Multivariate Regression Analysis in Modelling Geotechnical Properties of Soils Along Lambata-Minna-Bida Highway

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Abstract. In pavement design, three important geotechnical properties – CBR, OMC, and MDD are often used to determine the strength of a subgrade layer. To determine these properties in the laboratory is time consuming, laborious, very costly and sometimes infrequently performed due to lack of equipment. The aim of this study is therefore to develop regression models to estimate the strength properties using relatively easier index properties. Thirty – four soil samples were collected from various locations along Bida – Minna highway between 0.6–1.5 m depths for index, consistency, compaction and CBR tests. Based on the laboratory results, the CBR significantly related with sand, % fines, LL, PL, PI, OMC and MDD parameters. Satisfactory empirical correlations ($R^2 > 0.59$) were found between the three strength properties and other index properties of the experimented soils. Seven best predictive models were developed to estimate the strength properties based on multiple linear regression analysis.

Keywords: California bearing ratio · Soil physical properties · Pavement · Multiple regression analysis

1 Introduction

Roads are major means of transportation and economic development and most of them consist of flexible pavement. Flexible pavement is made up of different layers such as subgrade, subbase, base course and surface layer. Design and performance of flexible pavement mainly depends on the strength of subgrade material. The load from the pavement surface is ultimately transferred to subgrade and to the sub-base. The subgrade is designed such that the stress transferred should not exceed elastic limit. Hence, the suitability and stability of subgrade material is evaluated before construction of pavement. Soaked California bearing ratio (CBRs) value is considered a major strength parameter in subgrade design that influences the thickness of the subgrade. If the CBR value is higher, then the designed thickness of the subgrade is thinner and vice versa. Technically, CBR test is difficult to determine in a short duration, very expensive, tedious and requires large quantity of soil sample and consequently, leads to delay and high cost implication on any structural project. In Nigeria, most of these paved roads

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and other earth structures have witnessed different degrees of failures, which had become a cause for concern to geoscientists. To overcome this problem, a simple and less time consuming technique becomes inevitable through linear regression analysis of soaked CBR value with other easily determined soil properties.

Over the years, several researchers (Egbe et al. 2017; Noor 2011; Talukdar 2014; Ramasubbarao and Siva 2013; Akshay 2013; Patel and Desai 2010) have applied multiple linear regression analysis (MLRA) in modelling geotechnical soil properties and many correlations were developed. In addition, several attempts were made to predict CBR values based on physical properties such as index properties (Nguyen and Mohajerani 2015; Gregory 2007; Pal and Ghosh 2010). In this paper, soaked CBR is correlated with other soil properties such as liquid limit, plastic limit, and plasticity index, optimum moisture content (OMC), maximum dry density (MDD) and percentage fines using simple and multiple regression analyses. Their findings showed a strong correlation between the CBR and fines as well as plasticity index. Giasi et al. (2003) studied the index properties, such as liquid limit and plasticity index of various soils and proposed a numerous equations.

2 Materials and Methods

2.1 The Study Area and Geologic Setting

The study area is the Lambata – Minna highway, 105 km in distance, and located between longitude 6°20′–6°35′E and latitude 9°05′–9°35′N. The highway is underlain by Precambrian basement complex, made up of biotite granite, granite gneiss, migmatite, marble and schist. The granite has been affected by the Pan African Orogeny with late tectonic emplacement of granites and granodiorites (Olayinka 1992). Different disturbed soil samples were collected from different locations along the highway and subjected to geotechnical laboratory tests according to BS 1377 (1990) and West African standards. Index properties (grain size distribution and consistency limits), compaction (OMC and MDD using Standard Proctor mould) and CBR tests were conducted on the soils samples.

2.2 Relationship Between Soil Properties

To establish relationship between soaked CBR and different soil properties, scatter plots were generated with CBR against different soil parameters and suitable trend line was drawn with higher correlation coefficient. Correlation quantifies the degree to which dependent and independent variables are related. Linear regression quantifies goodness of fit with the coefficient (R^2) value. R^2 value provides a measure of how well future outcomes are likely to be predicted by the model.

2.3 Multiple Linear Regression Analysis (MLRA)

To develop the models of multiple linear regression analysis, soaked CBR value was considered as dependent variable and soil properties such as gravel (G), fines (F), sand (S), LL, PL, PI, OMC and MDD as the independent variables using SPSS and Microsoft Excel software to derive the relationship statistically. The regression equation is in Eq. 1.

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \ldots + b_nx_n \quad (1)$$

Where

Y is the dependent variable (i.e. CBRs)
b_1–b_n the intercept (constant), b_0 the slope (regression coefficient)
x_1–x_n the independent variables (soil properties considered in the analysis).

3 Results and Discussions

The geotechnical properties of thirty-nine soil samples collected are summarized in Table 1. Soils occurring within the granite and grandiorite terrain are well graded soils with high gravels (39.9%, 44.3%), moderate sands (46.4%, 36.7%) and high fines (11.7%, 14.5%) respectively. The sandstone terrain has high presence of sands (80%), MDD (2.0 mg/m^3), soaked and unsoaked CBR (76.4% and 112.4%) respectively. The migmatite gneiss terrain has high liquid content (38.2%), high OMC (21.0%), very low CBRs (8.5%).

From Table 1, it is observed that plasticity depends on grain size of soils. When the sand content in the soil increases the plasticity index decreases. Due to the decrease in attraction force, liquid limit of the soil decrease and accordingly plasticity index decrease. With the increase in fines intermolecular attraction force increases resulting in increase in liquid limit. Nath and Dalal (2004) also observed the same trend in their studies.

Table 1. Summary of geotechnical soil test

Proth		G	S	F	LL	PL	PI	OMC	MDD	CBRs	CBRu
GN = 17	MIN	6.4	15.9	2.0	24.0	2.5	12.6	12.2	1.4	2.6	2.7
	MAX	80.7	79.7	47.9	49.0	20.2	42.0	29.9	2.1	115.0	121.8
	MEAN	39.9	46.4	11.7	35.5	7.7	27.6	19.1	1.8	41.5	58.0
	STD	21.0	19.4	10.5	7.1	5.1	9.3	5.2	0.2	24.9	33.9
SS = 8	MIN	5.9	71.3	2.5	14.5	1.0	3.1	9.4	1.7	13.0	74.0
	MAX	25.4	91.6	8.8	45.0	36.9	40.0	18.6	2.2	132.4	144.4
	MEAN	14.9	80.0	5.2	26.6	10.8	16.0	12.1	2.0	76.4	112.4
	STD	5.7	6.1	2.5	11.3	12.1	11.0	2.8	0.1	34.1	24.8

(*continued*)

Table 1. (*continued*)

Proth		G	S	F	LL	PL	PI	OMC	MDD	CBRs	CBRu
MG = 10	MIN	4.3	14.2	2.3	28.7	5.7	13.0	14.1	1.5	0.9	1.4
	MAX	70.2	89.4	15.2	50.1	27.0	30.5	28.3	2.1	24.1	70.6
	MEAN	37.2	52.3	8.1	38.2	17.0	21.2	21.0	1.8	8.5	14.4
	STD	20.4	23.5	3.9	6.0	9.6	6.5	5.0	0.2	7.1	20.5
GD = 2	MIN	21.0	11.6	10.6	35.0	2.5	27.5	21.1	1.6	2.6	3.3
	MAX	67.7	61.9	18.5	40.0	7.5	37.5	23.7	1.9	4.3	4.9
	MEAN	44.3	36.7	14.5	37.5	5.0	32.5	22.4	1.7	3.5	4.1
	STD	33.0	35.6	5.5	3.5	3.5	7.1	1.8	0.2	1.2	1.1
SH = 1		24.1	54.7	21.0	38.5	5.4	23.1	31.7	1.8	18.7	19.6
MI = 1		33.8	50.2	16.0	39.0	8.0	31.0	20.0	1.7	33.4	35.9

G = gravels (%), S = sand (%), F = fines (%), LL = liquid limit (%), PL = plastic limit (%), PI = plasticity index (%), OMC = optimum moisture content (%), MDD = maximum dry density (mg/m^3), CBRs = soaked California bearing ratio (%), CBRu = unsoaked California bearing ratio (%), PROTH = Protholic rocks, GN = Granite, SS = Sandstone, MG = Migmatite gneiss, GD = Granodiorite, SH = Schist, MI = Migmatite

3.1 Relation Between Soaked CBR and Soil Properties

The statistical evaluation of soil properties has always attracted the interest of geotechnical engineers. In this section, various correlations have been established between different soil parameters. The relationship between CBR and different soil properties are developed and mathematical equations are shown in Fig. 1. The variation between soaked CBR and both liquid limit and plasticity index showed a suitable trend line with a third degree polynomial equation. However, the influence of plasticity index on CBRs is not clear as the points scatterred about in the plot. As the moisture content increases, there is progressive reduction in CBR with corresponding decrease in MDD due to the reduction in shear strength and the density of the fine-grained soils. This therefore implies that moisture content influences the strength of soil. This observation agrees with the reports from Nguyen and Mohajerani (2015).

The correlation matrix of different soil properties is shown in Table 2. Relationship of soil properties vary from positive to negative correlation. There is a weak correlation of CBRs and other soil properties ($R < 0.5$) except for OMC ($R = 0.6$). Furthermore, the correlation with Atterberg limit indicates that CBR correlate better with liquid limit than plastic limit.

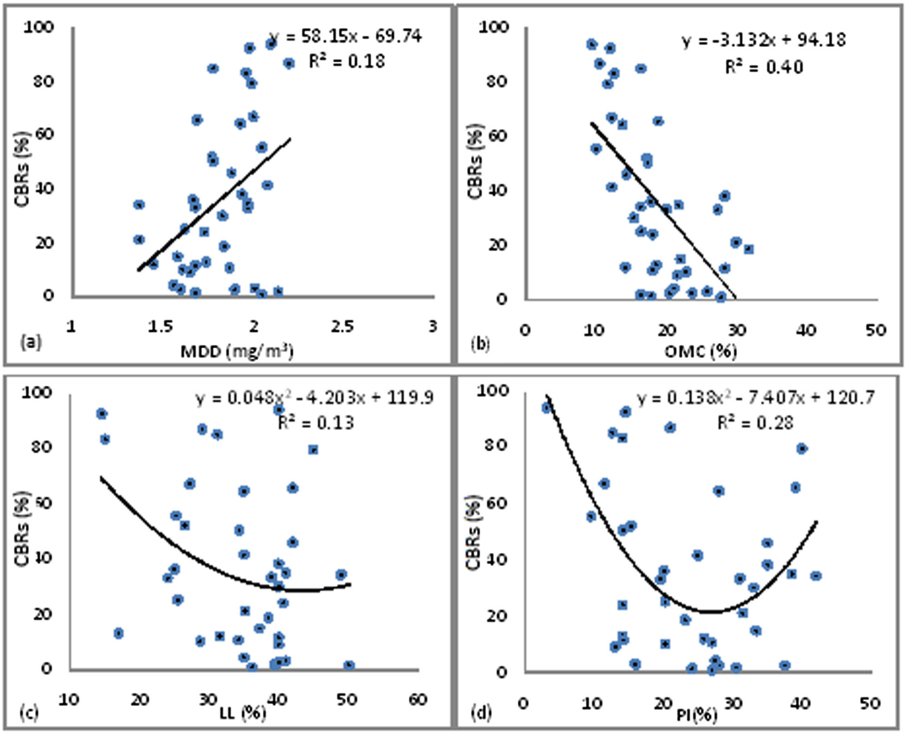

Fig. 1. (a) CBR vs MDD, (b) CBR vs OMC, (c) CBR vs LL, and CBR vs PI

Table 2. Correlation matrix of soil properties

	G	S	F	LL	PL	PI	OMC	MDD	CBRs	CBRu
G	1									
S	**−0.91**	1								
F	−0.16	−0.16	1							
LL	**0.50**	−0.49	−0.14	1						
PL	−0.10	0.16	−0.22	0.34	1					
PI	**0.53**	**−0.56**	0.04	**0.55**	**−0.59**	1				
OMC	0.36	−0.47	0.26	0.23	−0.07	0.22	1			
MDD	−0.14	0.27	−0.25	−0.16	0.07	−0.21	−0.30	1		
CBRs	−0.37	0.46	−0.20	−0.37	−0.03	−0.28	**−0.60**	0.39	1	
CBRu	−0.36	**0.50**	−0.29	−0.45	−0.02	−0.36	−0.65	0.41	**0.87**	1

3.2 Multiple Linear Regression Analysis

Besides correlating the soil parameters in order to examine their relationships, the relationship of strength properties (OMC, MDD and CBRs) with index properties such as grain size distribution and Atterberg limit were also investigated. Several models were constructed and three best fit models were selected and shown in Table 3. The three strength properties were estimated and verified through the standard error and its significance. The errors in the values of CBRs, MDD and OMC obtained from the equations are within the range of +29.9, +0.2 and +5.6 respectively.

From the Table 3, it is observed that the correlation coefficient varies significantly from 0.39 to 0.65 for different soil functions. Regression was also developed for CBRs as a function of moisture content, maximum dry density and plasticity index. It should be noted that in the field, the subgrade soil is recommended to be compacted at the OMC initially in order to achieve the MDD. Under severe changes in seasonal climate and drainage conditions, the moisture content of the subgrade soils increases over the service life of the constructed road. This is buttressed by the significantly higher R^2 value of 0.68 in model no. 3.

Table 3. Regression equation for CBRs, MDD and OMC

Model no.	Regression equation	R^2	Significance	F
1	CBRs = 35.8 − 2.01(LL) + 1.21(PI) + 1.01(PL) + 0.13(G) + 0.61(S) − 0.59(F)	0.53	0.08	2.05
2	CBRs = 40.4 + 0.13(G) + 0.58(S) − 0.63(F) − 0.95(LL)	0.52	0.02	3.19
3	CBRs = 41.85 − 0.41(PI) − 2.88(OMC) + 32.77(MDD)	0.68	0.00	8.45
4	MDD = 1.39 + 0.015(LL) − 0.019(PI) − 0.017(PL) + 0.006(G) + 0.007(S) − 0.002(F)	0.42	0.36	1.13
5	MDD = 1.28 + 0.006(G) + 0.007(S) − 0.002(PI)	0.39	0.21	1.56
6	OMC = 24.12 + 0.94(LL) − 0.95(PI) − 0.91(PL) − 0.006(G) − 0.122(S) + 0.103(F)	0.57	0.03	2.59
7	OMC = 24.91 − 0.003(G) − 0.124(S) + 0.137(F) − 0.031(PI)	0.51	0.03	2.95

To examine the error in the prediction, the predicted strength parameters were plotted against the actual soil strength values in Fig. 2. From the below plots, it can be seen that the variations between the predicted and the measured values are not so significant particularly with OMC and MDD. Hence, can be considered as good prediction models.

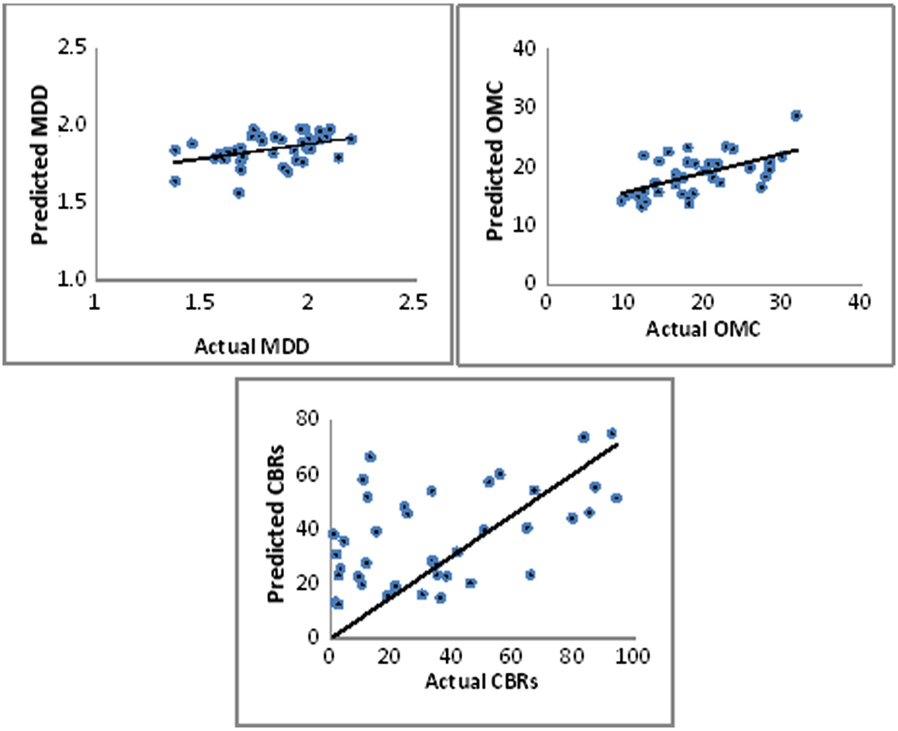

Fig. 2. The predicted strength values versus the experimented values for all soils

4 Conclusion

Maximum dry density and optimum moisture content are important strength properties used for preliminary investigation, design and control. This study investigated the relationship of different soil properties as a function of strength of the road. Multilinear regression analyses were conducted to develop predictive model from statistical point of view to estimate strength parameters such as CBR, MDD, OMC. Several conclusions have been drawn from the study:

i. With the increase in finer fraction and liquid limit, plasticity index increases.
ii. The effect of moisture content on CBRs is significant. As the moisture increases, the CBR decreases significantly.
iii. MDD and OMC are best correlated with plasticity index compared to liquid and plastic limits.
iv. MLRA provides reliable predictive models. However, these models should be limited to soils with similar characteristics and more samples are recommended to improve the prediction.

v. The regression of CBRs and moisture content, plasticity index and maximum dry density was found to be significantly strong (R^2 = 0.68).
vi. With less percentage errors, the empirical relations can be accepted as useful information for engineers in the field for preliminary design and estimation.

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