EASR

Engineering and Applied Science Research

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Published by the Faculty of Engineering, Khon Kaen University, Thailand

Experimental and optimization study of unconfined compressive strength of ameliorated tropical black clay

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Received 26 June 2020
Revised 25 August 2020
Accepted 8 September 2020

Abstract

In the field of soil re-engineering, unconfined compressive strength (UCS) of soil material is considered as an essential soil parameter. This is because it also provides the strength benchmark of soil materials for usage in road foundations. However, Scheffe's approach in conjunction with the utilization of waste materials have been comprehensively utilized in predicting and ameliorating various soil parameters in the field of civil infrastructural constructions. For this purpose, this study outlines the practicality of applying Scheffe's technique in optimizing UCS values of tropical black clay soil (BCS) treated with cement kiln dust (CKD) and metakaolin (MTK) blend. The tropical black clay which falls within the A-7-6 (14) group via AASHTO classification scheme and CH via the Unified Soil Classification Scheme. Qualitative tests such as scanning electron microscopy (SEM) and Fourier transform infrared (FTIR) were executed on both the natural and BCS ameliorated with optimal combination based on Scheffe's concept. These qualitative tests confirmed the build ups of major compounds in the soil matrix thereby promoting the use of Scheffe's technique in soil treatment studies. During the optimization exercise, the attained outcomes revealed that the peak values of 1206 and 1735 kN/m^2 (7 and 28 days curing) with a mix ratio of 1.0:0.30:0.35:0.50 for soil, water, cement kiln dust and metakaolin respectively. The formulated mathematical models considered UCS values of compacted soil materials as dependent variable (response) whereas CKD, MTK, BCS and water were considered as independent variables. Furthermore, the analysis of variance (Anova) and student t-test which are techniques for testing the goodness of a fit were applied to statistically scrutinize the mathematical models and ascertain the adequacy and validity. Hence, the outcomes of this research work portrays the feasibility of using predictive models for UCS prediction and this will aid in providing benchmarks when utilized as road construction material for sustainable infrastructure delivery.

Keywords: Soil stabilization, Unconfined compressive strength, Scheffe's approach, Scanning electron microscopy, Fourier transform infrared

1. Introduction

In most civil engineering construction sites, expansive soils deposit are sometimes encountered and their predominant existence in most tropical environment cannot be bypassed during construction activities. This situation have most time led to the construction failure of dams, roads, bridges etc. [1]. Black cotton soil (BCS) is known for its low strength behaviour during construction or even throughout the design life of engineering infrastructures. With this usual behaviour which is accountable for the swell-shrink actions, tropical BCS is considered as undesired foundation material for Civil engineers. They demonstrate an uncertain swell-shrink characteristics thereby causing problems when used as road construction material. Also, the clay mineralogy of this soil is controlled by the natural expansive mixed layers of minerals such montmorillonite, vermiculite, etc.

As a result of this unfavourable engineering behaviour of this soil, several research works are ongoing to proffer solution in remedying the characteristics of this soil. Hence, incorporation of some waste materials by means of stabilization with different types of additives will help ameliorate the geotechnical behaviour of this soil so as to make it an appropriate road construction material. Improvement of soil for general infrastructural development aids in enhancing as well as ameliorating the effects on both physical and chemical properties of soil [2]. In recent years, due to high cost of construction materials, several scholars are now paying attention to the use different types of waste and as well as eco-friendly materials in soil treatment studies and such materials include lime-iron ore tailing [3], cement kiln dust-bagasse ash [4], metakaolin [5], periwinkle shell ash [6], oyster shell ash [7], groundnut shell ash [8], concrete waste [9], rice husk ash [10], selected agricultural waste [11], waste wood ash [12], hair fibre [13], glass fine [14] and so on. These wastes may possibly be used as stand-alone stabilization agents so as to enhance the geotechnical behaviour of deficient soil or combined with other wastes [4]. From the forgoing, the incorporation of these wastes in enhancing deficient soil materials are gaining relevance and have thereby become very useful to the civil engineers.

Cement kiln dust (CKD) been a predominant industrial waste derived from cement production has been used in the enhancement of soil with poor geotechnical properties. Documented research work of [4] established that the use of

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doi: 10.14456/easr.2021.26

cement kiln dust – bagasse ash blend in soil improvement would be very useful in construction applications. Metakaolin (MTK) is gotten from the calcination of kaolin clay and as such enormous depositions of these kaolin are found in abundance several parts of the world, including Nigeria. However, previous investigators have established progressive outcomes on the use of calcined kaolin also known as metakaolin in soil improvement [15, 5].

In the past, several scholars had applied various optimization techniques such as Scheffe's optimization approach [16-21], response surface methodology [22-24], Taguchi [25, 26], genetic algorithm [27], artificial neural network [28, 29] etc. to predict soil behaviour, solve complex geotechnical problems and as well achieve the best economical and efficient mix during soil improvement. A sizeable volume of research works has been documented in the public domain on optimization and some of these studies focused on Scheffe's optimization approach applied in both soil and concrete materials, such as [16-21]. Firstly, despite the application of Scheffe's optimization technique in the area of civil engineering materials, they exist minute attempts in optimizing the additives for the purpose of ameliorating the unconfined compressive strength of a tropical black clay soil. Secondly, to the best of the authors' understanding, an in-depth examination of the microstructural behaviour in terms of scanning electron microscopy (SEM) and Fourier transform infrared (FTIR) of both natural and optimally treated soil material will bridge the gap of previous investigators in the field of soil re-engineering.

This particular investigation aims at applying Scheffe's approach in optimizing unconfined compression strength test (UCS) values of tropical black clay ameliorated with CKD-MTK blend. With this approach, it would proffer solution of achieving the most economical and optimum content of CKD-MTK blend in enhancing the UCS of tropical black clay.

1.1 Scheffe's factor space

Based on Scheffe [30] the response of a treated soil is a function of the unit of the various constituents' materials. Also, the higher the power of degree n in the regression model the larger or greater is the design points which will expectedly increase the number of coefficient. This may as well lead to a complexity in evaluation of the number of runs.

$$if\ n = 1; f(x)\ \sum_{i=1}^{q} \beta_i x_i \tag{1}$$

$$if\ n = 2: f(x)\ \sum_{i=1}^{q} \beta_i x_i + \sum_{1\le i\le j\le q} \beta_{ij}\, x_i x_j \tag{2}$$

$$if\ n = 3: f(x) \sum_{i=1}^{q} \beta_i x_i + \sum_{1\le i\le j\le q} \beta_{ij} x_i x_j + \sum_{1\le i\le j\le k\le q} (\beta_{iij} x_i^2 x_j + \beta_{iij} x_i x_j x_k) \tag{3}$$

The response of the mixtures studied is said to be a real valued function on the simplex. A mixture with a sum of q components and X_1 is the fraction of the ith constituent, such that $X_i \geq 0$ (i = 1, 2, ---q) and the summation of all constituent mixture must be unity.

$$X_1 + X_2 + X_3 + X_4 = 1\ or \sum X_i - 1 = 0 \tag{4}$$

$$n = b_0 + \sum_{1\le i\le q} b_i X_i + \sum_{1\le i\le j\le q} b_{ij}\, X_i X_j + \sum_{1\le i\le k\le q} b_{ijk}\, X_i X_j X_k +.+ \sum b_{i1i2} \dots in X_{i1} X_{i2} X_{jn} \tag{5}$$

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_{11}X_1^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{14}X_1X_4 + b_{22}X_2^2 + b_{23}X_2X_3 + b_{24}X_2X_4 + b_{33}X_3^2 + b_{34}X_3X_4 + b_{44}X_4^2 \tag{6}$$

Sum to one constant: $X_1 + X_2 + X_3 + X_4 = 1$
The reduced 2nd degree polynomial can be obtain by multiplying equation (4) by b_0:

$$b_0 = b_0X_1 + b_0X_2 + b_0X_3 + b_0X_4 \tag{7}$$
$$b_0 = b_0(X_1 + X_2 + X_3 + X_4)$$

Therefore, multiplying equation (4) by X_1, X_2, X_3 and X_4 will give us:

$$X_1^2 + X_1X_2 + X_1X_3 + X_1X_4 = X_1$$
$$X_1X_2 + X_2^2 + X_2X_3 + X_2X_4 = X_2$$
$$X_1X_3 + X_2X_3 + X_3^2 + X_3X_4 = X_3$$
$$X_1X_4 + X_2X_4 + X_3X_4 + X_4^2 = X_4$$

$$\left.\begin{aligned} X_1^2 &= X_1 - X_1X_2 - X_1X_3 - X_1X_4 \\ X_2^2 &= X_2 - X_1X_2 - X_2X_3 - X_2X_4 \\ X_3^2 &= X_3 - X_1X_3 - X_2X_3 - X_3X_4 \\ X_4^2 &= X_4 - X_1X_4 - X_2X_4 - X_3X_4 \end{aligned}\right\} \tag{8}$$

Substitute equation (7) and (8) into (6):

$$\begin{aligned} \hat{Y} = &(b_0 + b_1 + b_{11})X_1 + (b_0 + b_2 + b_{22})X_2 \\ &+ (b_0 + b_3 + b_{33})X_3 + (b_0 + b_4 + b_{44})X_4 \\ &+ (b_{12} - b_{11} - b_{22})X_1X_2 + (b_{13} - b_{11} - b_{33})X_1X_3 \\ &+ (b_{14} - b_{11} - b_{44})X_1X_4 + (b_{23} - b_{22} - b_{33})X_2X_3 \\ &+ (b_{24} - b_{22} - b_{44})X_2X_4 + (b_{34} - b_{33} - b_{44})X_3X_4 \end{aligned} \tag{9}$$

If we denote $\beta_i = b_0 + b_i + b_{ii}$ and $\beta_{ij} = b_{ij} - b_{ii} - b_{jj}$ (10)

Therefore, the reduced 2nd degree polynomial is obtained in eqn. (11)

$$\hat{Y} = \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_{12}X_1X_2 + \beta_{13}X_1X_3 + \beta_{23}X_2X_3 + \beta_{24}X_2X_4 + \beta_{34}X_3X_4 \tag{11}$$

$$\begin{aligned} Y_1 &= \beta_1, Y_2 = \beta_2, Y_3 = \beta_3, Y_4 = \beta_4, \beta_{12} \\ &= 4Y_{12} - 2Y_1 - 2Y_2, \beta_{13} = 4Y_{13} - 2Y_1 - 2Y_3, \beta_{14} \\ &= 4Y_{14} - 2Y_1 - 2Y_4, \beta_{23} = 4Y_{23} - 2Y_2 - 2Y_3, \beta_{24} \\ &= 4Y_{24} - 2Y_2 - 2Y_4, \beta_{34} = 4Y_{34} - 2Y_3 - 2Y_4 \end{aligned} \tag{12}$$

These are the coefficients of the second degree polynomial for a q component mixture.

2. Materials and test methods

2.1 Materials

Locally available BCS collected from a single deposit in Deba, Gombe State, Nigeria was studied. The raw CKD used for the study was acquired from Lafarge Cement Company, Calabar, Cross River State whereas the raw kaolin used for the production of metakaolin in this current research was obtained from Ohiya located in Abia State, Nigeria.

2.2 Test methods

In this study, the research methods involved experimental design, laboratory tests and formulation of mathematical models. They four number of constituent materials (independent variables) considered are as follows: BCS, CKD, MTK and water. The guiding principles described in BS 1377 [31] was used to scrutinize the behaviour of the untreated expansive soil and as such the following tests were carried out on the untreated soil specimens: particle size gradation, Atterberg limits, specific gravity, compaction, California bearing ratio and unconfined compressive strength test (UCS). Thereafter, the UCS (7 and 28 days) being the response (dependent variable) investigated upon in this study was tested with the proportions of it constituent materials achieved from iterations of the 4, 2 Scheffe's polynomial as shown in Table 1. These values represent the batching by weight of the dry solid to induce protocol of stabilization.

Table 1 Design matrix table as per Scheffe's (4, 2) - lattice polynomial.

Symbol of runs	Actual constituents				Outcome	Pseudo constituents			
	Z_1	Z_2	Z_3	Z_4		X_1	X_2	X_3	X_4
1	1.0	0.100	0.150	0.200	Y_1	1	0	0	0
2	1.0	0.160	0.200	0.250	Y_2	0	1	0	0
3	1.0	0.250	0.230	0.400	Y_3	0	0	1	0
4	1.0	0.300	0.350	0.500	Y_4	0	0	0	1
5	1.0	0.130	0.175	0.225	Y_{12}	0.5	0.5	0	0
6	1.0	0.175	0.190	0.300	Y_{13}	0.5	0	0.5	0
7	1.0	0.20	0.250	0.35	Y_{14}	0.5	0	0	0.5
8	1.0	0.205	0.215	0.325	Y_{23}	0	0.5	0.5	0
9	1.0	0.230	0.275	0.375	Y_{24}	0	0.5	0	0.5
10	1.0	0.275	0.290	0.375	Y_{34}	0	0	0.5	0.5

Table 2 Design matrix table for control points as per Scheffe's (4, 2) factor space

Symbol of runs	Actual constituents				Outcome	Pseudo constituents			
	Z_1	Z_2	Z_3	Z_4		X_1	X_2	X_3	X_4
1	1.0	0.182	0.216	0.31	CT_1	0.4	0.2	0.2	0.2
2	1.0	0.194	0.226	0.32	CT_2	0.2	0.4	0.2	0.2
3	1.0	0.212	0.232	0.35	CT_3	0.2	0.2	0.4	0.2
4	1.0	0.222	0.256	0.37	CT_4	0.2	0.2	0.2	0.4
5	1.0	0..2025	0.2325	0.3375	CT_{12}	0.25	0.25	0.25	0.25
6	1.0	0.223	0.249	0.365	CT_{13}	0.1	0.3	0.3	0.3
7	1.0	0.211	0.239	0.355	CT_{14}	0.3	0.1	0.3	0.3
8	1.0	0.193	0.233	0.325	CT_{23}	0.3	0.3	0.1	0.3
9	1.0	0.183	0.209	0.305	CT_{24}	0.3	0.3	0.3	0.1
10	1.0	0.197	0.224	0.33	CT_{34}	0.3	0.2	0.3	0.2

For each response, there were twenty (20) runs of experiment, the first ten (10) were obtained to formulate the models and are called trial mixes. The additional ten (10) mix ratios were also generated for each response and were used to validate the models for each response. However, a representative sample of the materials used were taken and examined for it chemical composition in the laboratory using the X-ray fluorescence (XRF) analysis.

2.2.1 Pseudo and real components

$$\mathrm{AZ} = \mathrm{AX} \quad (13)$$

Z and X indicates actual and pseudo constituents, respectively and A is equivalent to the constant in a 4x4 square matrix in this study. Matrix A is derived from the first four mix ratios as follows: Z_1 [1.0:0.1:0.15:0.2], Z_2 [1.0:0.16:0.2:0.25], Z_3 [1.0:0.25:0.23:0.4] and Z_4 [1.0:0.3:0.35:0.5]. Similarly, the pseudo mix ratios form an identity matrix using the following X_1 [1:0:0:0], X_2 [0:1:0:0], X_3 [0:0:1:0] and X_4 [0:0:0:1]

Putting Xi and Zi into eqn. (12) where X_1 = quantity of soil; X_2 = quantity of water ratio; X_3 = quantity of cement kiln dust and X_4 = quantity of metakaolin.

$$\begin{pmatrix} Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{pmatrix} \quad (14)$$

The values of the actual mix ratios are substituted into eqn. (14) at each point in the factor space and the subsequent equation is resolved.
For the first run;

$$\begin{pmatrix} 1.0 \\ 0.1 \\ 0.15 \\ 0.2 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (15)$$

$a_{11} = 1.0;\ a_{21} = 0.10;\ a_{31} = 0.15;\ a_{41} = 0.20$
For the second run;

$$\begin{pmatrix} 1.0 \\ 0.16 \\ 0.20 \\ 0.25 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \quad (16)$$

$a_{12} = 1.0;\ a_{22} = 0.16;\ a_{32} = 0.20;\ a_{42} = 0.25$
For the third run;

$$\begin{pmatrix} 1.0 \\ 0.25 \\ 0.23 \\ 0.40 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} \quad (17)$$

$a_{13} = 1.0;\ a_{23} = 0.25;\ a_{33} = 0.23;\ a_{43} = 0.40$
For the fourth run;

$$\begin{pmatrix} 1.0 \\ 0.30 \\ 0.35 \\ 0.50 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \quad (18)$$

$a_{14} = 1.0;\ a_{24} = 0.30;\ a_{34} = 0.35;\ a_{44} = 0.50$
Assembling the coefficients obtained from eqns. (15) to (18) yields the coefficient matrix A.

$$A = \begin{pmatrix} 1.0 & 1.0 & 1.0 & 1.0 \\ 0.10 & 0.16 & 0.25 & 0.30 \\ 0.15 & 0.20 & 0.23 & 0.35 \\ 0.20 & 0.25 & 0.40 & 0.50 \end{pmatrix} \quad (19)$$

In order to determine the actual constituent materials required in the batching mix, multiply the values of matrix A with values of matrix X and so on. The values of actual and pseudo constituents for the different experimental runs are shown on Table 1 whereas for the control points are demonstrated on Table 2.

Table 3 Geotechnical performance of the tropical black soil

Performance description of soil and units	Amount
NMC (%)	20.20
Gravel (%)	0.475
Sand (%)	27
Silt (%)	62.028
Clay (%)	10
LL (%)	56.30
PL (%)	27.60
PI (%)	28.70
LS (%)	18
FS (%)	53.50
G_S	2.40
Classification as per AASHTO	A-7-6 (14)
Classification as per USCS	CH
MDD (Mg/m^3)	1.61
OMC (%)	18
CBR (%)	3
Colour	Greyish black
Dominant clay mineral	Montmorillonite

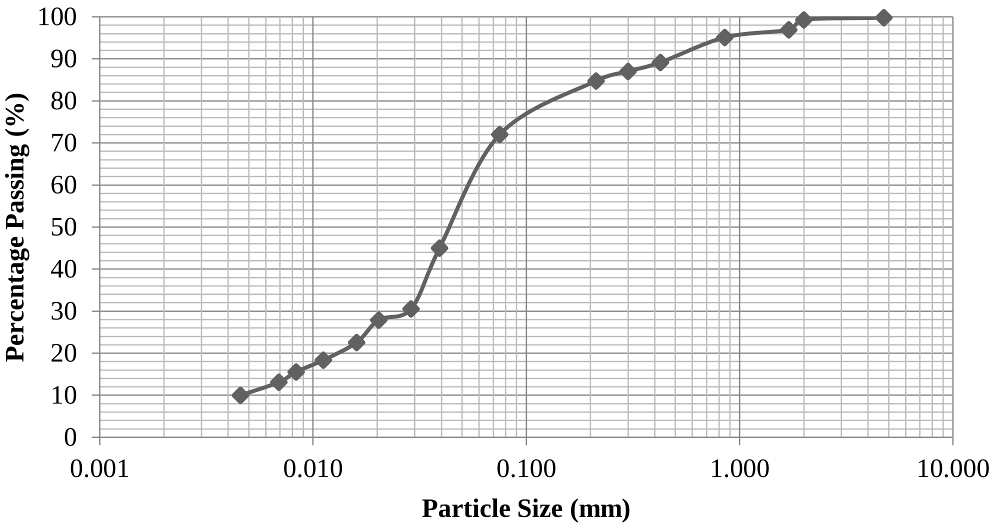


Figure 1 Grading curve analysis for the studied soil material

2.2.2 Unconfined compressive strength test (UCS)

The UCS experimentation protocols was executed based on the guidelines documented in [31, 32] for the natural and treated soil materials, respectively. During this testing exercise, the soil mixtures was compacted into a mould based on the standard proctor compaction effort and adopting a curing duration of 7 and 28 days before conducting the test.

2.2.3 Microstructural test

The micro fabric orientation and absorption bands of the tested soil materials were assessed via the means of two microstructural tests known as scanning electron microscopy (SEM) and Fourier transformation infrared (FTIR). Interestingly, the essence of carrying out microstructural test is to understand the changes in micro morphology and characterization of both untreated and treated soil samples. In addition, FTIR spectrometry was make use of in establishing the functional groups in the materials and the measurements was carried out using transmittance at a wave band from 650 to 4000 cm^{-1}.

3. **Results and discussion**

3.1 Material characterization

The results of various precursory experimentations executed on the untreated black cotton soil (BCS) in order to gauge its properties are shown on Table 3 and Figure 1. The outcomes of the tested soil depicted that the soil falls under A-7-6 (14) group by means of AASHTO soil classification scheme [33] and CH in the Unified Soil Classification scheme [34]. The oxide compositions of the CKD, MTK and BCS used were measured through X-ray florescent test (XRF) and the result is displayed on Table 4. For the CKD, the fundamental chemical constituents are calcium oxide (CaO) and silicon oxide (SiO2). Interestingly, the percentages of oxide compositions of CKDs varies from plant to plant and the resultant constituent composition could be as a result of the raw materials used. However, the percentage of calcium oxide (CaO) present in the CKD used is low compared to the report of [35] but on a high side compared to [36-37]. Secondly, it can also be been that the studied CKD has a relatively higher percentage of silicon oxide (SiO2) which makes CKD a good replacement of cement in soil re-engineering. The slight amount of calcium oxide in metakaolin to be meant for the stabilization process was supplemented by the calcium oxide present in cement kiln dust. The comparatively high silicon and aluminium oxides in metakaolin also aided those in cement kiln dust to provide the required improvement of the properties of the natural soil.

Table 4 Chemical composition of materials used.

Oxide	Composition by weight (%)		
	CKD	MTK	BCS
SiO_2	18.82	52.72	48.50
CaO	66.82	0.18	0.90
SO_3	2.01	0.99	-
MgO	0.01	0.09	2.22
TiO_2	0.40	-	-
Fe_2O_3	2.05	1.72	2.20
Al_2O_3	6.34	42.20	18.60
Na_2O	0.20	-	1.55
K_2O	1.0	-	0.70
LOI	1.03	0.25	10.10

Table 5 The 7 days UCS of BCS - CKD mixtures with MTK laboratory outcome.

Runs order	Sign of outcome	Real constituents				Lab. outcome	Pseudo constituents			
		Z_1	Z_2	Z_3	Z_4		X_1	X_2	X_3	X_4
1	Y_1	1	0.1	0.15	0.20	805	1	0	0	0
2	Y_2	1	0.16	0.20	0.25	925	0	1	0	0
3	Y_3	1	0.25	0.23	0.40	905	0	0	1	0
4	Y_4	1	0.30	0.35	0.5	1206	0	0	0	1
5	Y_{12}	1	0.13	0.175	0.225	900	0.50	0.50	0	0
6	Y_{13}	1	0.175	0.19	0.30	875	0.50	0	0.50	0
7	Y_{14}	1	0.20	0.25	0.35	1170	0.50	0	0	0.50
8	Y_{23}	1	0.205	0.215	0.325	921	0	0.50	0.50	0
9	Y_{24}	1	0.23	0.275	0.375	1200	0	0.50	0	0.50
10	Y_{34}	1	0.275	0.29	0.45	1195	0	0	0.50	0.50
11	CT_1	1	0.182	0.216	0.31	1043	0.40	0.20	0.20	0.20
12	CT_2	1	0.194	0.226	0.32	1063	0.20	0.40	0.20	0.20
13	CT_3	1	0.212	0.232	0.35	1056.5	0.20	0.20	0.40	0.20
14	CT_4	1	0.222	0.256	0.37	1162	0.20	0.20	0.20	0.40
15	CT_{12}	1	0.2025	0.2325	0.3375	1083	0.25	0.25	0.25	0.25
16	CT_{13}	1	0.223	0.249	0.365	1121	0.10	0.30	0.30	0.30
17	CT_{14}	1	0.211	0.239	0.355	1109	0.30	0.10	0.30	0.30
18	CT_{23}	1	0.193	0.233	0.325	1110.5	0.30	0.30	0.10	0.30
19	CT_{24}	1	0.183	0.209	0.305	917.5	0.30	0.30	0.30	0.10
20	CT_{34}	1	0.197	0.224	0.33	1052	0.30	0.20	0.30	0.20

3.2 Unconfined compressive strength

The unconfined compression strength test (UCS) is major factor used in appraising the strength and resistance of soil material. The UCS values of the BCS - CKD - MTK mixtures cured for 7 days is displayed in Table 5. The raw expansive soil with a minimum value of 102 kN/m^2 improved to the maximum value of 1206 kN/m^2 at a corresponding a mix ratio of 1.0:0.30:0.35:0.50 for black cotton soil, water, cement kiln dust and metakaolin respectively. The enhancement of UCS outcomes may possibly be indorsed to the bonding performance between the soil materials and the additives into a compacted matrix of BCS - CKD - MTK thereby ensuing to a greater load resistance [38, 39]. On the other hand, at some points the UCS values diminished which could be ascribed to deficient amount of water necessary to complete the pozzolanic activity [40]. Also, displayed on Table 6 is the UCS of BCS ameliorated with CKD - MTK mixtures cured for 28 days duration. A parallel trend of increment in UCS values observed for soil materials cured for 7 days was as well witnessed for 28 days curing duration except that the UCS outcomes improved with curing periods. The UCS for 28 days curing period enhanced from 509 kN/m^2 for natural soil to peak value of 1735 kN/m^2 corresponding to a mix ratio of 1.0:0.30:0.35:0.50 for BCS, water, CKD and MTK respectively. The highest UCS outcome of soil material cured for 7 days fell short of the minimum regulatory standard as documented by [41] although the condition was satisfied by soil specimens cured for 28 days duration.

Thus, $\beta_1 = 805, \beta_2 = 925, \beta_3 = 905, \beta_4 = 1206,$ $\beta_{12} = 140, \beta_{13} = 80, \beta_{14} = 658, \beta_{23} = 24,$ $\beta_{24} = 538$ and $\beta_{34} 558$ are known as the coefficients. If we replace the obtained coefficients into eqn. (9) we will arrive at;

$$Y_{UCS(7\ Days)} = 805X_1 + 925X_2 + 905X_3 + 1206X_4 + 140X_1X_2 + 80X_1X_3 + 658X_1X_4 + 24X_2X_3 + 538X_2X_4 + 558X_3X_4 \quad (20)$$

Hence, equation (20) is the model for predicting 7 days UCS values of tropical black clayey soil ameliorated with CKD-MTK blend.$\beta_1 = 953, \beta_2 = 1275, \beta_3 = 1105, \beta_4 = 1875,$ $\beta_{12} = -496, \beta_{13} = -236, \beta_{14} = 1232, \beta_{23} = -124,$ $\beta_{24} = 1000$ and $\beta_{34} = 1176$ are known as the coefficients. If we replace the obtained coefficients into eqn. (9) we will arrive at;

$$\hat{Y} = 953X_1 + 1275X_2 + 1105X_3 + 1875X_4 - 496X_1X_2 - 236X_1X_3 + 1232X_1X_4 - 124X_2X_3 + 1000X_2X_4 + 1176X_3X_4 \quad (21)$$

Therefore, equation (21) is the model for predicting 28 days UCS values of tropical black clayey soil ameliorated with CKD-MTK blend.

3.3 Validating and testing of adequacy of prediction models

After the model building process, it's imperative to scrutinize the validity and precision of the model and this was achieved through the use of statistical analysis such as ANOVA and

Table 6 The 28 days UCS of BCS – CKD mixtures with MTK laboratory outcome.

Runs order	Sign of outcome	Real constituents				Lab. outcome	Pseudo constituents			
		Z_1	Z_2	Z_3	Z_4		X_1	X_2	X_3	X_4
1	Y_1	1	0.1	0.15	0.20	953	1	0	0	0
2	Y_2	1	0.16	0.20	0.25	1275	0	1	0	0
3	Y_3	1	0.25	0.23	0.40	1105	0	0	1	0
4	Y_4	1	0.30	0.35	0.5	1875	0	0	0	1
5	Y_{12}	1	0.13	0.175	0.225	990	0.50	0.50	0	0
6	Y_{13}	1	0.175	0.19	0.30	970	0.50	0	0.50	0
7	Y_{14}	1	0.20	0.25	0.35	1722	0.50	0	0	0.50
8	Y_{23}	1	0.205	0.215	0.325	1159	0	0.50	0.50	0
9	Y_{24}	1	0.23	0.275	0.375	1825	0	0.50	0	0.50
10	Y_{34}	1	0.275	0.29	0.45	1784	0	0	0.50	0.50
11	CT_1	1	0.182	0.216	0.31	1365	0.40	0.20	0.20	0.20
12	CT_2	1	0.194	0.226	0.32	1426	0.20	0.40	0.20	0.20
13	CT_3	1	0.212	0.232	0.35	1395	0.20	0.20	0.40	0.20
14	CT_4	1	0.222	0.256	0.37	1675	0.20	0.20	0.20	0.40
15	CT_{12}	1	0.2025	0.2325	0.3375	1455	0.25	0.25	0.25	0.25
16	CT_{13}	1	0.223	0.249	0.365	1614	0.10	0.30	0.30	0.30
17	CT_{14}	1	0.211	0.239	0.355	1504	0.30	0.10	0.30	0.30
18	CT_{23}	1	0.193	0.233	0.325	1598	0.30	0.30	0.10	0.30
19	CT_{24}	1	0.183	0.209	0.305	1134	0.30	0.30	0.30	0.10
20	CT_{34}	1	0.197	0.224	0.33	1379	0.30	0.20	0.30	0.20

Table 7 Laboratory and model test results of UCS (7 days).

Symbol of Response	Response	
	Model	Laboratory
CT_1	1044.24	1043
CT_2	1061.20	1063
CT_3	1055.60	1056.5
CT_4	1159.48	1162
CT_{12}	1085.13	1083
CT_{13}	1118.44	1121
CT_{14}	1105.00	1109
CT_{23}	1111.40	1110.5
CT_{24}	985.68	917.5
CT_{34}	1050.72	1052

Table 8 T-Test analysis for 7 days UCS

Description	Model	Laboratory
Mean	1077.689	1071.75
Variance	2373.295	4322.792
Observations	10	10
Pearson Correlation	0.970051	
Hypothesized Mean Difference	0	
Df	9	
t Stat	0.855436	
P(T<=t) one-tail	0.207251	
t Critical one-tail	1.833113	
P(T<=t) two-tail	0.414502	
t Critical two-tail	2.262157	

student's t-test. Both the experimental response of the control points and predicted response of UCS experimentation (7 and 28 days) were further compared by adopting student's t-test and the results of the anova analysis. In the course of this particular exercise, two hypotheses were established and are as follows: (i) The null hypothesis which entails that they exist no significant variance among the laboratory and model outcome of the UCS experimentation at 0.05 significance level (ii) The alternate hypothesis which entails that they exist significant amongst laboratory and model outcome of the UCS experimentation at 0.05 significance level.

3.3.1 Student's t-test for 7 days UCS

The two-tailed student t-test at 0.05 significance level was accomplished by comparing the two groups of responses and the condition used in decision making states that if t stat is greater than t crit two tail, the null hypothesis is rejected. As per the data displayed in Table 7, it is the laboratory and model response of UCS (7 days) whereas the data displayed in Table 8 is the result of the t-test for the control points. It is clearly noticed that the t critical two-tail =2.262157 > t stat = 0.855436, hence, it is concluded that the null hypothesis is accepted.

3.3.2 ANOVA for 7 days UCS

The ANOVA technique was executed via means of testing the null hypothesis at 95 % confidence level. However, the condition for accepting or rejecting the null hypothesis is that, if F is greater than Fcrit, the null hypothesis is rejected. Table 9 provides the outcome of ANOVA for 7 days UCS and it can be seen that F value equals 0.0526 and F crit equals 4.4138 so F crit is greater than F. This entails that they difference between the laboratory and model outcome is insignificant and on that note we do not reject the null hypothesis. Thus, the built model is acceptable and could be beneficial in predicting 7 days UCS of BCS treated with the mixtures CKD-MTK.

Table 9 ANOVA Result for 7 days UCS

Groups	Count	Sum	Average	Variance		
Model	10	10776.89	1077.689	2373.295		
Laboratory	10	10717.5	1071.75	4322.792		
SOV	**SOS**	**DOF**	**MOS**	**F value**	**P-value**	**F crit**
BG	176.3289	1	176.3289	0.052666	0.821075	4.413873
WG	60264.78	18	3348.043			
Total	60441.11	19				

Table 10 Laboratory and model test results of UCS (28 days).

Symbol of Response	Response	
	Model	**Laboratory**
CT_1	1354.28	1365.00
CT_2	1413.88	1426.00
CT_3	1397.32	1395.00
CT_4	1655.00	1675.00
CT_{12}	1461.50	1455.00
CT_{13}	1571.48	1614.00
CT_{14}	1514.28	1504.00
CT_{23}	1522.12	1598.00
CT_{24}	1212.60	1134.00
CT_{34}	1373.44	1379.00

Table 11 T-Test analysis for 28 days UCS

Description	Model	Laboratory
Mean	1447.59	1454.5
Variance	15739.12	24209.61
Observations	10	10
Pearson Correlation	0.983103	
Hypothesized Mean Difference	0	
Df	9	
t Stat	-0.55182	
P(T<=t) one-tail	0.297252	
t Critical one-tail	1.833113	
P(T<=t) two-tail	0.594503	
t Critical two-tail	2.262157	

Table 12 ANOVA Result for UCS (28 days curing period)

Groups	Count	Sum	Average	Variance		
Model	10	14475.9	1447.59	15739.12		
Laboratory	10	14545	1454.5	24209.61		
SOV	**SOS**	**DOF**	**MOS**	**F value**	**P-value**	**F crit**
BG	238.7405	1	238.7405	0.011952	0.914153	4.413873
WG	359538.6	18	19974.37			
Total	359777.4	19				

3.3.3 Student's t-test for 28 days UCS

The two-tailed student t-test at 0.05 significance level was accomplished by means of comparing the two groups of responses and the condition used in decision making states that if t stat is greater than t crit two tail, the null hypothesis is rejected. As per the data displayed on Table 10, it is the laboratory and model response of UCS (28 days) whereas the data displayed on Table 11 is the result of t-test for the control points. It is clearly noticed that t critical two-tail = 2.262157 > t stat = -0.55182, hence, it is concluded that the null hypothesis is accepted.

3.3.4 Anova for UCS (28 days curing period)

The ANOVA technique was employed via means of testing the null hypothesis at 95 % confidence level. Nevertheless, the condition for accepting or rejecting the null hypothesis is that, if F value is greater than F crit, the null hypothesis is rejected. Table 12 provides the outcome of ANOVA for 28 days and it can be seen that F equals 0.011952 while F crit equals 4.413873 and as such F crit is greater than F value. This entails that they difference between the laboratory and model outcome is insignificant and on that note we do not reject the null hypothesis. Thus, the built model is acceptable and could be beneficial in predicting 28 days UCS of BCS treated with the mixtures CKD-MTK.

3.4 Discussion of optimization models

In order to study the interaction effects of the selected components (independent variables), experimental exercises were carried out by different mix ratios and combinations designed according to Scheffe's optimization technique. The soil property investigated upon was UCS (7 and 28 days) which is the response (dependent variable) and as such two models were built (formulated). The validity of the built models were further verified using the ANOVA and t-test statistical approach. The null hypothesis is accepted for the tested property based on the Student's t-test indicating that the built models have good prediction ability. The results obtained from the optimization exercise showed a peak UCS (7 and 28 days) values of 1206 and 1875 kN/m^2 which symbolises approximately 50 and 97 % enhancement. Furthermore, these peak values achieved as a result of Scheffe's concept could be as a result of individual roles played by the independent variables.

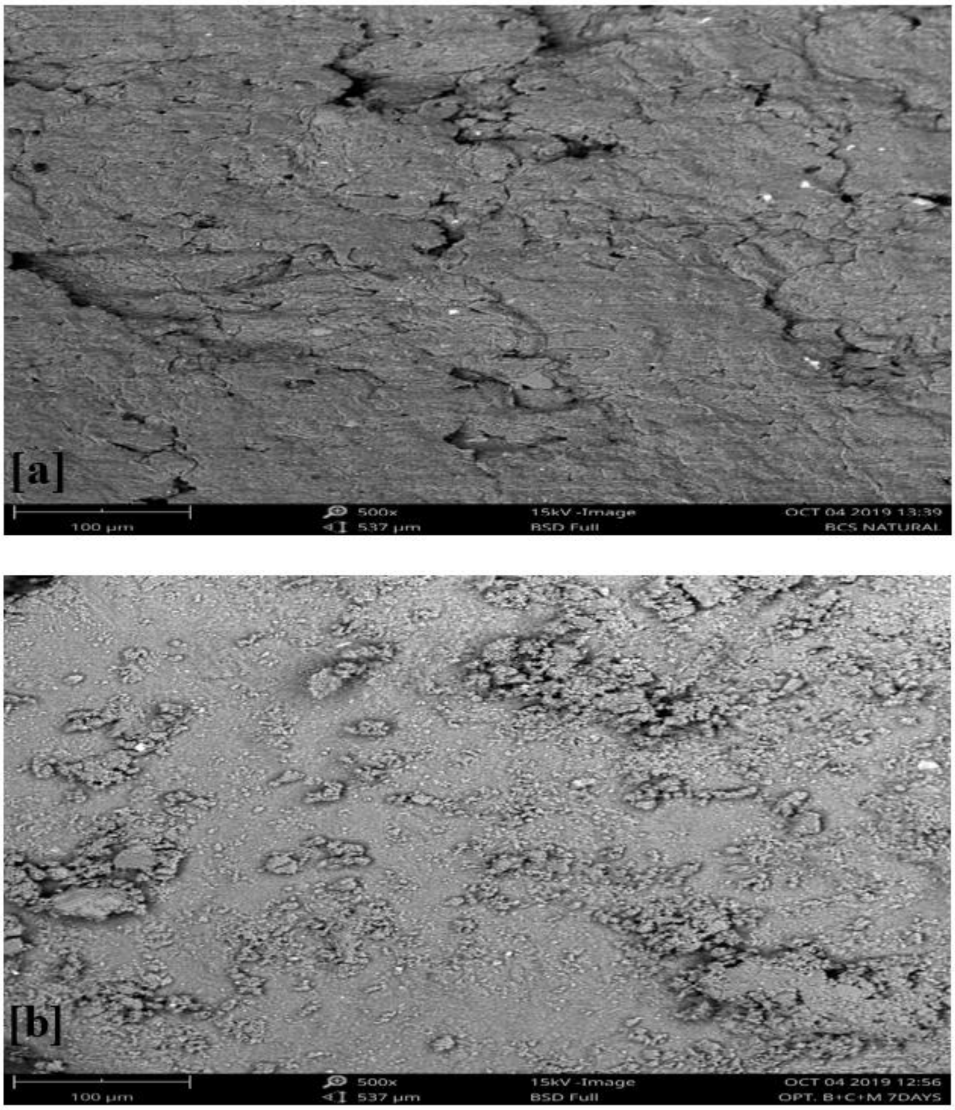


Figure 2 Micrographs of (a) raw expansive soil after 7 days curing period 100µm (500X) (b) optimally ameliorated expansive soil with the mixtures of 0.35 CKD - 0.50 MTK after 7 days curing period at 100µm (500X)

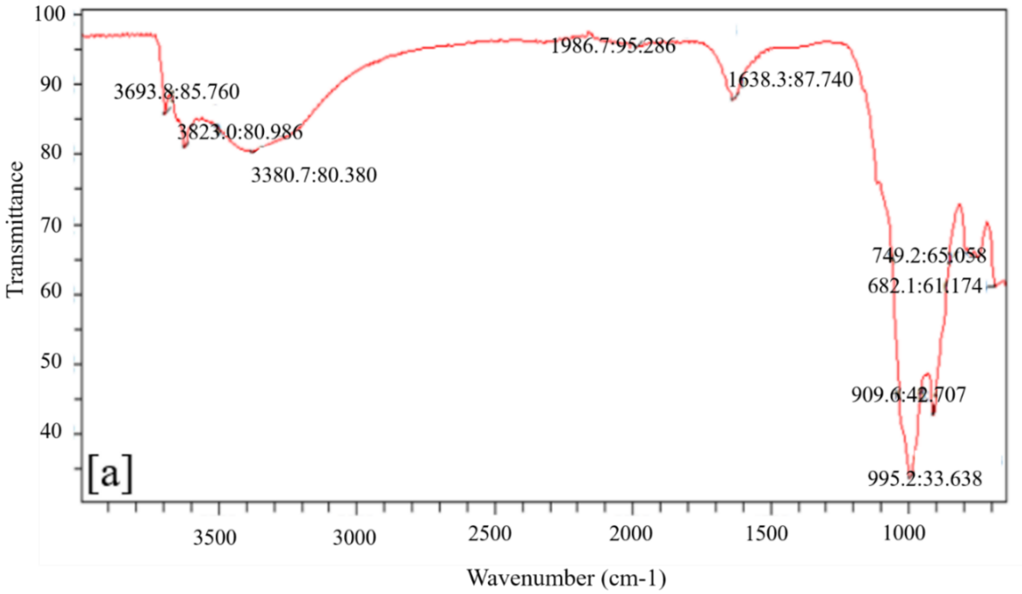
3.5 Structural characterization of soil materials

3.5.1 Scanning electron microscope (SEM)

In order to scrutinize the micro morphological changes in soil samples, SEM approach was used to further authenticate the results obtained from the optimization exercise. Depicted in Figures 2 (a and b) represents the morphology of the natural and ameliorated soil specimens. The natural soil material manifested a polished looking surface whereas an uneven surfaced morphology was exhibited by the ameliorated soil specimens. This behaviour could be corroborated with the alteration in orientation and fabric of the ameliorated soil material as a result of the cation exchange reaction taking place in the soil mixtures. A parallel behaviour was described by [42]. Also, large cavities evident in the natural soil diminished in the soil specimen optimally stabilized with CKD-MTK mixtures. The closed voids (dense soil) evident in the micrograph of the soil material treated with optimal additive demonstrates the possible build-ups of new cementitious compounds as a possible consequence of pozzolonic activity which brought about the closing up of the pore spaces noticed in the natural soil. These upshots agrees with the discoveries of other studies in which the microstructural alterations in due course contributes to strength enhancement [39, 6].

3.5.2 Fourier transformed infrared spectroscopy (FTIR)

Depicted in Figures 3 (a and b) are the FTIR spectrum of different bands of the raw BCS and optimally ameliorated BCS. The FTIR spectrum of untreated expansive soil displays band at 3893.8 cm^{-1} in -OH stretching region which is due to a hydroxyl group bonded with octahedral (Al+) cations [43]. Also, the characteristic vibration bands at 3893 cm-1 and 3623 cm-1 are attributed to the O–H stretching of kaolinite and montmorillonite, respectively. Also, the noticeable bands at 995.2, 682.1 cm-1 may be interconnected to Al-OH, Al-O bond stretching and Si-O vibration stretching, respectively [44]. The FTIR band of the raw BCS confirms the main vibration band at about 909 to 995 cm-1, this could be ascribed to the symmetric and asymmetric stretching vibration of Si-O-M+ where M is either Na+, K+, or Ca+2 present in clay minerals [45]. In the FTIR spectrum of the natural BCS, different absorption bands revealed the presence of several functional groups, apparently some of the bands changed after the stabilization process. Also, for the optimally ameliorated soil materials, a small number of evident alterations were observed and these alterations could be as a result of the reaction effect between the clay mineral and the mixtures of cement kiln dust and metakaolin. In addition, the bands at 3623.0 and 3693.8 cm^{-1} may perhaps be linked to the OH stretching vibrations of



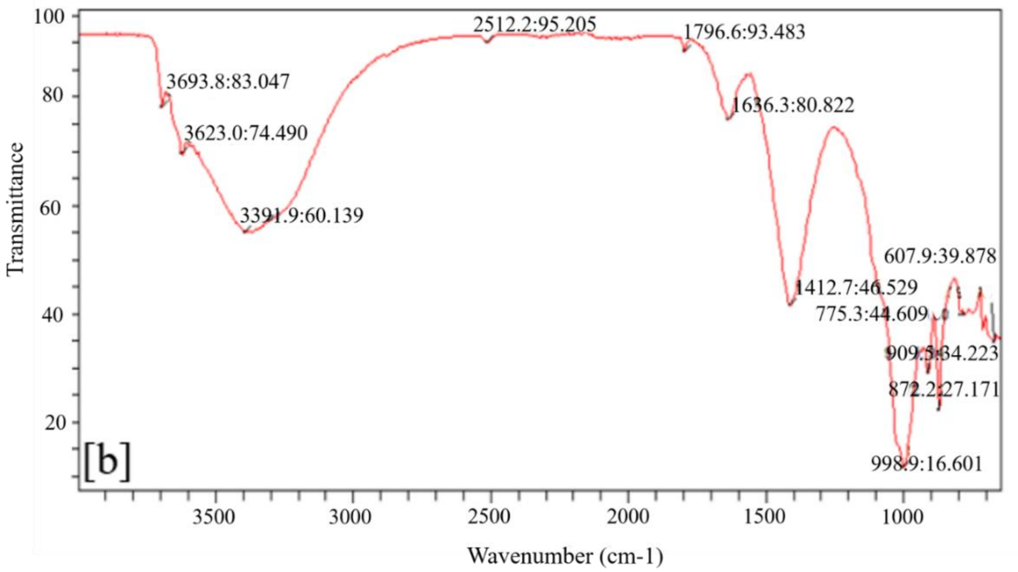


Figure 3 FTIR Bands of (a) raw expansive soil (b) optimally ameliorated expansive soil with the mixtures of 0.35 CKD - 0.50 MTK.

inner-surface hydroxyl groups [46]. The absorption band at 1638.3 cm^{-1} could be linked to the OH distortion mode of water whereas band at 775.3 cm^{-1} may be interrelated with the manifestation of quartz [47].

4. Conclusion

An investigational study was executed on an expansive clayey soil material ameliorated with cement kiln dust and metakaolin blend. New models were developed to aid in predicting the outcomes of unconfined compression strength test (7 and 28 days) of an expansive soil material enhanced using Scheffe's method. As per the outcomes of the investigational exercise, the resulting deductions were derived. The test soil falls under the class of A-7-6 material, with group index of 14 based on the AASHTO classification scheme and CH in the USCS scheme, respectively. On a general note, an optimization tool called Scheffe's 2nd degree polynomial was applied to formulate models for predicting the UCS outcomes of an expansive soil. The Scheffe models built are as follows $\hat{Y} = 805X_1 + 925X_2 + 905X_3 + 1206X_4 + 140X_1X_2 + 80X_1X_3 + 658X_1X_4 + 24X_2X_3 + 538X_2X_4 + 558X_3X_4$ and $\hat{Y} = 953X_1 + 1275X_2 + 1105X_3 + 1875X_4 - 496X_1X_2 - 236X_1X_3 + 1232X_1X_4 - 124X_2X_3 + 1000X_2X_4 + 1176X_3X_4$ for UCS (7 and 28 days curing). Based on Scheffe's technique, the peak values were achieved at an optimal mix ratio of 1.0:0.30:0.35:0.50 for BCS, water, CKD and MTK. Therefore, this optimal mix ratio meaningfully improved the soil properties and it is recommended for stabilization so as to make the soil material fit as road construction material. The outcome of this exercise indicates the feasibility of utilizing Scheffe's approach in conjunction with CKD-MTK blend in soil reengineering. With the use of this concept, the peak UCS values of 1206 and 1875 kN/m^2 for 7 and 28 days were achieved. Based on the rating by TRRL (1977), 7 days UCS soil mixtures were lesser than the 1720 kN/m^2 benchmark for adequate cement stabilization but it was achieved by the soil materials cured for 28 days. In terms of statistical assessment, the ANOVA and student t-test methods were utilised in appraising the level of accuracy and acceptability of the built models. Also, the built models showed some level of significant contributions made by the independent variables. With the aid of scanning electron microscopy, it revealed that the optimally treated soil had a compact micro structures thereby improving its geotechnical properties. Moreover, the changes in the FTIR spectrum of the optimally treated soil confirmed the stabilization process. Finally, the use of Scheffe's concept is highly recommended, this is as a result of achieving the optimal blend of constituent materials for peak performance of soil parameters. Also, in a bid to promote sustainable environment, the usage of waste materials such as CKD and MTK will encourage and aid in curbing the nuisance from poor waste management and as well the reduction in construction costs. The use of other optimization techniques would be a welcome development as it will create room for further studies and as much a more efficient optimal ratio could be achievable.

5. Funding

This research is funded by Federal Ministry of Education NEEDS Assessment Intervention Fund, Nigeria through Akwa Ibom State University. This support is gratefully acknowledged.

6. Acknowledgement

The authors of this paper acknowledge and are thankful to Akwa Ibom State University for their support fund.

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