	3	800	880	1040
10	11.5	3	960	1200	1360
11	11.5	5	1040	1120	1280
12	11.5	3	960	1200	1360
13	11.5	3	960	1200	1360

Table 4: ANOVA for UCS (BSL)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	6.341E+05	2	3.171E+05	70.84	< 0.0001
A-RHA	5.891E+05	1	5.891E+05	131.61	< 0.0001
B-Mk	45066.67	1	45066.67	10.07	0.0099
Residual	44758.97	10	4475.90		
Lack of Fit	44758.97	6	7459.83		
Pure Error	0.0000	4	0.0000		
Cor Total	6.789E+05	12			

Table 5: ANOVA for UCS (WAS)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	9.061E+05	5	1.812E+05	266.26	< 0.0001
A-RHA	8.214E+05	1	8.214E+05	1206.83	< 0.0001
B-Mk	35266.67	1	35266.67	51.82	0.0002
AB	16900.00	1	16900.00	24.83	0.0016
A^2	7488.01	1	7488.01	11.00	0.0128
B^2	32173.73	1	32173.73	47.27	0.0002
Residual	4764.37	7	680.62		
Lack of Fit	4764.37	3	1588.12		
Pure Error	0.0000	4	0.0000		
Cor Total	9.109E+05	12			

Table 6: ANOVA for UCS (BSH)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	9.062E+05	5	1.812E+05	69.57	< 0.0001
A-RHA	7.921E+05	1	7.921E+05	304.05	< 0.0001
B-Mk	19266.67	1	19266.67	7.40	0.0298
AB	52900.00	1	52900.00	20.31	0.0028
A^2	36416.75	1	36416.75	13.98	0.0073
B^2	20035.80	1	20035.80	7.69	0.0276
Residual	18235.63	7	2605.09		
Lack of Fit	18235.63	3	6078.54		
Pure Error	0.0000	4	0.0000		
Cor Total	9.244E+05	12			

Table 4 shows the ANOVA for UCS (BSL). The Model F-value of 70.84 implies the model is significant. P-values less than 0.05 indicate model terms are significant. In this case A and B are significant model terms. Table 5 shows the ANOVA for UCS (WAS). The Model F-value of 266.26 implies the model is significant. A, B, AB, A^2, B^2 are significant model terms. Table 6 shows the ANOVA for UCS (BSH). The Model F-value of 69.57 implies the model is significant. A, B, AB, A^2, B^2 are significant model terms.

Table 7: Fit Statistics for UCS

Parameter	UCS (BSL)	UCS (WAS)	UCS (BSH)
R^2	0.9341	0.9948	0.9803
Adjusted R^2	0.9209	0.9910	0.9662
Predicted R^2	0.8577	0.9483	0.8595
Adeq Precision	24.8921	50.40	27.59

The Predicted R^2 of 0.8577, 0.9483 and 0.8595 are in reasonable agreement with the Adjusted R^2 of 0.9209, 0.9948 and 0.9341 for UCS (BSL), UCS (WAS) and UCS (BSH) respectively. The difference between the predicted and adjusted is less than 0.2. Adeq Precision measures the signal to noise ratio. A ratio of 24.8921, 50.40 and 27.59 indicate an adequate signal. The model equation for UCS (BSL), UCS (WAS) and UCS (BSH) are shown in Equation 2– 4

$$UCS\ (BSL) = -190.29 + 89.52 * rha + 43.33 * mk \quad \ldots (2)$$
$$UCS\ (WAS) = 505.5 - 19.9 * rha + 93.4 * mk + 9.29 * rha\ (mk) + 4.25 rha^2 - 27 * mk^2 \quad \ldots (3)$$
$$UCS\ (BSH) = 1{,}674 - 161\, rha - 33\, mk + 16.4\, rha\ (mk) + 9.4\, rha^2 - 21.3 * mk^2 \quad \ldots (4)$$

Figure 1-3 shows 3D response surface graph of interaction between Mk and RHA and the effect on UCS BSL, UCS WAS and UCS BSH respectively.

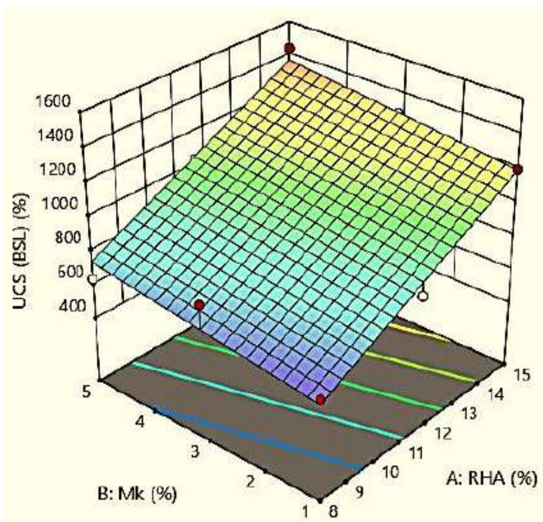

Figure 1: 3-D Response Graph of Effect of Mk and RHA on UCS (BSL)

From Figure 1-3, the 3D response surface graph of interaction between Mk and RHA and the effect on UCS BSL, UCS WAS and UCS BSH elucidates the correlation between the dependent variables (responses) and the independent variables (factors). The graph shows that increase in percentage of RHA causes an increase in UCS while an increase in Mk causes a slight increase in UCS.

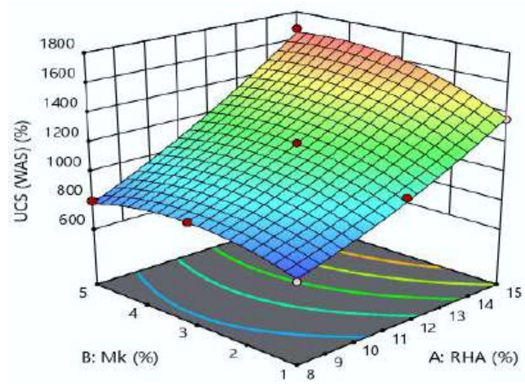

Figure 2: 3-D Response Graph of Effect of Mk and RHA on UCS (WAS)

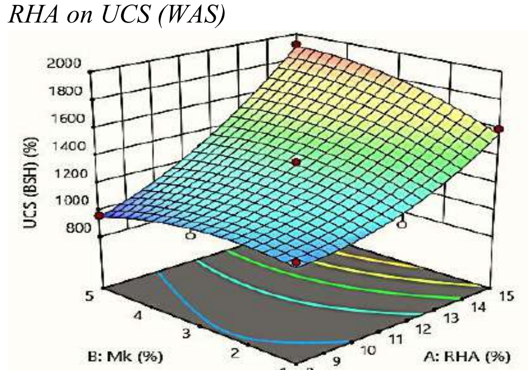

Figure 3: 3-D Response Graph of Effect of Mk and RHA on UCS (BSH)

The increase in UCS (BSL) by metakaolin and RHA is connected to the pozzolanic properties exhibited by both materials.

3.4 Analysis of California Bearing Ratio (CBR)

The result of CBR is presented in Table 8, ANOVA in Table 9 – 11 while the Fit statistics in Table 12.

Table 8: Result of California Bearing Ratio

Run	Factor 1 A:RHA %	Factor 2 B:Mk %	Response 4 CBR (BSL) %	Response 5 CBR (WAS) %	Response 6 CBR (BSH) %
1	15	5	4.4	12.1	16.7
2	15	3	4	9.6	12.9
3	11.5	3	3.5	10.3	14
4	15	1	3.8	9.4	13.5
5	8	1	3	6.7	14
6	11.5	3	3.5	10.3	14
7	8	5	2.7	7.2	12.2
8	11.5	1	3	10	14.4
9	8	3	2.9	7	13
10	11.5	3	3.5	10.3	14
11	11.5	5	3.4	11	15.5
12	11.5	3	3.5	10.3	14
13	11.5	3	3.5	10.3	14

Table 9: ANOVA for CBR (BSL)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	2.44	3	0.8147	44.01	< 0.0001
A-RHA	2.16	1	2.16	116.68	< 0.0001
B-Mk	0.0817	1	0.0817	4.41	0.0651
AB	0.2025	1	0.2025	10.94	0.0091
Residual	0.1666	9	0.0185		
Lack of Fit	0.1666	5	0.0333		
Pure Error	0.0000	4	0.0000		
Cor Total	2.61	12			

Table 10: ANOVA for CBR (WAS)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	31.10	5	6.22	63.61	< 0.0001
A-RHA	17.34	1	17.34	177.33	< 0.0001
B-Mk	2.94	1	2.94	30.07	0.0009
AB	1.21	1	1.21	12.37	0.0098
A^2	9.26	1	9.26	94.70	< 0.0001
B^2	0.3760	1	0.3760	3.85	0.0907
Residual	0.6845	7	0.0978		
Lack of Fit	0.6845	3	0.2282		
Pure Error	0.0000	4	0.0000		
Cor Total	31.78	12			

Table 11: ANOVA for CBR (BSH)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	13.85	5	2.77	12.50	0.0022
A-RHA	2.53	1	2.53	11.44	0.0117
B-Mk	1.04	1	1.04	4.70	0.0668
AB	6.25	1	6.25	28.21	0.0011
A^2	2.51	1	2.51	11.33	0.0120
B^2	3.03	1	3.03	13.65	0.0077
Residual	1.55	7	0.2216		
Lack of Fit	1.55	3	0.5170		
Pure Error	0.0000	4	0.0000		
Cor Total	15.40	12			

Table 9 shows the ANOVA for CBR (BSL). The Model F-value of 44.01 implies the model is significant. P-values less than 0.05 indicate model terms are significant. In this case A and B are significant model terms. Table 10 shows the ANOVA for CBR (WAS). The Model F-value of 63.61 implies the model is significant. A, B, AB, A^2 are significant model terms. Table 11 shows the ANOVA for CBR (BSH). The Model F-value of 12.5 implies the model is significant. A, AB, A^2, B^2 are significant model terms.

Table 12: Fit Statistics for CBR

Parameter	CBR (BSL)	CBR (WAS)	CBR (BSH)
R^2	0.9362	0.9785	0.8993
Adjusted R^2	0.9149	0.9631	0.8273
Predicted R^2	0.8535	0.7897	-0.0196
Adeq Precision	21.8628	23.625	12.55

The Predicted R^2 of CBR (BSL) 0.8535 and CBR (WAS) 0.7897 are in reasonable agreement with the Adjusted R^2 of 0.9149 and 0.9631 but CBR (BSH) with predicted R^2 of -0.0196 is not in reasonable agreement with the adjusted R^2 of 0.8273. The difference between the predicted and adjusted is less than 0.2 indicates significant terms. Adeq Precision measures the signal to noise ratio. A ratio of 21.8628, 23.625 and 12.55 indicates an adequate signal. The model equation for CBR (BSL), CBR (WAS) and CBR (BSH) are shown in Equation 5 – 7..

$$CBR\ (BSL) = 2.4 + 0.075 * A - 0.31 * B + 0.032 * AB \quad \ldots (5)$$

$$CBR\ (WAS) = -12.6 + 3.7 * A - 1.1 * B + 0.08 * AB - 0.149 * A^2 + 0.092 * B^2 \ldots (6)$$

$$CBR\ (BSH) = 9.43 + 1.44 * A - 3.4 * B + 0.18 * AB - 0.078 * A^2 + 0.26 * B^2 \ldots . \quad (7)$$

Figure 4-6 shows 3D response surface graph of interaction between Mk and RHA and the effect on CBR BSL, CBR WAS and CBR BSH respectively.

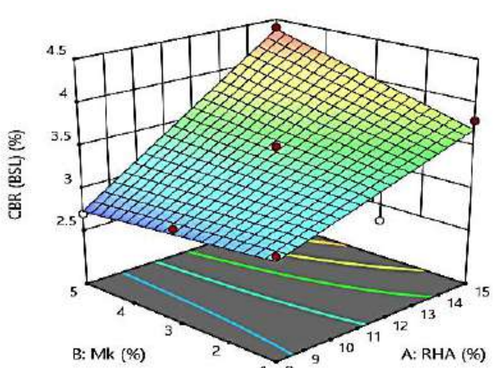

Figure 4: 3-D Response Graph of Effect of Mk and RHA on CBR (BSL)

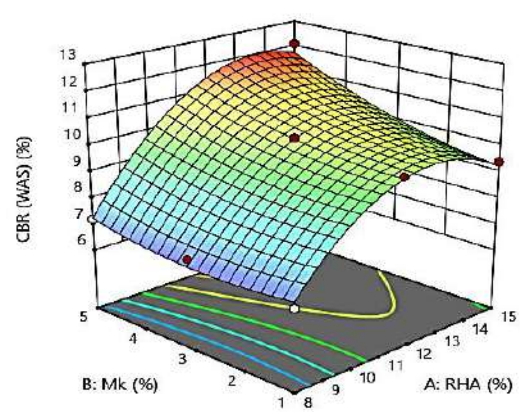

Figure 5: 3-D Response Graph of Effect of Mk and RHA on CBR (BSL)

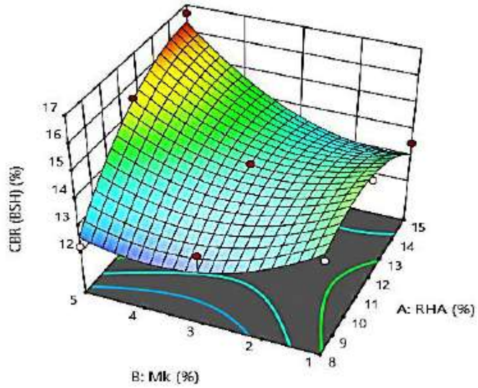

Figure 6: 3-D Response Graph of Effect of Mk and RHA on CBR (BSL)

Figure 4 – 6 show that the 3D response surface graph of interaction between Mk and RHA and the effect on CBR BSL, CBR WAS and CBR BSH elucidates the correlation between the responses and factors. The graph shows that increase in percentage of RHA causes an increase in CBR while an increase in Mk causes a slight increase in CBR. The increase in CBR by metakaolin and RHA is connected to the pozzolanic properties of Mk and RHA.

3.5 Optimization of Mixtures by Numerical Method

The goals set for responses in numerical optimization are presented in Table 13.

Table 13: Goals for Numerical Optimization

Name	Goal	Lower Limit	Upper Limit
A:RHA	is in range	8	15
B:Mk	is in range	1	5
UCS (BSL)	maximize	600	1440
UCS (WAS)	maximize	740	1680
UCS (BSH)	maximize	960	1920
CBR (BSL)	maximize	2.7	4.4
CBR (WAS)	maximize	6.7	12.1
CBR (BSH)	maximize	12.2	16.7

The automatic optimization function of Design-Expert software version 13 indicates that the optimal values of the factors for both factors and responses as shown in Figure 7.

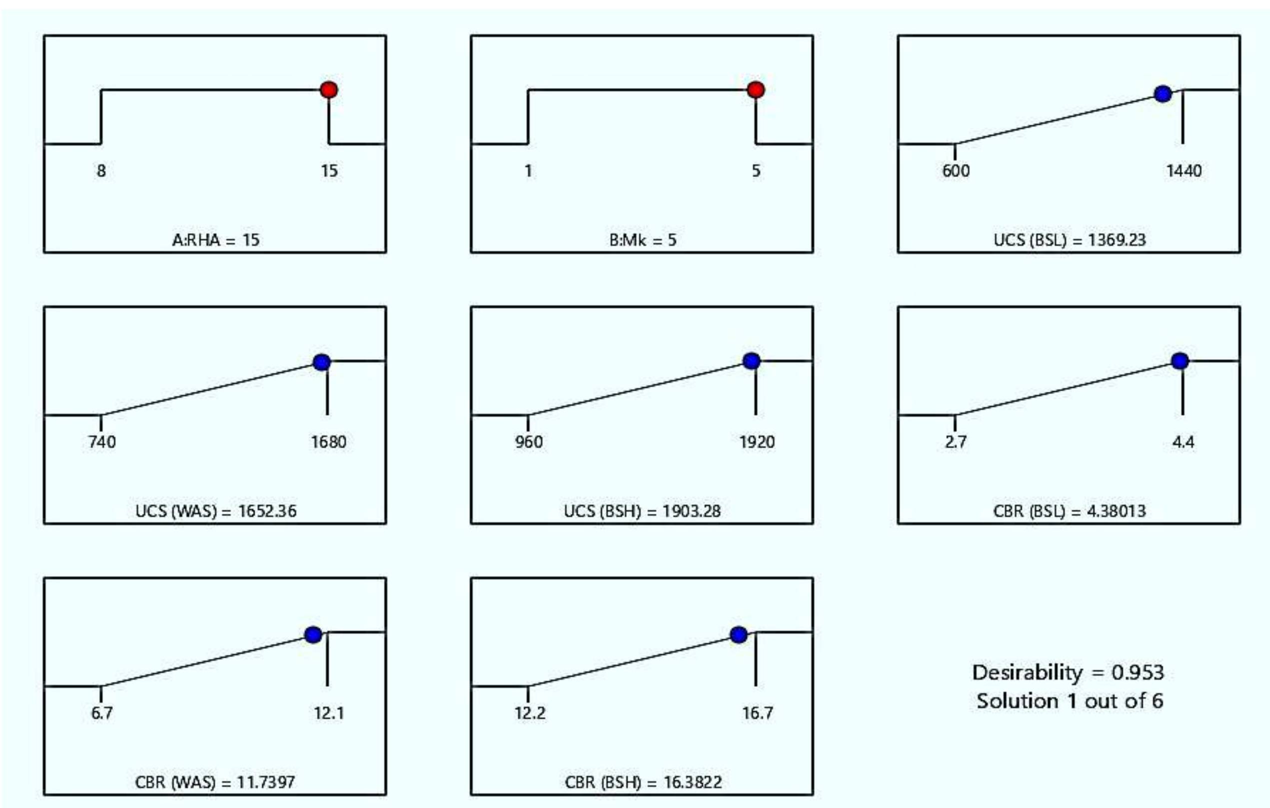

Figure 7: Ramp Plot Showing the Optimal Values for Factors and Responses

IV.CONCLUSIONS

Based on the findings, the following conclusions were made:

The BCS was classified as A-7-6 and CH according to the AASHTO and the unified soil classification system. The OMC was 9.8%, MDD was 1.69 Mg/m^3. The soil has specific gravity of 2.19, Natural moisture content of 0.71%, LL of 44.9% and PL of 25.8%.

The replacement of black cotton soil with Metakaolin and RHA increases both the Unconfined Compressive Strength and California Bearing Ratio. These findings have important implications for the construction industry, where stabilized black cotton soil can be used as a reliable and sustainable subbase material.

Optimization was carried out and models were developed for the estimation of UCS and CBR of admixed black cotton soil. The numerical optimization was done using central composite design and the ramp plot gave 15% Mk, 5% Mk as the best replacement after optimization.

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