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MODELLING AND PREDICTING CBR VALUES OF LATERITIC SOIL TREATED WITH METAKAOLIN FOR ROAD MATERIAL

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ABSTRACT

A design model was developed for the prediction of CBR values of lateritic soil treated with metakaolin. The laboratory test carried out on the lateritic soil showed that the soil was classified as A-7-5(4) or CL according to the American Association of State Highway and Transportation Officials classification system (AASHTO) and Unified Soil Classification System (USCS), respectively. Tests carried out included index test, compaction, California bearing ratio and unconfined compressive strength. Generally, the results showed that the use of metakaolin at varying percentages improved the strength properties of the treated soil. From the laboratory results, six out of the eleven data sets were used for the calibration of model while the remaining five were used for the validation. Comparing the measured and predicted California bearing ratio, the model gave a good coefficient of determination (R^2) of 0.9257. This signifies that the model can be used in soil stabilization and prediction of CBR values.

Keywords: compaction, california bearing ratio, metakaolin, modelling; lateritic soil.

INTRODUCTION

In Nigeria, most of the road networks consist of flexible pavement which is constructed in different layers and they are termed subgrade, sub-base, base and surfacing. In order to design this pavement, there is need to assess the strength of the material underneath (subgrade soil). The subgrade layer serves as the foundation of a road pavement and the wheel load from the pavement surface is distributed to the sub-grade [34]. CBR test is a strength test widely used in the design of flexible pavements over the world. The strength characteristics of this soil reveals it response when use as a construction material. The failure of some engineering infrastructures such as road pavement, retaining walls have been attributed to this strength behaviour and have called for the stabilization of this deficient soil for efficient performance [10, 16]. Portland cement is the most common and widely used soil stabilizer [21, 13]. The cost of blending this soil with cement so as to make it fit for use as construction material is usually high and the increasing emission of detrimental CO_2 contribute to environmental problems. The use of supplementary cementing materials like fly ash, pozzolanas, slag, cement kiln dust etc. have all been used by researchers to stabilize soil for construction purposes [30].

Metakaolin is an increasingly important material used as supplementary cementitious materials (SCM) in cement based systems. Metakaolin is not a waste rather it is derived from a natural mineral and is manufactured specifically for cementing applications. It is a pozzolanic material obtained by thermal treatment of kaolin clay within a temperature range of 650°C and 900°C depending on the source of the kaolin [23]. It's a very reactivealumino silicate pozzolan that is rich in silica and alumina. In the presence of water, these oxides combine with slake slime $Ca(OH)_2$ to form similar compounds in hydrated Portland cement [15]. It has high reactivity compared to other pozzolans and could be used as SCM to produce materials with higher strength, denser microstructure, lower porosity, higher resistance to ions with improved durability properties [32]. Several researchers have carried out experimental studies on the use of this material for different purposes in geotechnical engineering. Badogiannis *et al.* [9] investigated the effect of metakaolin on concrete properties. In their research work, locally produced metakaolin from Greek kaolin was compared to commercially source one with the aim at the utilization of Greek kaolin in concrete works. The result of their study showed that the metakaolin produced locally and the commercial one had similar behaviour in the area of strength development and durability. Umar *et al.* [38] reported that properties of lateritic soil can be improved by adding metakaolin for barrier system for the containment of municipal solid waste. Similarly, metakaolin possesses beneficial properties that can be used in improving both mechanical properties of soils and can be used as a structural material [22].

However, instead of spending much time, resources and going through a rigorous laboratory experiment with very many specimens in order to determine the CBR values of MTK treated lateritic soils. Generating models could be very useful to the geotechnical engineers in predicting the optimal mix for soil-admixture stabilization. Previously, attempts had been made to develop methods and approaches to achieving a stabilized matrix of soil [12]. Also, Black [11] predicted CBR values from plasticity index while [2] proposed a relationship between the CBR and the optimum moisture content and liquid limit for 48 soils in India. In this study, the main aim is to develop, calibrate, verify a mathematical model for the prediction of CBR values of lateritic soil stabilized with metakaolin with a fixed 4 % of Portland limestone cement (PLC) as a binder for both natural and treated soil.

MATERIALS AND METHODS

Materials

The lateritic soil sample, used for this research, was collected from a borrow pit at a depth of about 2 m in Ikot Inyang area which lies within longitude 7° 55′ 2.478″ E, latitude 5° 10′ 34.656″ N in Ibiono local government area, Akwa Ibom State, Nigeria. The laterite was obtained in a semi-solid state and its reddish brown in colour. The kaolin used in producing metakaolin was sourced from Ohiya in Umuahia South Local Government area, Abia State, Nigeria. The collected kaolin was sun dried for a period of two weeks so as to remove the natural moisture. After the sun drying process, it was calcined at a temperature set of 750° C in an electric furnace of Department of Civil Engineering, Akwa Ibom State University, Ikot Akpaden. Metakaolin has the sum of components of the oxide responsible for pozzolanic behaviour: of SiO_2 (52.72 %), Al_2O_3 (41.18 %) and Fe_2O_3 (1.74 %) equal to 95.64 % which makes it a highly pozzolanic material [6].

Index properties

Experimental tests were carried out to determine the index characteristics of the natural and treated lateritic soils as outlined in [7, 8] respectively.

Compaction

Compaction tests were performed on the natural soil and treated soil using the Standard Proctor compactive effort only, as outlined in [7, 8] for the natural and treated soil, respectively. They air dried soil samples passing through British Standard Sieve with 4.75mm aperture were thoroughly mixed with metakaolin at a threshold concentration of 0, 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 % by dry weight of the soil.

Strength

Strength tests carried out on lateritic soil-metakaolin mixtures were used to evaluate California bearing ratio (CBR) and unconfined compressive strength (UCS). Soil samples were compacted at their individual optimum moisture content (OMC) and cured for 7 days before testing for UCS while the CBR tests were performed as stipulated with Nigerian general Specifications [24].

RESULTS AND DISCUSSIONS

Preliminary tests were conducted on the natural soil and Table-1 shows the engineering properties of the soil. It can be deduced that the lateritic soil was classified as A-7-5(4) using the AASHTO soil classification system [1] and CL in the Unified Soil Classification System [5]. Figure-1 shows the particle size distribution curve of the untreated soil while Table-2 shows the chemical composition of kaolin, metakaolin and lateritic soil used in the study.

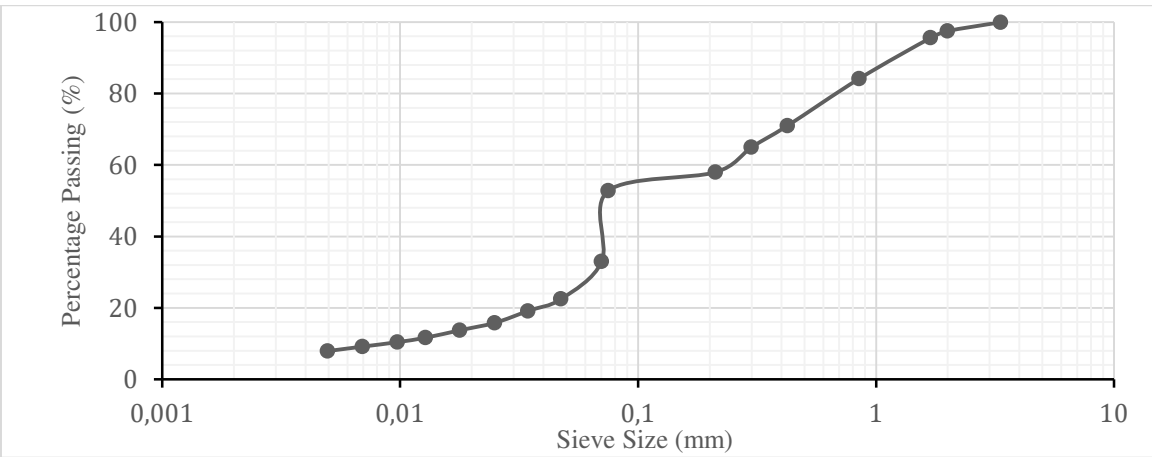

Figure-1. Particle size distribution curve of the untreated soil.

Table-1. Properties of the natural lateritic Soil.

Property	Quantity
Percentage passing BS No 200 sieve, %	52.8
Natural moisture content, %	19.80
Liquid limit, %	41.30
Plastic limit, %	28.1
Plasticity index, %	13.2
Specific gravity	2.60
AASHTO classification	A-7-5(4)
USCS	CL
Maximum dry density, Mg/m^3	1.65
Optimum moisture content, %	17.4
Colour	Reddish-brown

Table-2. Chemical composition of kaolin, metakaolin and lateritic soil.

Oxide	*Kaolin (%)	*Metakaolin (%)	Lateritic soil (%)
Silica (SiO_2)	51.25	52.72	36.8
Alumina (Al_2O_3)	40.70	41.18	33.36
Ferric oxide (Fe_2O_3)	1.18	1.74	17.52
Calcium oxide (CaO)	0.32	0.20	0.061
Magnesium oxide (MgO)	0.28	0.10	-
Sodium oxide (Na_2O)	0.16	0.06	-
Alkalies (K_20)	0.20	0.18	-
Loss on ignition (LOI)	10.17	1.33	16.4

*Akinyele *et al*. [4]

Atterberg limit

The variation of Atterberg limit tests (liquid limit, plastic limit and plasticity index) conducted on lateritic soil stabilized with varying metakaolin content is shown in Figure-2. There was a decreasing trend in liquid limit from 41.30 % to 29.8 % with increasing metakaolin content from 0 % to 20 % andthis could be as a result of the porous nature of metakaolin replacing the soil fine particles. The gradual reduction in liquid limit could also be associated with the agglomeration and flocculation of clay particles, which is as a result of ion exchange at the surface of the clay particles [33, 31]. Plastic limit generally decreased with higher metakaolin contents, from a natural soil value of 28.10% to minimum value of 19 % at 20 % MTK. This result is similar to the report of [32]. The reduction in liquid limit and plastic limit resulted in a general decrease in the plasticity index values of the lateritic soil - metakaolin mixtures. Plasticity index value for the natural soil was 13.20 % and it reduced to 10.80 % at 20 % MTK treatment. The general decrease in the values of plasticity index is indicative of improvement of the natural soil. This reduction in plasticity index is in agreement with the findings of [26].

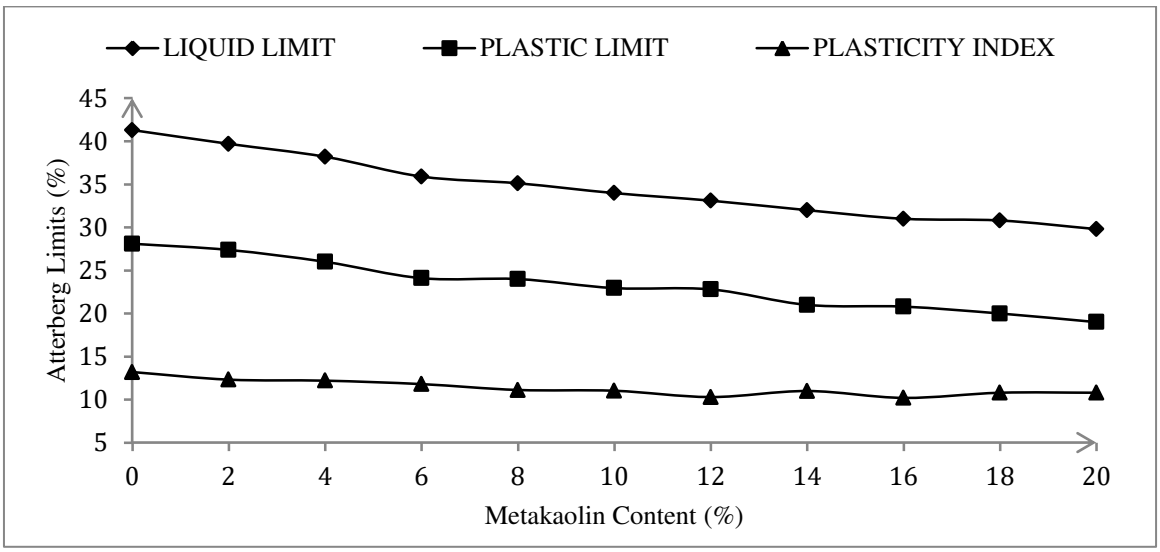

Figure-2. Variation of Atterberg limit of lateritic soil treated with metakaolin content.

Compaction characteristics

The compaction behaviour i.e. maximum dry density (MDD) and optimum moisture content (OMC) of lateritic soil treated with varying metakaolin content is shown in Figure-3. The results obtained from the compaction tests carried out showed a steady increasing trend in MDD with increase in metakaolin content. The MDD values for the natural soil increased from 1.65 Mg/m^3 to a topmost value of 1.89 Mg/m^3 when treated with 18 % MTK content. However, the MDD values increased with higher proportion of metakaolin, because MTK with higher specific gravity (2.60) replacing the soil with lower specific gravity (2.45). The increase in MDD could also be attributed to the flocculation and agglomeration of the clay particles due to cation exchange [29]. Similar trends were reported by [14, 31].

The OMCs indicated an initial increase from 17.40 % for the natural soil to a peak value of 18 % at 6 % MKP. This trend is in agreement with results reported by [17, 28]. The treatment of soil beyond 6 % MKP leads to lower OMC values. This trend of results could be due to the desire for water by MTK for pozzolanic reaction with the silt and clay fractions of the soil. This result is consistent with the work of Salahudeen and Ochepo [35]. Also, the subsequent decrease in OMC with increase in MTK content might be due to cation exchange reaction that caused the flocculation of clay fractions of the soil.

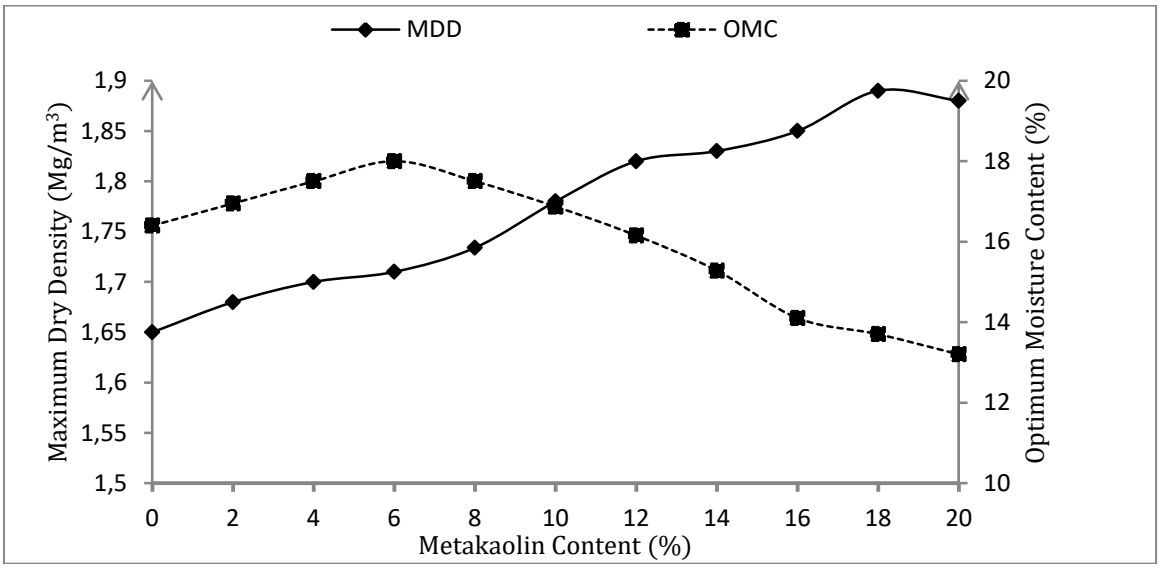

Figure-3. Variation of maximum dry density and optimum moisture content with metakaolin content.

California Bearing Ratio

California bearing ratio (CBR) is one of the common tests used in evaluating the strength of stabilized soils. It's also an indicator in strength of compacted soil and bearing capacity, it is widely used in the design of base and sub-base material for road pavement. The results from the CBR test carried out are clearly shown in Figure-4 and it can be deduced that the treated lateritic improved

from 18 % of the untreated soil to 178 % at 20 % optimum metakaolin content. There was a tremendous increase in CBR values with the addition of MTK at fixed PLC content. This improvement in strength could be attributed to the secondary cementitious materials resulting from the reaction between cement and MTK. This reaction also contributed to interparticle bonding [25]. The Nigerian General Specification [24] outlined the strength requirements in terms of CBR for road pavement structures on Nigerian roads. It recommends that a CBR value of 180 % should be achieved in the laboratory for cement stabilization. However, an unsoaked CBR value of 80 % is required for bases and soaked value of 20 - 30 % for sub-bases both when compacted at optimum moisture [18]. Based on the above criterion, it can be inferred from Figure-4 that the optimal CBR values of 178 % at 20 % MTK met the requirement for base course material.

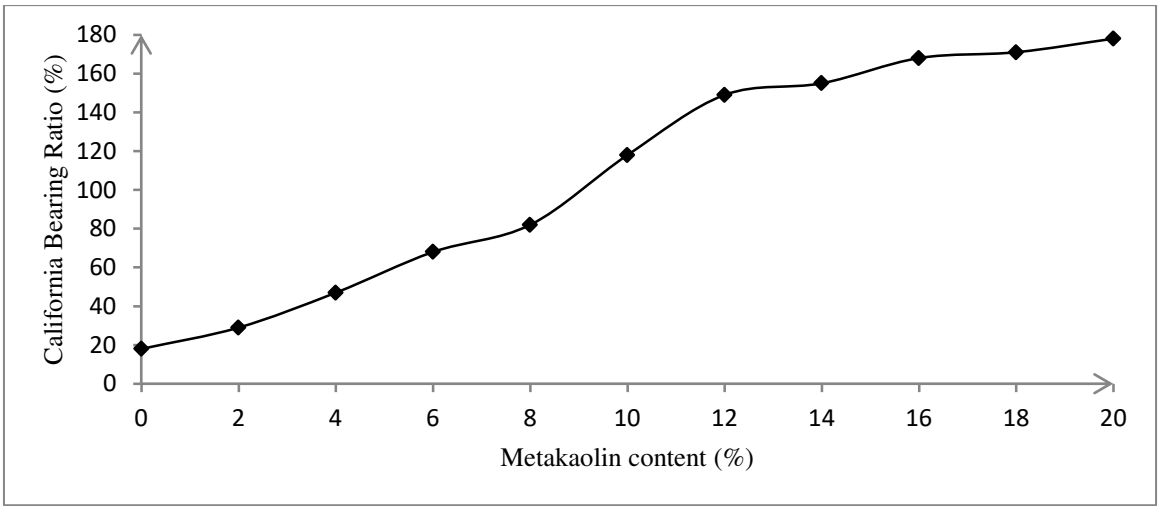

Figure-4. Variation of California Bearing Ratio with metakaolin content.

Unconfined Compressive Strength

Unconfined compressive strength (UCS) is the key test recommended for the determination of the required amount of additive to be used in the stabilization of soils [36]. The variation of UCS with varying proportion of metakaolin from 0 to 20 % at British Standard Light energy level and cured 7 days period is shown in Figure-4. Generally, the UCS test result revealed that the UCS value for the untreated soil increased from 390 kN/m^{2}to a peak value of 960 kN/m^2 at 20% metakaolin content for the treated soil, this implies that there was about 41 % strength increase. Although, the UCS values increased with increase in MTK content, they did not meet the 1710 kN/m^2 value specified by [37] for adequate soil stabilization using ordinary Portland cement (OPC). However, the UCS values of 960 kN/m^2 at 20% metakaolin content falls within the 687 - 1373 kN/m^2 range specified for sub-base by [20]. This increase in UCS values portrays an increase in strength of the materials, improving their geotechnical properties and making them fit for engineering works.

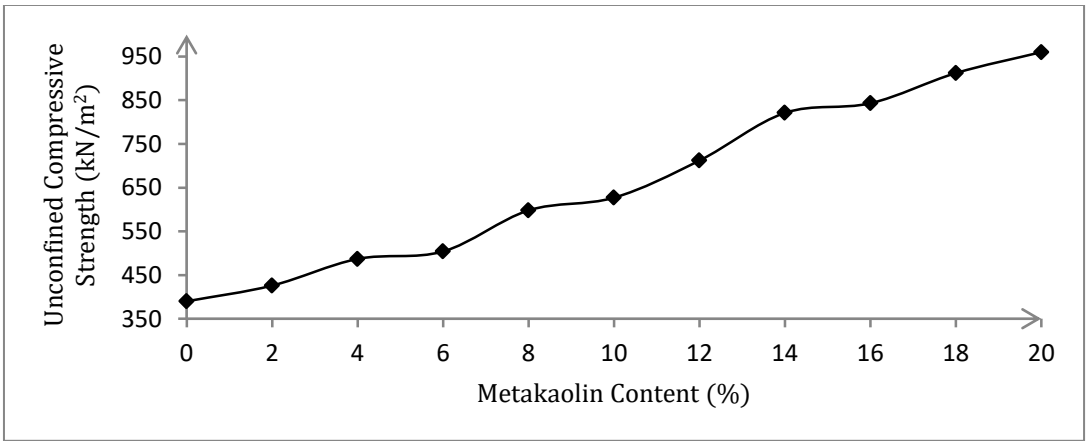

Figure-5. Variation of unconfined compressive strength (7 days curing period) with metakaolin content.

Model Formulation

To formulate the model, California bearing ratio (CBR) was the dependent variable with optimum moisture content (OMC), maximum dry density (MDD) and percentage by weight additive of metakaolin (MTK) as the independent variables. The strength (CBR) behaviour of soil (stabilized and unstabilized) used in road construction is highly influenced by certain properties, which some are the independent variables. However, recent developments in the field of geotechnical engineering have led to renewed interest in modelling and predicting the strength performance in soil stabilization. This is imperative due to the development of mathematical relationship that utilizes some admixtures in treatment of deficient soils.

The relationship between these variables is a nonlinear objective function of the form [19, 27].

$$Y = P\,Q^{\beta_1} R^{\beta_2} S^{\beta_3} \quad (1)$$

where Q, R and S are the independent variables and P, β_1, β_2 and β_3 are constants that takes care of the nonlinearity of the relationship [19].

Linearizing Equation 1 by taking logarithm of equation (1) [3], we have:

$$\mathrm{Log}(Y) = \mathrm{Log}(P) + \beta_1\,\mathrm{Log}(Q) + \beta_2\,\mathrm{Log}(R) + \beta_3\,\mathrm{Log}(S) \quad (2)$$

By setting;

$$\mathrm{Log}(y) = Y_i; \mathrm{Log}(P) = \beta_0; \mathrm{Log}(Q) = x_1; \mathrm{Log}(R) = x_2; \mathrm{Log}(S) = x_3 \quad (3)$$

Putting equation (3) into (2):

$$Y_i = \beta_0 + \beta_1 x_{1(i)} + \beta_2 x_{2(i)} + \beta_3 x_{3(i)} + \varepsilon; i = 1,2,3 \ldots nY_i \quad (4)$$

Y_i = California bearing ratio (C);
x_1 = admixture (A);
x_2 = maximum dry density (M),
x_3 = optimum moisture content (O)and
ε = error

Model Calibration

Minimizing the least square form of equation (4), we have:

$$\sum Y = \beta_0 n + \beta_1 \sum x_1 + \beta_2 \sum x_2 + \beta_3 \sum x_3 \quad (5)$$

$$\sum Y_{x_1} = \beta_0 \sum x_1 + \beta_1 \sum x_1^2 + \beta_2 \sum x_1 x_2 + \beta_3 \sum x_1 x_3 \quad (6)$$

$$\sum Y x_2 = \beta_0 \sum x_2 + \beta_1 \sum x_1 x_2 + \beta_2 \sum x_2^2 + \beta_3 \sum x_2 x_3 \quad (7)$$

$$\sum Y x_3 = \beta_0 \sum x_3 + \beta_1 \sum x_1 x_3 + \beta_2 \sum x_2 x_3 + \beta_3 x_3^2 \quad (8)$$

A total of eleven data sets were obtained from the study. Six out of the eleven data sets were used for the calibration of model while the remaining five were used for the validation.

Translating equation (5, 6, 7, 8) to a matrix form, we have:

$$\begin{bmatrix} \sum Y \\ \sum Y x_1 \\ \sum Y x_2 \\ \sum Y x_3 \end{bmatrix} = \begin{bmatrix} n & \sum x_1 & \sum x_2 & \sum x_3 \\ \sum x_1 & \sum x_1^2 & \sum x_1 x_2 & \sum x_1 x_3 \\ \sum x_2 & \sum x_1 x_2 & \sum x_2^2 & \sum x_2 x_3 \\ \sum x_3 & \sum x_1 x_3 & \sum x_2 x_3 & \sum x_3^2 \end{bmatrix} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} 11.49 \\ 13.37 \\ 2.89 \\ 13.69 \end{bmatrix} = \begin{bmatrix} 6 & 6.71 & 1.48 & 7.18 \\ 6.71 & 7.85 & 1.69 & 7.99 \\ 1.48 & 1.69 & 0.37 & 1.77 \\ 7.18 & 7.99 & 1.77 & 8.60 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} \quad (10)$$

Solving equation (10) using MATLAB R2014a. The solution yielded the following result:

$$\beta_0 = 0.3534, \beta_1 = 1.4842, \beta_2 = 0.0834, \beta_3 = -0.0992 \quad (11)$$

Substituting the results of equation 11(10) into equation (1), we have:

$$y = \frac{2.26 Q^{1.484}\, R^{0.083}}{S^{0.099}} \quad (12)$$

Equation (12) is the modelled California bearing ratio equation where,

y = California bearing ratio (%), Q = admixture (%), R = maximum dry density (mg/m^3) and S = optimum moisture content (%).

Comparison between Measured and Predicted California Bearing Ratio (CBR) Values

Correlation test was carried out to ascertain the coefficient of correlation (R^2) between the measured CBR and the predicted CBR. The predicted values of CBR were close to the measured values though in some cases the model was under predicting. It can be deduced from Figure-6 that the model has a high correlation with R^2 value of 0.9257 and 0.14 - 23.04 % error (see Table-3).

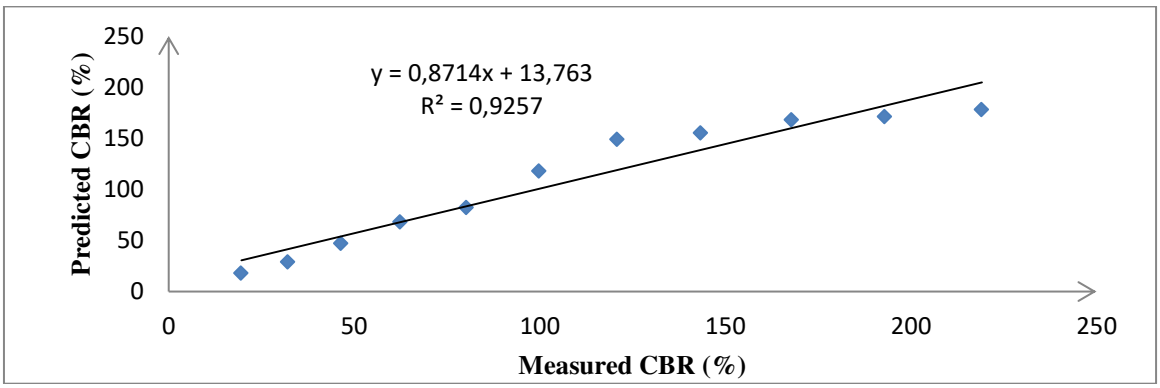

Figure-6. Correlation relationship between predicted CBR and measured CBR.

Table-3. Predicted CBR values and Measured CBR values from the model.

MTK content (%)	Predicted CBR (%)	Measured CBR (%)	Error	% Error
0	**19.46**	**18**	**1.46**	**8.12**
2	32.01	29	3.01	10.37
4	46.37	47	0.63	1.33
6	62.32	68	5.68	8.36
8	80.16	82	1.84	2.24
10	99.71	118	18.29	15.50
12	120.80	149	28.20	18.93
14	143.33	155	11.67	7.53
16	167.76	168	0.24	0.14
18	192.90	171	21.90	12.80
20	219.01	178	41.01	23.04

Correlation analysis for lateritic soil-MTK mixtures

The relationship between the dependent variable (CBR) and the independent variables (MTK; OMC and MDD) shows varying degree of relationships. From the results of the correlation test, a high and positive correlation was observed between MTK and MDD (0.989; P<0.05); CBR (0.980; P<0.05).Whereas, in the case of MTK and OMC (-0.835; P<0.05) a high and negative correlation was recorded. Generally all the independent variables (MTK, OMC and MDD) had significant effect on the dependent (CBR) variable. (see Table-4). Results of coefficient of determination are shown in Table-5.

Table-4. Correlation matrix (Pearson).

Variables	MTK	MDD	OMC	CBR
MTK	1	0.989	-0.835	0.980
MDD	0.989	1	-0.838	0.988
OMC	-0.835	-0.838	1	-0.790
CBR	0.980	0.988	-0.790	1

Table-5. Coefficients of determination (Pearson).

Variables	MTK	MDD	OMC	CBR
MTK	1	0.978	0.697	0.961
MDD	0.978	1	0.702	0.977
OMC	0.697	0.702	1	0.624
CBR	0.961	0.977	0.624	1

Analysis of Variance (ANOVA)

One way analysis of variance (ANOVA) using was used to ascertain whether or not the source of variation (MTK) content have any effect on the lateritic soil specimen. The one-way analysis of variance on compaction characteristics reveals that MTK (F_{CAL} = 16.91 > F_{CRIT} = 4.35) for maximum dry density (MDD) and MTK (F_{CAL} = 8.36 > F_{CRIT} = 4.35) for optimum moisture content (OMC) had significant effects on the tested soil (see Table-6). Also the one-way analysis of variance on strength properties reveals that MTK (F_{CAL} = 28.11> F_{CRIT} = 4.35) for CBR and MTK (F_{CAL} = 116.00> F_{CRIT} = 4.35) had significant effects on the tested soil (see Table-7).

Table-6. One-way analysis of variance result for Compaction Characteristics of soil - MTK mixture.

Property	Variable	Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remarks
Compaction Characteristics	MDD	MTK	1	16.91	0.000541	4.35	SS
	OMC	MTK	20	8.38	0.008959	4.35	SS

Table-7. One-way analysis of variance result for Strength Characteristics of soil - MTK mixture.

Property	Variable	Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remarks
Strength Characteristics	CBR	MTK	1	28.11	3.45E-05	4.35	SS
	UCS	MTK	20	116.00	8.95E-10	4.35	SS

CONCLUSIONS

Based on the results and discussion, the following conclusions may be drawn:

- The strength behaviour of the soil treated with metakaolin was modelled; the dependent variable was the CBR while the independent variables were optimum moisture content, maximum dry density and additive content.
- The lateritic soil classified as A-7-5(4) using the AASHTO classification system and CL using the USCS was used in the study. The CBR values of the treated soil increased with an increase in metakaolin content.
- The model had a good coefficient of determination (R^2) of 92.57 % which makes it a good model. Comparison between measured and predicted California bearing ratio, the predicted result possess better values than the measured, though in some cases the model was under predicting.
- The model can be applied in the field of geotechnical engineering for predicting CBR values, design and monitoring.

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