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Improvement in Strength Properties of Black Cotton Soil Reinforced with Metakaolin and Calcium Chloride

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ABSTRACT

This study covers the improvement in strength properties of black cotton soil (BCS) using metakaolin (Mk) and calcium chloride ($CaCl_2$) as stabilizing agents. 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. To maximize the enhancement of the geotechnical properties of BCS, the proportions of Mk and $CaCl_2$ were optimized using a central composite design (CCD). The findings of the preliminary investigation indicated that BCS had moisture content of 25.3%. The soil's high flexibility was validated by the BCS's liquid limit, plastic limit, and plasticity index, which were 66.8, 35.2, and 31.6%, respectively. According to the American Association of States Highway and Transportation Officials, the soil was categorized as clay of high plasticity (CH) and A-7-6 (13) by the Atterberg limits and sieve analysis test. The UCS and CBR of admixed black cotton soil with metakaolin and calcium chloride were optimized. The central composite design was used for numerical optimization, and the ramp plot revealed that the optimal replacement was 18% Metakaolin and 2% Calcium Chloride. Regression models for prediction of CBR and UCS were developed. Finally, this study revealed that more studies should be conducted to assess the impact of more locally accessible resources that may be utilized to enhance black cotton soil.

KEYWORDS: Road Base Soils, Metakaolin, Black Cotton Soil, Calcium Chloride, Stabilization

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1.0 INTRODUCTION

Expansive soils usually contain clay mineral montmorillonite which includes sedimentary and residual soils, clay stones, and shales (Zumrawi *et al*., 2017; Abdulkarim *et al*., 2015). The expansive nature of soil is most obvious near ground surface where the profile is subject to seasonal, environmental changes. Black cotton soil (BCS) or black clays or tropical black earth are known to be potentially expansive soils which are "black" or "greyish black" or in their eroded phase "greyish white" heavy loam or clay (usually 50%), with predominant clay mineral of the smectite group, rich in alkali earth elements and the horizons sometimes contain calcium carbonate or magnesium oxide concretions (Gidigasu and Gawu, 2013; Ikara *et al.,* 2019).

The BCS are organic clay, which consist of high argillaceous content of medium to high compressibility, which undergoes excessive volume changes and low strength, making their use in the construction project very difficult (Ofuyatan *et al*, 2021).

Generally, black cotton soil (BCS) swells when absorbed water in the soil mass and shrinks on drying (Ikara *et al.,* 2016; Ikeagwuani, 2016). These soils are characterized by intrinsic swelling and shrinkage. For this reason, there is need for effective utilization of different stabilisers to modify and improve the geotechnical properties of black cotton soil and to study the consequences of these stabilisers on geotechnical properties of Black cotton soil modified (Reddy *et al*., 2019).They are found predominantly in the North-Eastern part of Nigeria, in regions lying within the Chad Basin and partly within the Benue trough. When dry, Black Cotton Soils appear very hard with attendant high bearing capacity but when wet, BCS absorbs large volumes of water, swell rapidly and lose their high bearing capacity thereby leading to excessive settlement and failure of building structures and road pavements built on them (Mai-Bade*et al.,* 2021, Saraf *et al.,* 2022). These geotechnical characteristics make black cotton soils highly problematic when used as foundation for buildings and road pavements. This therefore underscores the various efforts being employed in order to successfully stabilise it with various additives.

Metakaolin is a pozzolanic material and obtained by calcinations of kaolinite clay at temperatures from 700°C to 800°C (Afolayan *et al*., 2022; Abdullahi *et al*., 2024). Kaolin chemical composition is basically aluminous silicates hydrates associated with Mn, Fe, Ca, K, Na. Its crystal has a lattice structure of tetrahedral and octahedral layers.

2.0 MATERIALS AND METHODS

2.1 Materials

The soil sample for this study was collected from Baure village of Yamaltu Deba Local Government Area of Gombe state, Nigeria (Deba is located at Latitude 10^0 13" N and Longitude 11^0 23"). The community called the soil *'Kasan Kalari'*. The method of disturbed sampling was used. Sampling was done at a depth of 1.5m and the soil samples was collected in sacks and sealed in plastic bags for appropriate moisture measurement. The samples were air–dried, pulverized and sieved with the largest sieve being BS no. 4 sieve (4.76 mm aperture). The mineral composition of Black cotton soil was determined at the National Steel Raw Material Exploration Agency (NSRMEA), Kaduna Nigeria, using the method of X-Ray Diffraction.

Metakaolin was obtained from calcination of kaolinitic clay at 750^{O}C. Kaolin chemical composition is basically aluminous silicates hydrates associated with Mn, Fe, Ca, K, Na.

Calcium Chloride is an inorganic compound, a salt with the chemical formula $CaCl_2$. It is a colourless crystalline solid at room temperature, highly soluble in water and the efficacy of calcium chloride helps in improving swell and strength properties of Black Cotton Soil. The use of calcium chloride in black cotton soil stabilisation shows higher shear strength parameters and higher safe bearing capacity of soil. (Krishna and Ramesh, 2012).

2.2 Methods

The tests carried out on the samples were in accordance with relevant standards such as BS1377 Part I, 1990,BS 1377 (1990), BS 1924 (1990) and the Nigerian General Specification for roads and bridgeworks (1997). These tests include classification tests (Atterberg limits and sieve analysis), Physical/identification tests (specific gravity and compaction tests) and Strength tests (California Bearing Ratio CBR and Unconfined Compressive Strength UCS tests).

2.2.1 Compaction Test

The objective of the compaction tests described in BS 1377 (1990) is to obtain relationships between compacted dry density and soil moisture content, using two magnitudes of manual compactive effort, or compaction by vibration.There are different compactive efforts, modified AASHTO, the British standard light (BSL), West African Standard (WAS) and British standard heavy(BSH) of modified proctor. This research considered British Standard Light (BSL) and West African Standard (WAS) only.

2.2.1.1 British Standard Light (BSL)

For the British Standard Light compactive effort (standard proctor) test, the soil was compacted in a mould that has a volume of 1000cm^3. The internal diameter of the mould is 105 mm with 115 mm internal height. During the laboratory test, a base plate was placed at the bottom of the mould and an extension (collar) at the top, approximately 50 mm height. A subsidiary mould (CBR mould) diameter 152 mm and height 127 mm. The BC soil was mixed with varying amount of water and then compacted in three layers by a rammer that delivers twenty-seven (27) blows to each layer. The rammer weighs 2.5 kg and has a drop of 300 mm.

For each of the compacted samples, protruding soils was carefully levelled off with a spatula. The soil samples then removed from the mould and a little portion taken for moisture content determination.

Various percentages by weight of the additives was added to the black cotton soil again with increasing water content from 2%-10%. The bulk density p_i was calculated for each compacted sample as

$$p_i = \frac{M_2 - M_1}{V} \text{x } 1000(\text{Kg/m}^3) \quad \ldots (1)$$

Where,

M_1 = Mass of mould and base (g)

M_2 = Mass of mould, base and soil (g)

And the dry density P_d is calculated as

$$P_d = \frac{100}{100+W} \text{ (Mg/m}^3\text{)} \quad \ldots (2)$$

Where,

W = Moisture content

For each percentage of water that was added to the soil samples, the dry density was plotted against the moisture content and from these the maximum point on the resultant curves gives the Maximum Dry Density (MDD) on the ordinate axis and Optimum Moisture Content (OMC) on the abscissa.

The procedure was repeated for the stabilized material by adding requisite proportions by weight of additives to the natural soil sample. The MDD and OMC values were tabulated.

2.2.1.2 West Africa Standard Test (WAS)

The West African standard compaction is identical to the British standard heavy compaction except that only 10 blows of the rammer per lift were applied rather than the usual 27 blows. In this test the compactive effort is greater than the British Standard Light (BSL) test. The mass of the hammer is increased to 4.5 Kg, the height of the drop to 450 mm, and the number of compacted layers is increased from three (3) to five (5). The test is performed on material passing the 20mm test sieve using the CBR mould as described above. The sample preparation and the testing procedure is identical to the BSL with the exception of the weight of the rammer, the height of drop, and the number of layers. Calculations, plotting of curves and expression of results including the test report are the same as for the BSL. The West African Standard (WAS) compaction test is a type of compaction procedure that utilises intermediate compaction energy (compactive effort) for densification of soils. It has been recommended for densification of soils for highway construction in Nigeria and some other West African Countries. The compaction energy of WAS lies between the compaction energy of BSL (Standard Proctor) and BSH (Modified Proctor).

2.2.2 California Bearing Ratio Test

The California Bearing Ratio Test (CBR Test) is a penetration test developed by California State Highway Department (U.S.A.) for evaluating the bearing capacity of subgrade soil for design of flexible pavement. Tests are carried out on natural or compacted soils in water soaked or un-soaked conditions and the results so obtained are compared with the curves of standard test to have an idea of the soil strength of the subgrade soil.

The principle of California bearing ratio is to determine the relationship between force and penetration when a cylindrical plunger of a standard cross-sectional area is made to penetrate the soil at a given rate. At certain values of penetration, the ratio of the applied force to a standard force, expressed as a percentage, is defined as the California Bearing Ratio (CBR). The tests were carried out as specified in BS 1377 (1990), BS 1924 (1990) and the Nigerian General Specification for roads and bridgeworks (1997).

A 5kg of the sample passing BS sieve 20mm was collected and mixed with an amount of water corresponding to the soil optimum moisture content. The soil sample was covered and allowed to mature for five minutes before being compacted in the CBR mould. Compaction was effected on the 5 layers of approximately equal depths, each layer receiving 62 blows oaf the

2.5kg rammer evenly spread over the surface ensuring that the surface of the fifth layer is not 6mm above the surface of the mould. The soil was then trimmed and the mould with its content was weighed to obtain the density. Surcharge weights were placed on the sample and the whole arrangement was arranged centrally under the plunger on the CBR machine. The plunger was set to an initial setting and allowed to penetrate the sample at the rate of 1.0mm/min. The plunger loads were recorded for each 0.25mm up to a maximum of 7.5mm. The same penetration test was also performed on the base in the form of load against penetration. The plunger resistances at 2.5mm and 5.0mm penetrations was expressed as percentages of 13.24kN and 19.96kN respectively and the higher of the two values was taken as the CBR of the soil.

2.2.3 Unconfined Compressive Strength Test

The Unconfined Compression Test is an important laboratory test which determines the unconfined and undrained compressive strength of a cohesive soil. Unconfined Compressive Strength (UCS) stands for the maximum axial compressive stress that a cohesive soil specimen can bear under zero confining stress. Unconfined compression test is one of the fastest and cheapest methods of measuring shear strength of soil. The specimen was prepared from a disturbed soil sample. The material was wrapped in a thin rubber membrane and thoroughly worked with the fingers to assure complete remoulding. Care was taken to avoid entrapped air, to obtain a uniform density.

A 2.5 kg of the sample was prepared for the CBR test and compacted in the compaction mould. Specimens of height 76mm and diameter of 38mm (but can also be performed on specimens up to 100 mm diameter) was extracted from the compacted samples. The soil specimen was placed at the desired water content and density in the large mould. The sampling tube was pushed into the large mould. The sampling tube was removed fulfilled with the soil specimen. For undisturbed samples, the sampling tube will be pushed into the clay sample. The soil sample was saturated in the sampling tube by a suitable method. The split mould was coated lightly with a thin layer of grease. The mould was weighed. The sample was extracted out of the sampling tube into the split mould, using the sample extractor and the knife. The two ends of the specimen were trimmed in the split mould. The mould with the specimen was weighed. The specimen was removed from the split mould by splitting the mould into two parts. The initial length, diameter and weight of the soil specimen were measured with Vernier Callipers and the soil specimen was placed on the bottom plate of the loading device. The upper plate was adjusted to make contact with the specimen. The dial gauge was adjusted to zero and the proving ring gauge seated. Compression load was applied so as to produce axial strain at a rate of 0.5 to 2 percent per minute causing failure with 5 to 10. The dial gauge reading and the proving ring reading was recorded. The reading was taken at strains of 0, 0.1, 0.2, 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18 and 20 percent. The reading was taken after every thirty seconds up to a strain of 6 percent and after every 60 seconds for a strain between 6% to 12% and after every 2 minutes or so beyond 12%. The compression load (force) reading was taken at interval of 0.5 mm of the deformation dial reading. The test continued until failure surfaces have definitely developed or the stress-strain curve well past its peak or until an axial strain of 20% was reached. The stress-strain curve was plotted. The compressive stress was taken as ordinate and axial strain as abscissa. The angle between the failure surface and the horizontal was measured. The sample from the failure zone of the specimen was taken and the water content of the specimen was determined (in accordance with 7.2 of BS 1377-7:1990). The UCS is given by Equation (3),

$$\sigma_u = \frac{P}{A} \quad \ldots (3)$$

Where,
σ_u = Unconfined compressive strength,
P = the compressive force (axial load at failure), and
A = average cross-sectional area.

2.2.4 Experimental Design and Analysis

Experiment Design Optimization is a method of designing an experiment in the sense that shows how the observations or measurements should be obtained to answer a research questions in a valid, efficient and economical way (Sani and Adetoye, 2024). The designing of the experiment and the analysis of obtained data are inseparable. If the experiment is designed properly keeping in mind the question(s), then the data generated is valid and proper analysis of data provides the valid statistical inferences.

In simple terms, experimental design is a technique that enables scientists and engineers to efficiently assess the effect of multiple inputs, or factors, on measures of performance, or responses. Compared to one-factor-at-a-time, trial-and-error approaches, a well-designed experiment can provide clear results while dramatically reducing the required amount of testing. Therefore, experimental design research encapsulates a wide range of research designs, sharing fundamental design conventions (Cash *et al.* 2016*).*

Table 1: Experimental Design Table

Run	Factor 1 A:Metakaolin (%)	Factor 2 B:Calcium chloride (%)
1	20	3
2	10	1
3	20	5
4	10	5
5	10	3
6	20	1
7	10	3
8	0	3
9	10	3
10	0	1
11	10	3
12	10	3
13	0	5

The responses are: UCS at 28 days, CBR (WAS) and CBR (BSL).

3.0 RESULTS AND DISCUSSION

3.1 Properties of Black Cotton Soil

The Table 2 below presents the summary of the properties of the Black Cotton Soil.

Table 2: Summary of Properties of Black Cotton Soil

Property	Value
Natural moisture content (%)	25.32
Liquid limit (%)	66.8
Plastic limit (%)	35.2
Plasticity index (%)	31.6
Linear shrinkage (%)	18.9
Activity	1.12
Specific gravity	2.54
Particle size distribution	
Percentage PASSING No. 200 sieve	72
Percentage of sand (%)	65
Percentage Silt (%)	23
Percentage of Clay fraction (%)	28
Compaction properties	
Maximum Dry Density (MDD) Mg/m^3	1.69
Optimum Moisture Content (OMC) %	9.8
Strength properties	
7 days UCS kN/m^2	245
7 + 7 days UCS kN/m^2	95
14 days UCS kN/m^2	253
28 days UCS kN/m^2	410
Colour	Dark
Dominant clay mineral	Montmorillonite
AASHTO Classification	A - 7 - 6
Clay Soil (AASHTO)	Fair to poor
UCSC Classification	CH

The results of the preliminary analysis presented in Table 2 showed that BCS had moisture content of 25.3% and showed that the soil is dark in colour. The liquid limit, plastic limit and plasticity index of the BCS were 66.8, 35.2 and 31.6% respectively, which confirmed that the soil is highly plastic. The Atterberg limits and sieve analysis test classified the soil as A-

7-6 (13) according to the American Association of States Highway and Transportation Officials (AASHTO, 2004) and Clay of high plasticity (CH) in accordance with the Unified Soil Classification System (ASTM, 1992).

The percentage sand fraction of 65%, percentage silt fraction 23%, percentage clay fraction 28% and an Activity of 1.12 which indicated that Montmorillonite clay minerals is dominant in the soil. With these parameters the soil falls far below the standard recommended for most Engineering work based on the (Nigeria General Specification, 1997).

The Unconfined Compressive Strength (UCS) value of 410 at OMC 9.8 is relatively low which indicates that the material does not meet the minimum requirement of the (Nigeria General Specification, 1997) and other research findings by (Ikara *et al*., 2019; Mai-Bade *et al.*, 2021).

The chemical test results for oxide composition of metakaolin are presented in Table 3.

Table 3: Oxide Compositions of Soil and Metakaolin

Oxide Composition	Mk (%)
SiO_2	51.9
Al_2O_3	35.1
Fe_2O_3	4.3
CaO	0.34
MgO	0.06
SO_3	0.23
K_2O	0.50
Na_2O	0.13

The respective percentage contents of the major oxides of MK are SiO_2 as 51.9%, Al_2O_3 as 35.1, Fe_2O_3 as 4.3% and CaO as 0.34% and the alkalis Na_2O as 0.13%. This shows that metakaolin have enough silica and alumina which enhance better strength development of soil. The finding is in agreement with Adeniyi *et al*. (2020).

3.2 Result of OMC against MDD

The results of OMC and MDD using WAS and BSL methods are presented in Table 4.

Table 4: Results of OMC and MDD

A:Mk %	B:$CaCl_2$ %	OMC (WAS) %	MDD (WAS) mg/m^3	OMC (BSL) %	MDD (BSL) mg/m^3
20	3	14.0	1.72	14.9	2.21
10	1	13.0	2.68	10.7	2.14
20	5	12.6	2.44	12.6	2.44
10	5	16.0	2.42	16.0	2.42
10	3	54.7	2.29	15.0	2.18
20	1	14.3	1.77	16.6	2.15
10	3	54.7	2.29	15.0	2.18
0	3	10.8	2.1	14.7	1.74
10	3	54.7	2.29	15.0	2.18
0	1	14.4	2.0	12.0	1.73
10	3	54.7	2.29	15.0	2.18
10	3	54.7	2.29	15.0	2.18
0	5	16.6	1.87	12.9	1.77

Where;

Mk = Metakaolin,
OMC = Optimum Moisture Content,
MDD = Maximum Dry Density.

The results shown in Table 4 revealed that at different mix of Mk and $Cacl_2$, OMC and MDD were achieved. Using BSL method, the lowest MDD value of 1.73 mg/m^3 at OMC value of 12% were achieved with 1% $Cacl_2$ and 0% Mk. Using WAS, the lowest MDD value of 1.72 mg/m^3 at OMC of 14% were also achieved with 1% $Cacl_2$ and 20% Mk using WAS. The study on the combined effect of metakaolin and calcium chloride on black cotton soil showed promising results in improving the soil's OMC and MDD. Addition of the materials reduced the OMC and increased the MDD, making the soil more suitable for construction purposes.

3.3 Unconfined Compressive Strength Results

The summary of result and analysis of the test conducted on UCS at 28 days are shown in Tables 5 – 6.

Table 5: Summary of Results of UCS

Run	A:Mk %	B: $Cacl_2$ %	UCS at 28 days kN/m^2
1	20	3	1344
2	10	1	2523
3	20	5	883
4	10	5	984
5	10	3	1696
6	20	1	3278
7	10	3	1696
8	0	3	1943
9	10	3	1696
10	0	1	1306
11	10	3	1696
12	10	3	1696
13	0	5	1102

Where,
Mk = Metakaolin,
$Cacl_2$ = Calcium chloride,
UCS = Unconfined Compressive Strength.

Table 6: ANOVA for UCS at 28 days

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	5.039E+06	7	7.198E+05	1512.00	< 0.0001
A-Metakaolin	1.794E+05	1	1.794E+05	376.83	< 0.0001
B-Calcium chloride	1.184E+06	1	1.184E+06	2487.54	< 0.0001
AB	1.200E+06	1	1.200E+06	2520.85	< 0.0001
A^2	18059.20	1	18059.20	37.93	0.0016
B^2	2344.91	1	2344.91	4.93	0.0772
A^2B	19120.08	1	19120.08	40.16	0.0014
AB^2	7.257E+05	1	7.257E+05	1524.33	< 0.0001
A^3	0.0000	0	476.08		
B^3	0.0000	0	2380.39		
Residual	2380.39	5	0.0000		
Lack of Fit	2380.39	1			
Pure Error	0.0000	4			
Cor Total	5.041E+06	12			

In Table 6, the Model F-value of 1512 implies the model is significant. P-values less than 0.05 indicate model terms are significant. In this case A, B, AB, A^2, A^2B, AB^2 are significant

model terms. Values greater than 0.1 indicate the model terms are not significant. The Fit – statistics is presented in Table 7.

Table 7: Fit – Statistics for UCS

Parameter	UCS at 28 days
R^2	0.9995
Adjusted R^2	0.9989
Predicted R^2	0.9451
Adeq Precision	139.924

The model equation for UCS at 28 days is presented in Equation (3) below;

$$UCS\ at\ 28\ Days\ =\ 1{,}704 - 300A\ - 769.5B - 547.75AB - 80.9A^2\ +\ 29B^2\ + \\ 120A\text{^}2B\ +\ 738AB^2 \ldots(3)$$

Where;
A = Metakaolin (%)
B = Calcium chloride (%)

Figure 1 shows 3D response surface graph of interaction between Mk, Calcium chloride and the effect on UCS at 28 days.

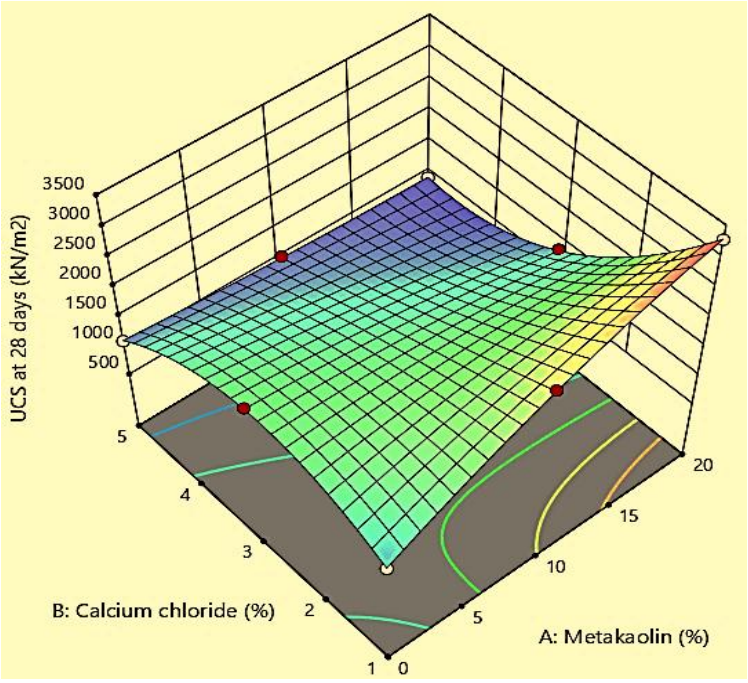


Figure 1. 3-D Response Graph of Effect of Mk and $CaCl_2$ on UCS at 28 Days

From Figure 1, the 3D response surface graph of interaction between Mk and $CaCl_2$ and the effect on UCS at 28 day elucidates the correlation between the dependent variables

(responses) and the independent variables (factors). The graph shows that increase in percentage of Mk causes an increase in UCS while an increase in calcium chloride causes a slight decrease in UCS at 28 days. The increase in UCS by metakaolin is connected to its pozzolanic properties.

3.4 California Bearing Ratio (CBR) Result

The result of CBR is presented in Table 8, the ANOVA in Table 9 – 10 and the Fit statistics in Table 11.

Table 8: Summary of Results of CBR

A:Mk %	B: $Cacl_2$ %	CBR (WAS) %	CBR (BSL) %
20	3	43.8	27.9
10	1	36.6	13.6
20	5	47.1	34.2
10	5	38.5	29.5
10	3	37.8	24.2
20	1	40	14.4
10	3	37.8	24.2
0	3	18.1	16.2
10	3	37.8	24.2
0	1	13.5	12.8
10	3	37.8	24.2
10	3	37.8	24.2
0	5	18.9	22.7

The California Bearing Ratio values of admixed BCS with Mk and Calcium chloride shown in Table 8 indicated that both metakaolin and calcium chloride contributes significantly to the percentage increase in CBR of the soil. However, the results indicated short-fall in the minimum requirement by Nigeria Specification Standard, (1997)

Table 9: ANOVA for CBR (WAS)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	1295.30	5	259.06	235.99	< 0.0001
A-Metakaolin	1077.36	1	1077.36	981.41	< 0.0001
B-Calcium chloride	34.56	1	34.56	31.48	0.0008
AB	0.7225	1	0.7225	0.6582	0.4439
A^2	145.10	1	145.10	132.18	< 0.0001
B^2	1.16	1	1.16	1.06	0.3380
Residual	7.68	7	1.10		
Lack of Fit	7.68	3	2.56		
Pure Error	0.0000	4	0.0000		
Cor Total	1302.99	12			

In Table 9, the Model F-value of 235.99 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. In this case A, B, A^2 are significant model terms. Values greater than 0.1 indicate the model terms are not significant.

Table 10: ANOVA for CBR (BSL)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	497.11	5	99.42	63.10	< 0.0001
A-Metakaolin	102.51	1	102.51	65.06	< 0.0001
B-Calcium chloride	346.56	1	346.56	219.95	< 0.0001
AB	24.50	1	24.50	15.55	0.0056
B^2	9.61	1	9.61	6.10	0.0428
Residual	11.03	7	1.58		
Lack of Fit	11.03	3	3.68		
Pure Error	0.0000	4	0.0000		
Cor Total	508.14	12			

Table 10 shows the ANOVA for CBR (BSL). The Model F-value of 63.10 implies the model is significant. P-values less than 0.05 indicate model terms are significant. In this case A, B, AB, B^2 are significant model terms. The Fit-statistics is shown in Table 11

Table 11: Fit Statistics for CBR

Parameter	CBR (BSL)	CBR (WAS)
R^2	0.9783	0.9941
Adjusted R^2	0.9628	0.9899
Predicted R^2	0.7911	0.9412
Adeq Precision	27.5182	44.3943

The Predicted R^2 of CBR (BSL) 0.7911 and CBR (WAS) 0.9412 are in reasonable agreement with the Adjusted R^2 of 0.9628 and 0.9899. The difference between the predicted and adjusted R^2 is less than 0.2 indicates significant terms. Adeq Precision measures the signal to noise ratio. A ratio of 27.5182 for CBR (BSL) and 44.3943 for CBR (WAS) indicates an adequate signal. The model equation for CBR (WAS) and CBR (BSL) are shown in Equations 4 to 5.

$$CBR\ (WAS) = 37.9 + 13.4A + 2.4B + 0.425AB - 7.25A^2 - 0.648B^2 \quad \ldots (4)$$

$$CBR\ (BSL) = 23.97 + 4.13A + 7.6B + 2.48AB - 1.366A^2 - 1.866B^2 \quad \ldots (5)$$

Figures 2 – 3 show 3D response surface graph of interaction between Mk and $CaCl_2$ and the effect on CBR (BSL) and CBR (WAS) respectively.

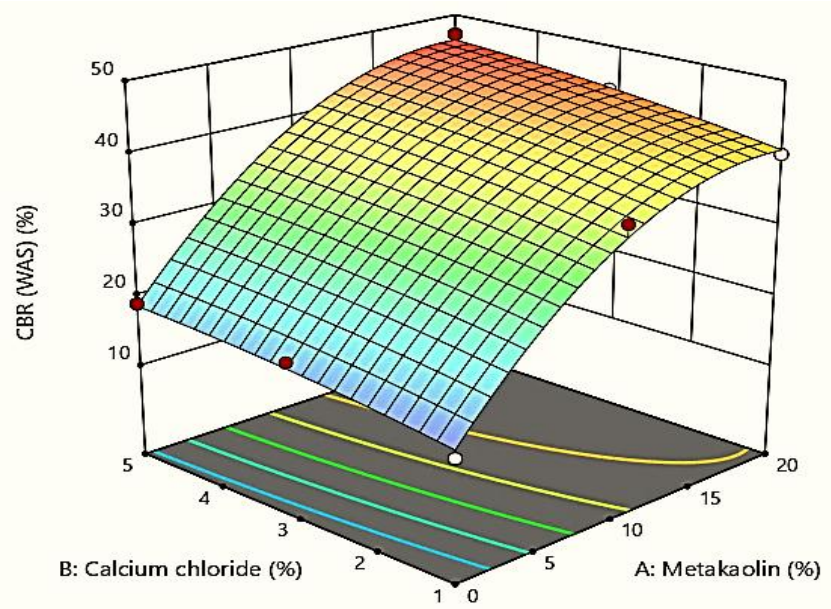


Figure 2: 3-D Response Graph of Effect of Mk and $CaCl_2$ on CBR (WAS)

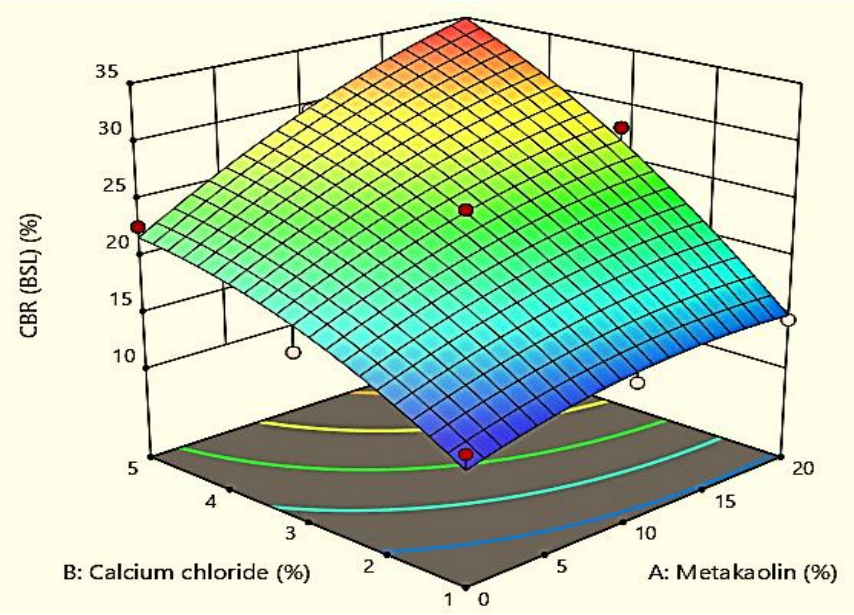


Figure 3: 3-D Response Graph of Effect of Mk and $CaCl_2$ on CBR (BSL)

Figures 2 and 4 show that the 3D response surface graph of interaction between Mk and $CaCl_2$ and the effect on CBR (BSL) and CBR (WAS) elucidates the correlation between the responses and factors. The graph shows that increase in percentage of Mk and $CaCl_2$ cause an increase in percentage of CBR. The increase in CBR by Mk is connected to the possibility of having high content silica oxide and aluminium oxide.

3.5 Optimization by Numerical Method

The goals set for responses in numerical optimization are presented in Table 12.

Table 12: Goals for Numerical Optimization

Name	Goal	Lower Limit	Upper Limit
A:Metakaolin	is in range	0	20
B:Calcium chloride	is in range	1	5
UCS at 28 days	maximize	883	3278
CBR (WAS)	maximize	13.5	47.1
CBR (BSL)	maximize	12.8	34.2

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 4.

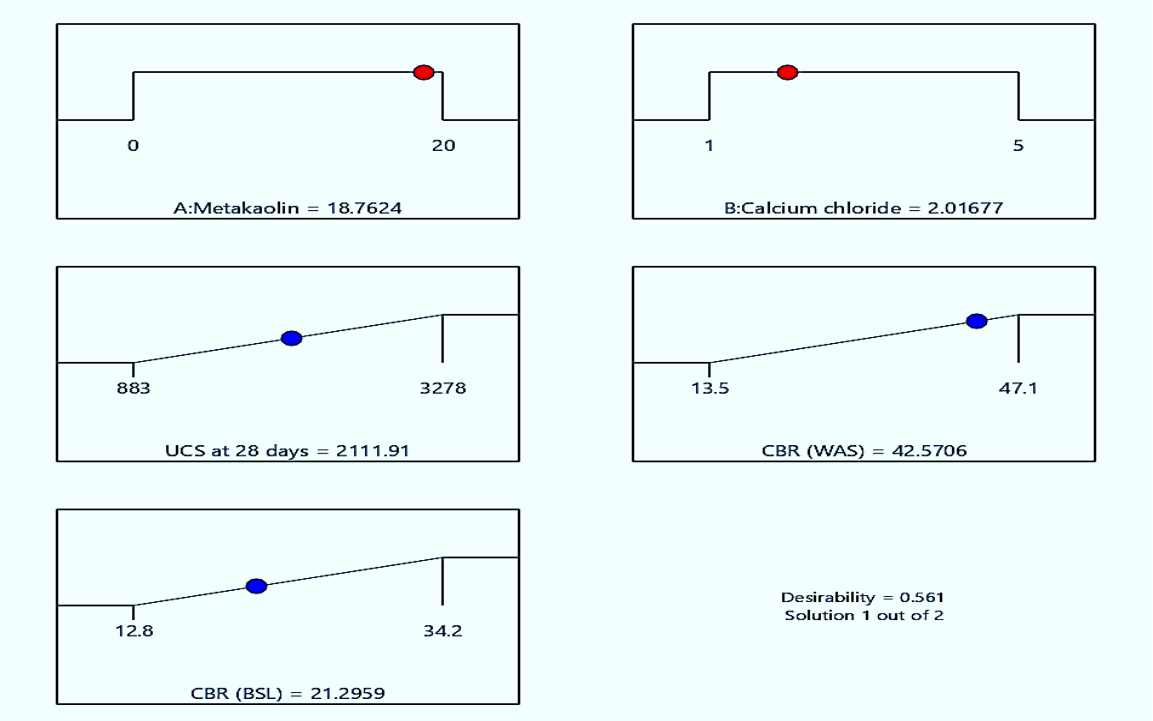


Figure 4: Ramp Plot Showing the Optimal Values for Factors and Responses

5.0. CONCLUSIONS

The following conclusions were made:

i The BCS had moisture content of 25.3% and the soil is dark in colour. The liquid limit, plastic limit and plasticity index of the BCS were 66.8, 35.2 and 31.6% respectively, which confirmed that the soil is highly plastic. The Atterberg limits and sieve analysis test classified the natural soil as A-7-6 (13) according to the American Association of States Highway and Transportation Officials (AASHTO, 2004) and Clay of high plasticity (CH).

ii The replacement of black cotton soil with Metakaolin and calcium chloride increase 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.

iii The UCS and CBR of admixed black cotton soil was optimized and models were created. The central composite design was used for numerical optimization, and the ramp plot revealed that the optimal replacement was 18.7% Metakaolin and 2.6% Calcium Chloride.

iv Regression models for prediction of CBR and UCS were developed.

REFERENCES

Abdulkarim. I, Kundiri A. and Mohammed A. (2015). Effects of Waste Glass on the Strength Characteristics of Cement Stabilized Expansive Soil. *American Journal of Engineering Research*. Volume-4, Issue-11, pp-33-41.

Abdullahi Y.M., Sani A., and Adetoye O. (2024). Optimization of Concrete Containing Metakaolin and Cement Kiln Dust using Central Composite Design. *International Journal of Built Environment and Earth Science*. Vol. 5 (4). pp. 1-12.

Adeniyi, F.I.; Ogundiran, M.B.; Hemalatha, T.; Hanumantrai, B.B. (2020). Characterization of raw and thermally treated Nigerian kaolinite-containing clays using instrumental techniques. *SN Appl. Sci*. 2020, 2, 821.

Afolayan T., Adetoye O., Aliyu S., (2022): A Review on the Effect of Pozzolanic Properties of Metakaolin in Concrete. *International Journal of Research Publication and Reviews*, Vol. 3, (1), pp 1383-1388, January 2022.

Cash, P., Stanković, T., & Štorga, M. (2016). *An introduction to experimental design research. Experimental design research: Approaches, perspectives, applications*, 3-12.

Gidigasu S. S. R and Gawu S. K. Y (2013). The Mode of Formation, Nature and Geotechnical characteristics of Black Cotton Soils - A Review. *Standard Scientific Research and Essays* Vol1 (14): 377-390.

Ikara, I. A., Kundiri, A. M., & Mohammed, A. (2019). Predicting CBR Values of Black Cotton Soil Stabilized with Cement and Waste Glass Admixture Using Regression Model. *American Journal of Traffic and Transportation Engineering*, *4*(1), 31-36.

Ikara, I., Kundiri, A., & Mohammed, A. (2016). Influence of Standard and Modified Proctor Compactive Efforts on Cement Stabilized Black Cotton Soil (BCS) with Waste Glass (WG)Admixture. *IOSR Journal of Mechanical and Civil Engineering*, 13(3), 7–16.

Ikeagwuani C. C. (2016) Compressibility Characteristics of Black Cotton Soil Admixed With Sawdust Ash and Lime. *Nigerian Journal of Technology*. Vol. 35, No. 4. http://dx.doi.org/10.4314/njt.v35i4.5.

Krishna, K.N., and H. N. Rames (2012). *Strength and F O S Performance of Black Cotton Soil Treated with Calcium Chloride*. *Journal of Mechanical and Civil Engineering*. Volume 2, Issue 6, PP 21-25.

Mai-Bade U.Y., Chinade A.U., Batari A., and Saeed S.M., (2021). Stabilization of Black Cotton Soil Using Various Admixtures: A Review, *Composite Materials*. (5) 2:37-45. doi: 10.11648/j.cm.20210502.12

Ofuyatan, O., Olowofoyeku, A., & Oluwafemi, J. (2021*).* Effect of snail shell ash on black cotton soil. *In Journal of Physics: Conference Series*. Vol. 1734, No. 1. IOP *Publishing. Journal of Physics*. doi:10.1088/1742-6596/1734/1/012030

Reddy M. M. (2019). *Experimental Investigation on Physical Properties of Black Cotton Soil with Admixtures.International Journal of Recent Technology and Engineering*. Volume-8, Issue-1.

Sani A., & Adetoye O. (2024): Optimization of Self-Compacting Concrete Incorporating Granite Dust and Rice Husk Ash Using Response Surface Methodology. *KIU Journal of Science, Engineering and Technology.* Vol. 3(1), 39-46. https://doi.org/10.59568/KJSET-2024-3-1-04

Saraf S., Langote G., Dehankar S, Kalmegh R., Ashutosh C., Bokde P. (2022). Stabilization of Black Cotton Soil: A Review. Vidyabharati *International Interdisciplinary Research Journal* 14(2) June 2022

Zumrawi, M. M., Abdelmarouf, A. O., & Gameil, A. E. (2017). Damages of Buildings on Expansive Soils: Diagnosis and Avoidance. *International Journal of Multidisciplinary and Scientific Emerging Research*, 6(2), 108-116.