

Application of Response Surface Method in Predicting and Optimizing the Engineering Properties of Activated Metakaolin Treated Non-Lateritic Soil

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Abstract

This study focuses on using response surface methodology (RSM) to predict and optimize the unconfined compressive strength (UCS) and California bearing ratio (CBR) of activated metakaolin (MK) treated non-lateritic soil for road construction purposes. The experimental results of various blends compacted using British standard light, West African standard, and British standard heavy methods were used to create a useful model for overall response variation. The design consists of two design factors, MK and sodium hydroxide (SH), with MK and SH as independent variables, and UCS and CBR as the responses. Predictive equations for the responses were obtained using the independent variables. Statistical analysis and analysis of variance for all responses showed that quadratic models were successful in predicting the UCS and CBR of activated MK-treated non-lateritic soil with R^2 (0.9835-0.9999), Adj R^2 (0.9718-0.9999), and Pred R^2 (0.8776-0.9998). F-values are greater than the critical F-value (3.59), indicating that the factors have a significant effect on the model behaviour. The P value of the models was less than $P_{\alpha}(0.05)$, indicating that the factors are significant in predicting the responses. Furthermore, optimized factors were predicted to obtain optimal values for UCS and CBR that met the Nigerian General Specification for road base course usage. These predictions were validated, and a good correlation was observed between the experimental and predicted values, as judged by the absolute relative percent error (0.0232–1.1628). The proposed models are capable of predicting the UCS and CBR values, which can help make early decisions during the construction process.

Keywords: Response Surface Methodology, Compaction, Sodium Hydroxide, Metakaolin.

Introduction

Access to essential services by many people in developing countries is severely impeded by poor roads and the consequential poor transport services. It is estimated that some 1.2 billion people do not have access to an all-weather road and that 40 – 60 % are more than 8 km from a health center. Transport is also recognized as an essential ingredient in achieving the Millennium Development Goals (MDGs) and is key for inclusive, sustainable globalization to overcome poverty, promote growth, access challenges in fragile states and for Public Private Partnership (Juhel, 2008). Furthermore, transport costs are 9 % of export

values in developing countries compared with 4% in developed countries, which is a further inhibiting factor on economic growth. In Africa, 80 % of the continent's goods are transported by road, but the transport costs are the highest in the world; which in turn leads to increased costs to the community.

The good all-weather road is an essential component in the provision of reliable transport services required for safe access to markets, employment opportunities, education facilities, and health centres, which comprise the components of social and economic development. The most durable roads are those in which the underlying materials are surfaced with wearing course materials bound with bitumen tar or are surfaced with concrete or stones. However, these roads are also the most expensive to provide in terms of initial costs. Consequently, 70 % of the road network in sub-Saharan Africa and most rural roads in other less developed regions of the world remain unpaved (O'Neill and Greening, 2010). In some countries in Africa, unpaved roads comprise over 90 per cent of the road network.

In Nigeria, the total road kilometres for federal, state and local government has increased from 45,128 km (with 1,648 km paved and 43,480 km unpaved). Today, Nigeria has the largest road network in West Africa and the second largest south of the Sahara, with roughly 193,200 km total roadway length (CIA World Fact Book, 2014) out of which 28,980 km is paved and 164,220 km unpaved.

Based on the growing development of Nigeria, it is essential to establish low-cost remote access roads to natural or less populated areas. These roads are built to provide easier, faster and better access to the local villages or uninhabited areas from main roads or major cities. However, in most cases, the unpaved roads have to be constructed on soft foundation soil where large deformations usually occur, which causes increases in maintenance costs and leads to interruption of traffic service, especially during the wet season.

To take care of such circumstances it is necessary to stabilize or improve the in-situ soils, either with other selected soils/aggregates or with binders, building a stronger in-situ on top to support heavier vehicles or higher traffic flows and resist moisture. This will help spread vehicle loads without causing deformation. Thus, this research intends to evaluate the effect of activated metakaolin-treated non-lateritic soils for road construction using response surface methodology.

A large and growing body of available literature has studied the use of geopolymeric binders in soil improvement applications (Cristelo, Glendinning, Fernandes, and Pinto 2012; Zhang, Guo, El-Korchi, Zhang, and Tao, 2013; Rios, Cristelo, Viana da Fonseca, and Ferreira, 2015; Teerawattanasuk and Voottipruex, 2018; Corrêa-Silva, Araujo, Cristelo, Miranda, Gomes, and Coelho, 2019; Abdeldjounad *et al.*, 2019; Rios, Ramos, Viana da Fonseca, Cruz, and Rodrigues, 2019; Adhikari, Khattak, and Adhikari, 2020; Abdulkarim and Umar 2020; Amulya, Ravi Shankar, and Praven, 2020 and Sukprasert, Hoy, Horpibulsuk, Arulrajah,

Rashid, and Nazir, 2021), and very promising results were found namely in terms of its stress-strain behaviour.

Geopolymer is an inorganic alumino-silicate material synthesized by alkaline activation of materials rich in alumina (Al_2O_3) and silica (SiO_2). It is formed through polycondensation of tetrahedral silica (SiO_4) and alumina (AlO_4), which are linked with each other by sharing all the oxygen atoms (Davidovits, 1991; Gambrell, He, and Zhang, 2010). It is also described that geopolymer is a commercial and industrial utilization of alkali-activated alumino-silicate cement (i.e., fly ash, slag, burned clay or kaolin, rice hush ash bottom ash and other alumino-silicate materials) with low CO_2 emission and energy consumption (Rashad, 2014). It is a new binder with mechanical performance equal to or better than that of cement and other traditional calcium-based binders with lower environmental ill effects and minimum processing costs (Pourakbar, Huat, Asadi, and Fasinikoutalab, 2016).

Metakaolin is a dehydroxylated form of kaolinite, following the chemical removal of the bonded hydroxyl ions from the kaolinite minerals, typically through heating to approximately 750°C . As kaolin contains no carbonates, no CO_2 is released during heating leading to reduced embodied CO_2 in the final materials when replacing cement or lime (Ilić, Mitrović, and Miličić, 2010). Due to the pozzolanic properties of metakaolin, there has been growing interest in its use as a cement replacement as well as an additive to lime or for geopolymer concrete (Mejía de Gutiérrez, Torres, Vizcayon, and, Castello, 2008; Ramezani pour and Jovein, 2012). In this study, MK is used as a source binder for alkali activation due to its rich alumina (Al_2O_3) and silica (SiO_2) content.

Response surface methodology (RSM) uses statistical techniques for empirical model building; it comprises regression surface fitting to obtain approximate responses, design of experiments to obtain minimum variances of the responses and optimizations using the approximated responses. The RSM also aims to reduce the cost and numerical complexity of other expensive analysis methods such as finite element and finite difference methods and artificial neural network ANN (Yang and Gao, 2005). RSM provides statistically validated predictive models that can be manipulated for finding optimal process configurations, Alsanusi and Bentaher, (2015). RSM typically is useful in situations where several factors influence one or more performance characteristics, or responses. It can also be utilized to optimize one or more responses to meet a given set of specifications. It is an effective statistical tool for experimental design, model building, factors effects evaluation and optimum condition search (Alyamac, Ghafari, and Ince, 2017; Şimşek, Uygunoğlu, Korucu, and Kocakerim, 2018). RSM proportions the constituent material to obtain an optimum mix proportion used as a mathematical model for the prediction of the desired properties, Hassan and Kabir (2011).

This study aims at applying RSM for predicting and optimizing the unconfined compressive strength and soaked California bearing ratio of activated metakaolin-treated non-lateritic soil for road construction by developing and assessing predictive models for determination of geotechnical properties of activated MK-treated non-lateritic soil, by evaluating the

interactive effects of MK concentration and NaOH molar concentration on the geotechnical properties of the treated soil and also optimizing the activated MK treated non-lateritic soil for road construction application.

Statement of the Problem

The Nigerian general specification (NGS, 2013) requires that for treated soil to be used for sub-base, the 7 days unconfined compressive strength (UCS) be in the range of 750 – 1500 kN/m² while for the base course, it should be in the range of 1500 – 3000 kN/m². Similarly, a soaked California bearing ratio (CBR) value ≥ 30 % is recommended for the sub-base while a CBR value ≥ 80 % for the base course. Achieving this is usually difficult, as random sampling of UCS and CBR values of the experimental data often produce values both above and below the recommended values and engineering analysis and design require the application of probabilistic methods, as deterministic approaches do not rigorously account for uncertainties, especially in experimental results. Therefore, a complete probabilistic characterization of UCS and CBR requires the application of statistical analysis using the response surface method to establish model equations and determine the adequacy and efficiency of the experimental results.

Objectives

The objective of this research is to use Response Surface Methodology (RSM) to forecast and enhance the unconfined compressive strength (UCS) and soaked California bearing ratio of non-lateritic soil treated with activated metakaolin (MK) for road construction. This will be achieved by creating and evaluating predictive models to determine the geotechnical properties of the treated soil, examining the combined effects of MK concentration and NaOH molar concentration on the soil's geotechnical properties, and optimizing the activated MK-treated non-lateritic soil for use in road construction applications.

Materials and Methods

Materials

The materials used in this study are;

- i. Non-Lateritic soil (NLS)
- ii. Metakaolin (MK)
- iii. Alkali activator (Sodium hydroxide (NaOH))
- iv. Water

Non-Lateritic Soil (NLS)

The NLS used in the study was obtained by using the method of disturbed sampling from an area near the Abubakar Umar Secretariat, in Bauchi, Bauchi State, Nigeria (latitude

10°18'7.59" N and longitude 9°49'31.41"E), at a depth of at least 1000 mm below ground level. The soil is greyish brown.

Metakaolin

The raw material for the production of metakaolin (MK) is kaolin clay, which was sourced from Alkalari, Alkalari Local Government Area of Bauchi State. The kaolin was burnt at a temperature ranging from 700 – 800°C in a kiln at the Department of Industrial Design, Faculty of Environmental Technology, Abubakar Tafawa Balewa University, Bauchi to obtain the metakaolin used in this study.

Alkali Activator

The alkali activator was a solution of sodium hydroxide (NaOH) which was obtained by dissolving sodium hydroxide flakes in distilled water. It should be noted that based on various literature on alkali activation, the suitable concentration is generally between 3 and 18 molars (Somna, Jaturapitakkul, Kajitvichyanukul, and Chindaprasirt, 2011; Phummiphan *et al.*, 2016). However, in this study, the choice for a lower concentration of (NaOH) is to avoid health harm to workers and to have cost-effectiveness. The Sodium hydroxide (NaOH) solution was prepared by mixing distilled water with NaOH pallets in a plastic jar and allowed to cool for 24 hours, (i.e., 1 molar concentration (M) represents 40 g of NaOH dissolved in 1 litre of water).

Water

The water used is portable drinking water and therefore, no laboratory test was conducted on it.

Methodology

Designing Set of Experiments

Face-centred central composite design (FCCCD) was used for the design experiment consisting of two independent variables namely: (MK concentration coded as A and NaOH molar concentration coded as B) and four dependent variables namely: 7 days UCS, 14 days UCS, 28 days UCS and soaked CBR. This choice of independent variables (factors) and dependent variables (responses) is dependent on the objective of the study.

Design Expert software version 13 was used to carry out the design of experiment (DOE) with the input factors being MK and NaOH to arrive at the design matrix of 13 runs for the activated soil blend compacted using BSL, WAS and BSH energy levels denoted as L, W and H respectively. Each numerical factor was varied over the three (3) coded levels of -1 (Axial points), 0 (Center/mid points) and +1 (Cube/factorial points).

The factor and factor levels are presented in Table 1 while Table 2 presents the experimental runs, factor combination, translation of coded levels to actual experimental units and space type used in the study.

Face-centred central composite design (FCCCD) used enabled the prediction of the dependent variables also known as response by means of the experimental data, with all parameters varied in preferred range.

Table 1: Factors and factor levels adopted for RSM

Factor	Code	Factor levels of code		
		Lower level	Mid-level	upper level
		-1	0	+1
Metakaolin (%)	A	5	17.5	30
Sodium hydroxide (mol)	B	1	5.5	10

Table 2: Factor Combinations as Per the Face-Centred Central Composite RSM

Run	Coded factor levels		Actual factors		Space type
	A	B	MK (%)	SH	
1	-1	-1	17.5	5.5	Centre
2	1	-1	17.5	5.5	Centre
3	-1	1	30	10	Factorial
4	1	1	17.5	5.5	Centre
5	-1	0	5	5.5	Axial
6	1	0	5	10	Factorial
7	0	-1	30	1	Factorial
8	0	1	30	5.5	Axial
9	0	0	17.5	5.5	Centre
10	0	0	17.5	1	Axial
11	0	0	5	1	Factorial
12	0	0	17.5	5.5	Centre
13	0	0	17.5	10	Axial

Hypotheses Testing

Probability values (P-values), were used in determining the adequacy of the models. P-value is used in hypothesis testing to help in deciding whether to accept or reject the null hypothesis. The research hypotheses are:

H₀: The Factor (MK or SH) has no effect on the strength behavior of the treated soils.

H₁: The Factor (MK or SH) has effect on the strength behavior of the treated soils.

Where H₀ is the null hypothesis and H₁ is the alternative hypothesis.

The p-value is the probability of obtaining a test statistic that is at least as extreme as the actual calculated value, if the null hypothesis is true. The p-value for this research work is 0.05 (α-value). If the calculated p-value of a test statistic is less than 0.05, you reject the null hypothesis, which means the factor is significant in predicting the response.

Determining the Optimal Value of the Response

The RSM technique conventionally optimizes responses singly. However, it can also optimize multiple responses concurrently. Thus, the objective of the optimization is to obtain the best possible blends that will yield the optimum for particular response. Optimization was carried out to develop mixtures that satisfies the 7 days UCS and soaked CBR criteria of NGS (2013) for base and subbase application. In light of this, a numerical optimization technique, using desirability functions (d_i) defined for each response, was utilized to optimize the responses. Desirability is an essential function where the predictable response is analyzed into a scale-free value (d_i) with limits from 0 (worse case) to 1 (ideal case), and it's reliant on closeness to the lower and upper boundaries of the model, Antony, Coleman, Montgomery, Anderson, and Silvestrini, 2011.

Results and Discussions

Statistical Analysis and Model Development

Design expert 13 statistical software was used on the experimental data to developed models for prediction of 7, 14 and 28 days UCS and CBR. The design expert 13 statistical software output gave predictive model equations, normal probability plots, residual versus run plots, analysis of variance (ANOVA), F-statistics, R-squared (R^2), Adjusted R-squared ($\text{Adj } R^2$), Predicted R-squared ($\text{Pred } R^2$), Adequate precision (AP) and probability (p - values) amongst other statistical parameters. These statistical parameters were used to check the adequacy of the developed models.

The ANOVA analysis is performed via testing the hypothesis of equal variance, which is the test of a null hypothesis at 95% confidence level or 5% significance level ($p < 0.05$). The p-value is the probability of obtaining a test statistic that is at least as extreme as the actual calculated value, if the null hypothesis is true. The p-value for this research is 0.05 (α -value). If the calculated p-value of a test statistic is less than 0.05, the null hypothesis is rejected, which means the factor is significant in predicting the response. Similarly, the F-values in ANOVA table were compared with the F-values from the Fisher distribution proposed for the significance level of 0.05. In the Fisher distribution, the F-values are determined according to the number of degree of freedom of the associated factors and residuals together with the significance level (Siegel, 2016). Furthermore, to check the adequacy of the built RSM models are carried out with respect to R-squared (R^2); which is a measure of the amount of variation around the mean explained by the fitted model, Adjusted R-squared ($\text{Adj } R^2$) which measure the amount of variation around the mean explained by the model, adjusted for the number of terms in the model. The $\text{Adj } R^2$ decreases as the number of terms in the model increases if those additional terms don't add value to the model, Predicted R-squared ($\text{Pred } R^2$); this measure of the amount of variation in new data explained by the model. The $\text{Pred } R^2$ and the $\text{Adj } R^2$ should be within 0.20 of each other. Otherwise, there may be a problem with either the data or the model. Adequate Precision (AP): It compares the range of the predicted values at the design points to the average

prediction error. Ratios greater than 4 indicate adequate model discrimination (Vining, 2010; Costa, 2019).

Application of Design Expert 13 Statistical Software on Unconfined Compressive Strength Data

Quadratic models were suggested for the 7, 14 and 28 days UCS of alkali-activated MK treated non-lateritic (L-MKNLS-M, W-MKNLS-M, H-MKNLS-M) soil by the software and the model equations obtained from the analysis is presented in Table 3 while Figures 1-3 shows the 3D interactive effects plots of 7, 14 and 28 days UCS for various alkali activated MK treated non-lateritic blends against metakaolin content and sodium hydroxide concentration. The plots showed UCS increases with increase in either MK content, SH concentration or both, thereby giving credence to the fact that there exist individual and interactive effect of the factors (MK and SH) on the responses which was observed on the experimental results obtained and that the second order polynomial model selected is well suited for the evaluation of the effects of the factors on the responses.

Table 3: Model Equations for 7, 14 and 28 days UCS

Blend	Model equation
L-MKNLS-M	7days UCS = $551.63 - 5.36MK - 15.42SH + 1.01MKSH + 0.31MK^2 + 8.38SH^2$
	14 days UCS = $600.25 + 11.27MK + 72.68SH + 0.09MKSH + 0.01MK^2 + 4.29SH^2$
	28 days UCS = $536.20 + 18.14MK + 183.34SH + 1.29MKSH - 0.18MK^2 - 3.87SH^2$
W-MKNLS-M	7days UCS = $719.78 - 30.04MK + 55.14SH + 1.65MKSH + 1.27MK^2 + 3.30SH^2$
	14 days UCS = $467.83 + 8.22MK + 341.55SH + 1.79MKSH + 0.05MK^2 - 19.45SH^2$
	28 days UCS = $849.08 + 0.49MK + 388.21SH + 1.01MKSH + 0.44MK^2 - 23.32SH^2$
H-MKNLS-M	7days UCS = $366.36 + 6.89MK + 402.09SH + 2.86MKSH + 0.11MK^2 - 22.18SH^2$
	14 days UCS = $241.90 + 12.35MK + 748.05SH + 5.19MKSH + 0.21MK^2 - 47.53SH^2$
	28 days UCS = $714.22 + 13.11MK + 664.36SH + 9.15MKSH - 0.59MK^2 - 38.96SH^2$

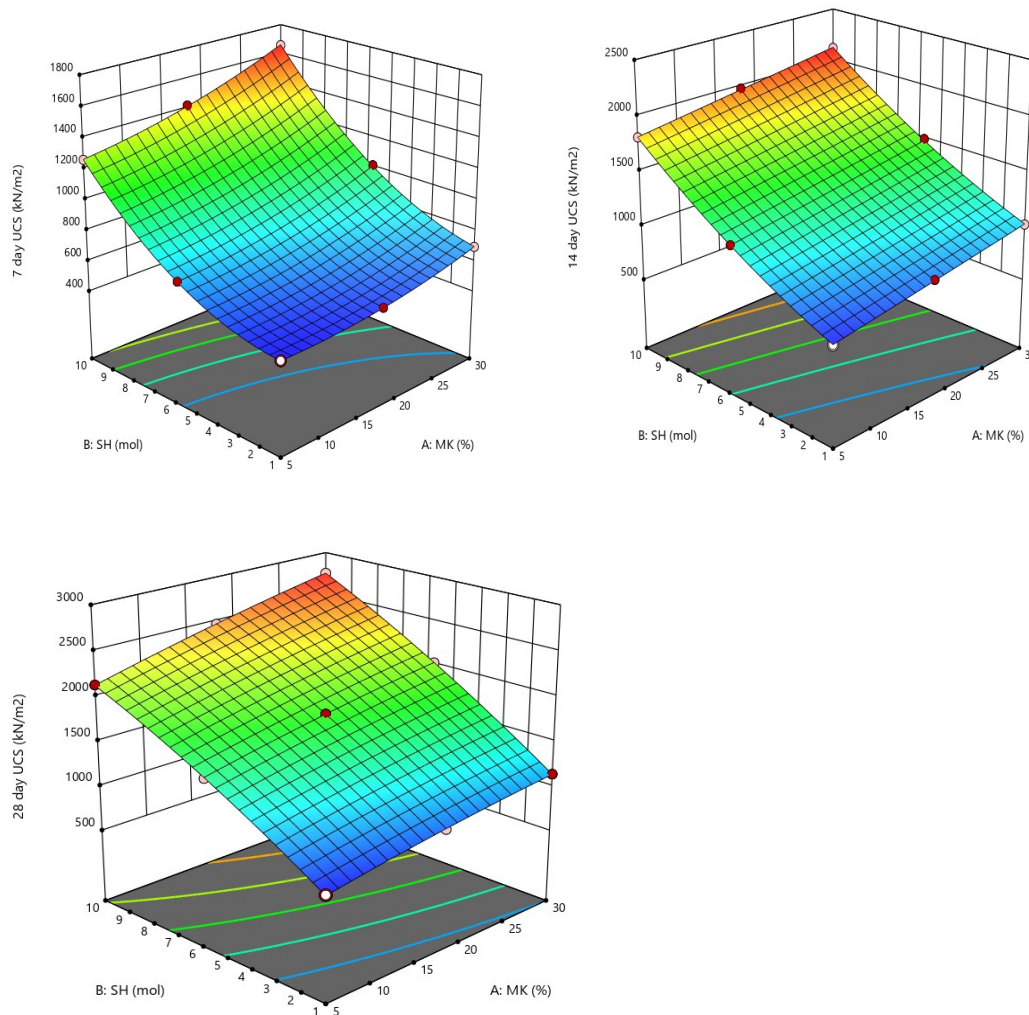
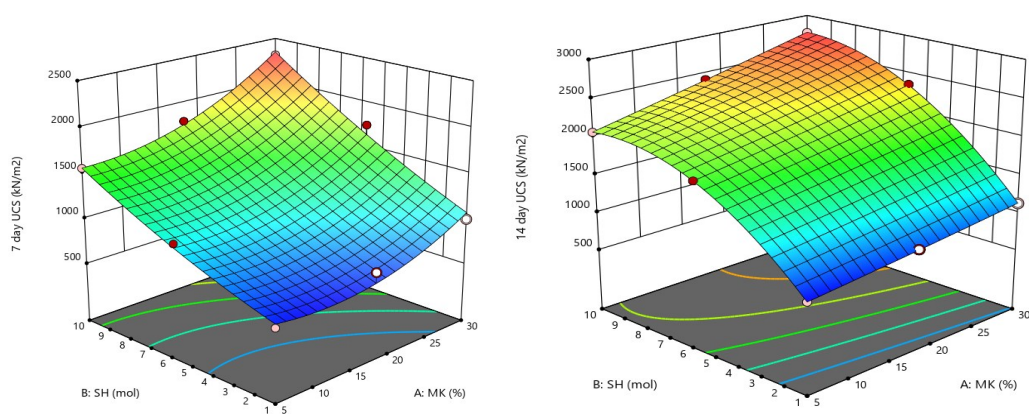


Figure 1: 3D response plots of 7, 14 & 28days UCS of L-MKNLS-M blend



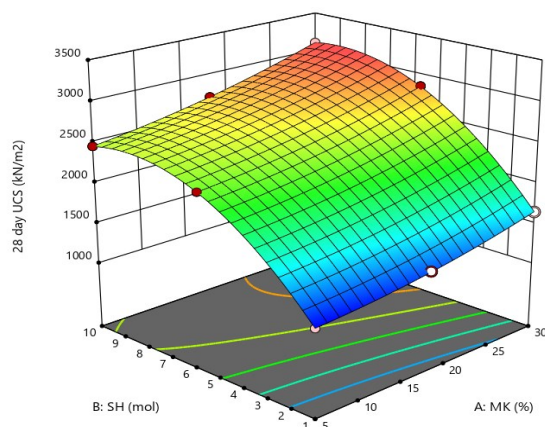


Figure 2: 3D response plots of 7, 14 & 28days UCS of W-MKNLS-M blend

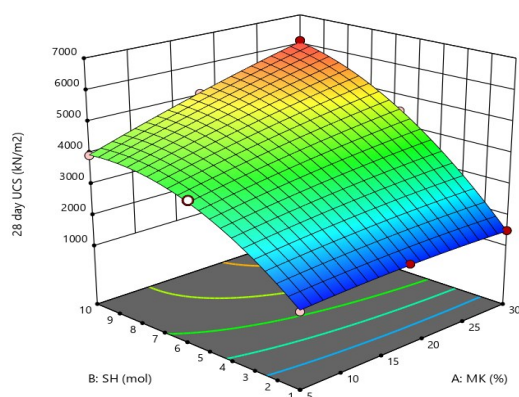
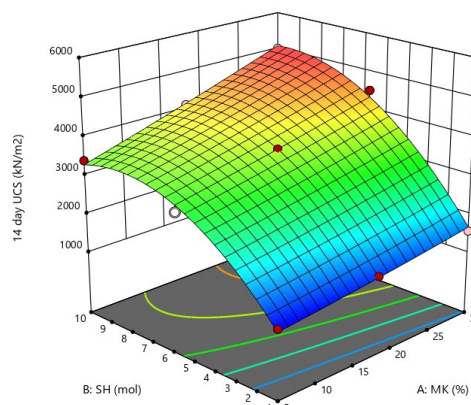
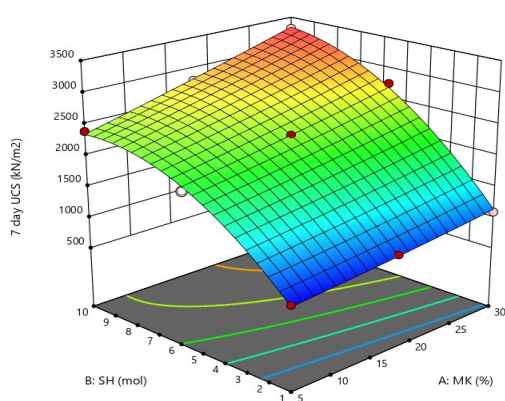


Figure 3: 3D response plots of 7, 14 & 28days UCS of H-MKNLS-M blend

ANOVA for the UCS Response Surface Quadratic Models

The results of analysis of variance (ANOVA) for 7, 14 and 28 days UCS for various alkali activated MK treated non-lateritic blends (L-MKNLS-M, W-MKNLS-M and H-MKNLS-M) is presented in Table 4.

The model calculated F-values are in the range of 83.67 to 55732.69; these values are greater than the critical F-value (3.59) obtained from statistical table. This implies that the models are adequate at 5% level of significance. The P-value for all the models is <0.0001 which indicates that the models are significant. Similarly, the P-values of all for the factors are presented in Table 5. The factors A, B, AB, A^2 and B^2 for all the various UCS models in the range of <0.0001 to 0.049 (less than $P-\alpha = 0.05$) as observed from Table 5 are significant and therefore the null hypothesis is rejected since the calculated p-value is less than 0.05. This implies that the factors are significant in predicting the UCS of the treated soil. Concerning the summary of statistics for the 7, 14 and 28 days UCS models for various alkali activated MK treated non-lateritic blends, shown in Table 4. The standard deviation of the models ranged between 3.66 to 118.05 while the mean ranges from 921.38 to 3714.38 and coefficient of variation ranges from 0.1585 to 6.08 percent. The predicted residual error sum of squares (PRESS) value for the models is in the range of 721.20 to $9.932E+05$; these values are less than the sum of squares value for the respective models. The smaller the PRESS value, the better the model's predictive ability (Johnson & Montgomery, 2009; Costa, 2019). With regards to checking the adequacy of the built models, the magnitudes of the coefficient determination (R^2), adjusted R^2 (Adj R^2), predicted R^2 (Pred R^2), and adequate precision (AP) of the built models are presented in Table 4. Coefficient of determination R^2 is a measure of the amount of variation around the mean defined by the fitted model and as seen from the table, the R^2 for all the models of both activated soil blends ranged from 0.9835 to 0.9999, these values are close to unity (1). This means that the variation in the response variable is largely explained through input factors by a strong fitting. However, this high values of R^2 does not imply that the models are good, since the addition of any variable to a built model always enhances R^2 value irrespective of whether the added variable is statistically significant (Antony, Coleman, Montgomery, Anderson, and Silvestrini, 2011). As for Adj R^2 , it measures the amount of variation around the mean explained by the model, adjusted for the number of terms in the model and it decreases as the number of terms in the model increases if those additional terms do not add value to the model, Johnson and Montgomery (2009). Furthermore, as seen from Table 4, the value of Adj R^2 for all the models ranges from 0.9718 to 0.9999. The similarity among the values of the R^2 and Adj R^2 verifies that the predicted and measured UCS values are in good harmony with each other. The other evaluation criterion Pred R^2 measures the variation in new data explained by the built model. The Pred R^2 of all the models are in the range of 0.8776 to 0.9998 as shown in Table 4, this indicates that the built models have the ability to explain approximately 87.76 to 99.98% of variability in estimating new response values compared to the 97.18 to 99.99% of the variability in the original data expressed via the least squares fits.

Moreover, based on the difference between the magnitudes of Pred R^2 and Adj R^2 , it can be said that these statistics are in a good agreement with the developed models, since the

difference is less than 0.20 in accordance with the suggestion of Antony, Coleman, Montgomery, Anderson, and Silvestrini, 2011 and Costa, 2019.

Table 4: ANOVA results of activated Mk treated non-lateritic soil UCS response parameters (7, 14 & 28 days)

Response parameters	7 Days UCS			14 Days UCS			28 Days UCS		
	L-MKNLS-M	W-MKNLS-M	H-MKNLS-M	L-MKNLS-M	W-MKNLS-M	H-MKNLS-M	L-MKNLS-M	W-MKNLS-M	H-MKNLS-M
Standard deviation	3.66	77.20	46.82	8.24	5.88	118.05	6.47	3.70	46.68
Mean	921.38	1269.23	2136.92	1377.85	1909.92	3268.46	1766.69	2331.85	3714.38
Coefficient of variation (%)	0.3969	6.08	2.19	0.5980	0.3079	3.61	0.3665	0.1585	1.26
Predicted residual error sums of squares (PRESS)	721.20	3.104E+05	1.562E+05	3501.70	1773.74	9.932E+05	2256.47	741.57	1.550E+05
R-squared (R ²)	0.9999	0.9835	0.9977	0.9998	0.9999	0.9945	0.9999	1.0000	0.9994
Adjusted R-squared (Adj R ²)	0.9999	0.9718	0.9961	0.9996	0.9999	0.9905	0.9999	1.0000	0.9989
Predicted R-squared (Pred R ²)	0.9995	0.8776	0.9766	0.9982	0.9996	0.9438	0.9994	0.9998	0.9936
Adequate precision (AP)	455.1925	31.9184	79.6839	248.6722	481.2797	50.4840	442.8597	747.7588	146.2339
Model F-value	19992.72	83.67	607.52	5746.74	22951.98	252.19	17336.36	55732.69	2207.70
P-values	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Adequate precision (AP) was also used in evaluating the performance of the models. It compares the range of values predicted at design point with the average prediction error. All values of AP obtained are in the range of 31.9184 to 747.758, these values were greater than 4 which indicate that the models can be used to navigate the space defined by the FCCD (Johnson & Montgomery, 2009).

Table 5: P values for each term in activated Mk treated non-lateritic soil UCS models

Terms	7 Days UCS		
	L-MKNLS-M	W-MKNLS-M	H-MKNLS-M
Constant	<0.0001	<0.0001	<0.0001
A(Mk)	<0.0001	<0.0001	<0.0001
B(SH)	<0.0001	<0.0001	<0.0001
AB	<0.0001	0.0468	0.0002
A ²	<0.0001	0.0037	0.5645

B ²	<0.0001	0.1934	<0.0001
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	14 Days UCS		
	L-MKNLS-M	W-MKNLS-M	H-MKNLS-M
Constant	<0.0001	<0.0001	<0.0001
A(Mk)	<0.0001	<0.0001	<0.0001
B(SH)	<0.0001	<0.0001	<0.0001
AB	0.2642	<0.0001	0.0017
A ²	0.8590	0.0823	0.6615
B ²	<0.0001	<0.0001	<0.0001

	28 Days UCS		
	L-MKNLS-M	W-MKNLS-M	H-MKNLS-M
Constant	<0.0001	<0.0001	<0.0001
A(Mk)	<0.0001	<0.0001	<0.0001
B(SH)	<0.0001	<0.0001	<0.0001
AB	<0.0001	<0.0001	<0.0001
A ²	0.0002	<0.0001	0.0140
B ²	<0.0001	<0.0001	<0.0001

Application of Design Expert 13 Statistical Software on California Bearing Ratio Data

Statistical analyses performed on the experimental results using Design expert 13 statistical software gave second order polynomial models for the soaked CBR. The models consist of constant terms, individual effects, and interactions effects of the parameters. The model equations obtained from the analysis are presented in Table 6 while the interactive effects of Mk and SH on the responses is presented Figure 4 in the form of contour plots for the various alkali activated MK treated non-lateritic blends against metakaolin content and sodium hydroxide concentration for adequate assessment. From the contour plots, an increase in CBR was observed with increase in both MK content and SH concentration. This trend is similar to the earlier observed trends for UCS responses.

Table 6: Model Equations for CBR

Blend	Model equation
L-MKNLS-M	$CBR = 58.95 + 0.29MK - 4.64SH + 0.05MKSH - 0.003MK^2 + 0.74SH^2$
W-MKNLS-M	$CBR = 63.60 + 0.65MK - 3.94SH + 0.03MKSH - 0.01MK^2 + 0.76SH^2$
H-MKNLS-M	$CBR = 73.15 + 0.79MK - 5.27SH - 0.04MKSH - 0.004MK^2 + 1.03SH^2$

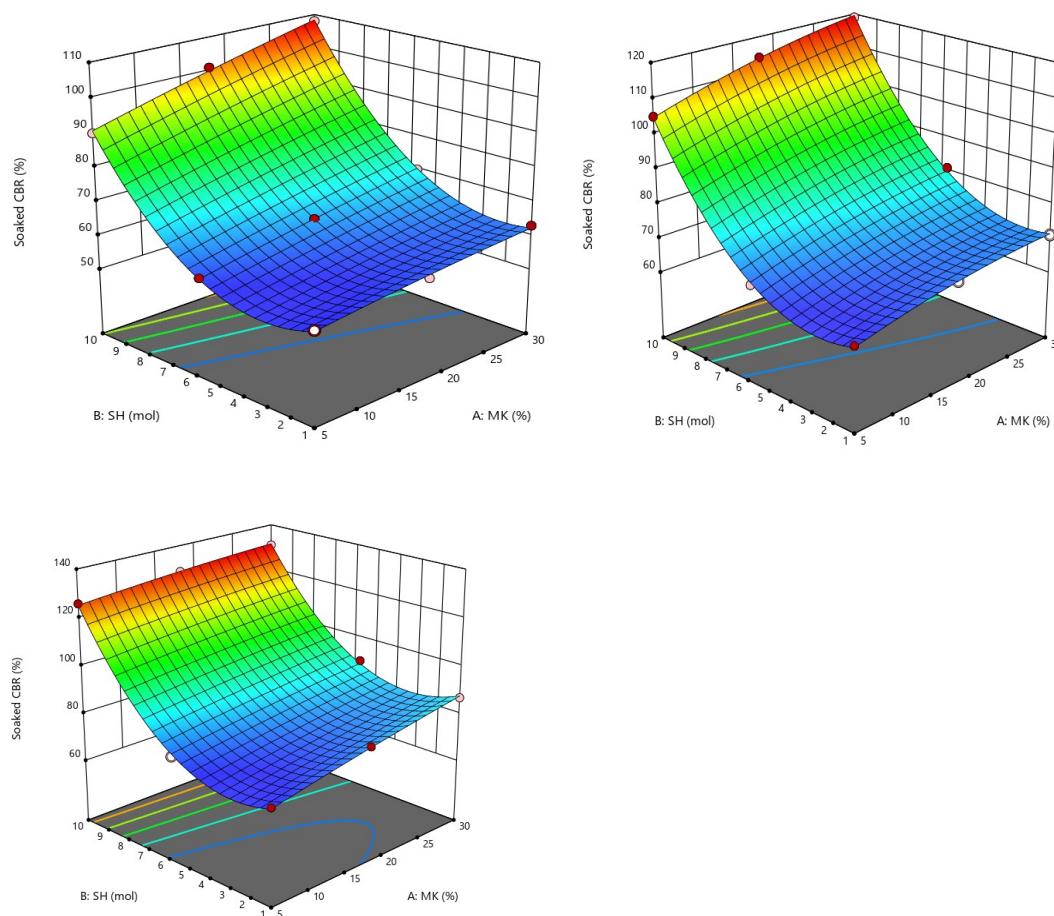


Figure 4: 3D response plots of CBR against MK & SH for (a) L-MKNLS-M blend, (b) W-MKNLS-M blend (c) H-MKNLS-M blend

ANOVA for the CBR Response Surface Quadratic Models

Table 7 presents the ANOVA performed on the CBR response results while Table 8 shows the P values for each of the terms in the models. From Table 7, it is seen that the adjusted R^2 value for the CBR of the alkali-activated MK treated non-lateritic (L-MKNLS-M, W-MKNLS-M, H-MKNLS-M) soil) are in the range of 0.9983 to 0.9990. The adjusted R^2 obtained for the responses were very high, which is a clear indication that second-order polynomial is well suited for the models. In addition, from the same Table 7, the P values obtained for all the CBR models is <0.0001 , which is less than 0.05 that was selected as the confidence level. This indicates that the models are significant and that the models will perform better in the prediction of the various responses within the designed experiment. The coefficient determination (R^2) and predicted R^2 (Pred R^2) of the models are also presented in Table 7. Coefficient of determination R^2 for all the models ranged from 0.9990 to 0.9994. These values are close to unity (1), and as earlier stated, the high values of R^2 does not imply that the models are good, since the addition of any variable to a built model always enhances R^2 value irrespective of whether the added variable is statistically

significant Antony, Coleman, Montgomery, Anderson, and Silvestrini, 2011. The similarity among the values of the R^2 and Adj R^2 implies that the predicted and measured UCS values would be in good harmony with each other. The Predicted R^2 measures the variation in new data that is explained by the built model, it is in the range of 0.9899 to 0.9943 as shown in Table 7. This indicates that the models can explain approximately 98.99 to 99.43% of the variability in the estimation of new response values. Similarly, the AP obtained for the models are in the range of 110.208 to 146.709, these values were greater than 4 which indicate that the model can be used to navigate the space defined by the FCCD (Johnson & Montgomery, 2009).

Table 7: ANOVA results of activated Mk treated non-lateritic soil for CBR response parameters

Response parameters	NLS CBR		
	L-MKNLS-M	W-MKNLS-M	H-MKNLS-M
Standard deviation	0.6901	0.5619	0.7755
Mean	71.69	82.38	93.38
Coefficient of variation (%)	0.9625	0.6820	0.8304
Predicted residual error sums of squares (PRESS)	33.94	22.35	42.72
R-squared (R^2)	0.9990	0.9994	0.9992
Adjusted R-squared (Adj R^2)	0.9983	0.9990	0.9986
Predicted R-squared (Pred R^2)	0.9899	0.9943	0.9916
Adequate precision (AP)	110.2088	146.7099	111.9871
Model F-value	1406.76	2476.46	1687.03
P-values	<0.0001	<0.0001	<0.0001

Table 8: P values for each term in activated Mk treated non-lateritic soil for CBR models

S/N	Terms	NLS		
		L-MKNLS-M	W-MKNLS-M	H-MKNLS-M
1	A(Mk)	<0.0001	<0.0001	<0.0001
2	B(SH)	<0.0001	<0.0001	<0.0001
3	AB	<0.0001	0.0004	0.0007
4	A ²	0.2677	0.0020	0.2252
5	B ²	<0.0001	<0.0001	<0.0001

The significance of the various terms (P values) in the models are presented in Table 8. As mentioned earlier, the P-values for the factors A, B, AB, A² and B² for all the various CBR models in the range of <0.0001 to 0.049 (less than $P-\alpha = 0.05$) have a high significance and therefore the null hypothesis is rejected since the calculated p-value is less than 0.05. This implies that the factors are significant in predicting the CBR of the treated soils.

Optimization of Response Parameters

Based on the developed RSM models, all independent variables were varied simultaneously and independently, in order to optimize the responses. The objective of the optimization process was to obtain the best possible blend that will yield the optimum for particular responses, reduce cost and thereby promoting sustainability, based on the 7 days UCS and soaked CBR criteria of NGS (2013) for base and subbase application as shown in Table 9.

Table 9: Nigerian general specification requirement for road construction, 2013

S/no.	Property	Range
1	7- days UCS sub-base requirement (kN/m ²)	750 - 1500
2	7- days UCS base course requirement (kN/m ²)	1500 - 3000
3	Soaked CBR sub-base requirement (%)	≥ 30
4	Soaked CBR base course requirement (%)	≥ 80

The optimization of alkali-activated MK treated non-lateritic (L-MKNLS-M, W-MKNLS-M, H-MKNLS-M) blends was carried out based on goals and limits stated in Table 10. Based on that, the obtained desirability for L-MKNLS-M, W-MKNLS-M, and H-MKNLS-M blends are 0.46, 0.49 and 0.51 respectively. The numerical optimization of the factors and responses for the blends considered, corresponding to the various desirability's stated are also presented in Table 10.

Validation of the optimal results obtained through optimization of the factors was carried out by conducting experimental test on prepared alkali-activated MK treated non-lateritic (L-MKNLS-M, W-MKNLS-M, H-MKNLS-M) blends containing the optimum proportioning of the factors. The experimental results were then compared with that of the optimized response presented in Table 10. The compared result is presented in Table 11, from the results, it is observed that the experimental values are in close agreement with the optimized values and also, the absolute relative percent error (PE) of the RSM models were also observed to be low which validate the response surfaces models. Therefore, the model predicted the desired responses with good accuracy. The estimation of PE was done using Equation 1.

$$PE = (1 - (\text{predictive values}/\text{experimental value})) \times 100 \quad \dots (1)$$

Table 10: Classification of response goals and limits for optimizing activated Mk treated non-lateritic soils blends

Blend: L-MKNLS-M						
S/no.	Name of response	Goals	Lower limit	Upper limit	Optimized response	Desirability
1	Mk (%)	In range	5	30	30	0.46
2	SH (molar)	Minimize	1	10	7.91	
5	7-days unconfined compressive strength (kN/m²)	Maximize	531	1658	1316.14	
6	Soaked CBR (%)	Maximize	57	108	87	
Blend: W-MKNLS-M						
S/no.	Name of response	Goals	Lower limit	Upper limit	Optimized response	Desirability
1	Mk (%)	In range	5	30	30	0.49
2	SH (molar)	Minimize	1	10	7.49	
5	7-days unconfined compressive strength (kN/m²)	Maximize	626	2308	1935.06	
6	Soaked CBR (%)	Maximize	64	119	94	
Blend: H-MKNLS-M						
S/no.	Name of response	Goals	Lower limit	Upper limit	Optimized response	Desirability
1	Mk (%)	In range	5	30	30	0.51
2	SH (molar)	Minimize	1	10	7.36	
5	7-days unconfined compressive strength (kN/m²)	Maximize	822	3310	3060.74	
6	Soaked CBR (%)	Maximize	73	131	101	

Table 11. Validation of optimized results

Blends	Predicted 7 days UCS (kN/m ²)	Experimental 7 days UCS (kN/m ²)	Absolute relative percent error	Predicted CBR (%)	Experimental CBR (%)	Absolute relative percent error
L-MKNLS-M _i	1316.14	1311.85	0.3270	87	86	1.1628
W-MKNLS-M	1935.06	1930.46	0.2383	94	93	1.0753
H-MKNLS-M	3060.74	3061.45	0.0232	101	101	0.0000

Summary and Conclusion

This study focuses on the application of RSM in predicting and optimizing the UCS and CBR of activated metakaolin treated non-lateritic soils for use as road construction material.

From the results, the following conclusions were drawn.

- The developed models provided a good prediction of the response and are adequate at 5% level of significance, statistical analysis and ANOVA of the experimental results shows that the factors have significant effect in the model behavior and they are significant in predicting the response, the null hypotheses was rejected as the P-values for all the models are less than $P\alpha$ (0.05), high R^2 values were observed which are very close to the Adj R^2 and the difference between Pred R^2 and Adj R^2 is less than 0.20.
- The interactive effects of MK and SH on the responses were presented in the form of contour plots for the various alkali activated MK treated non-lateritic blends against MK content and SH concentration. The plots showed an increase in UCS and CBR with increase in either MK content, SH concentration or both, thereby giving credence to the fact that there exist individual and interactive effect of the factors (MK and SH) on the responses which were observed on the experimental results obtained and the second order polynomial models selected.
- Desirability values of 0.46 – 0.51 were obtained for optimization of the best possible blend that yielded the optimum for particular responses based on the 7 days UCS and soaked CBR criteria of NGS (2013) for base and subbase application, and the corresponding numerical responses were validated by conducting experimental test on prepared alkali-activated MK treated non-lateritic blends containing the optimized proportioning of the factors.

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