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Evaluation of the compaction characteristics of some selected lateritic soils

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ABSTRACT

The compaction characteristics of some selected lateritic soils was the focus of this research. The soils fall under soil class A-2-6 (0), A-6(4), A-7-5(2), A-7-6(2) and A-6(0) using AASHTO system and SC and SM using ASTM-USCS. Important index property tests were done and compaction tests at the British Standard Light, West African Standard and British Standard Heavy energy levels. SPSS rank Spearman correlation tool, graphs (third order polynomial) and some analysis tool pack (regression, descriptive statistics, analysis of variance in Microsoft Excel were used to analyse the data. Third order polynomial was shown to be a viable alternative method to determine compaction parameters. Compactive effort was also shown to be significant by coefficient of determination (R^2) with average values of 0.884 and 0.865 for MDUW and OMC respectively which is a good fit. Descriptive statistics, correlation matrix and analysis of variance show that some index properties of soils such as liquid limit, plasticity index, fines content, sand content, fines content: sand content ratio and derived variables such as plasticity modulus, plasticity product and grading modulus which are

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easier to find and consume less materials have significant relationship with MDUW and OMC. Thus, it is possible to develop models to predict these quantities from index properties.

Keywords: Laterite, Compaction, Third order polynomial, Regression, Correlation, Descriptive Statistics.

1. INTRODUCTION

The term soil has different meanings, depending on the area of specialization in which it is being considered. The Agriculturist sees soil as the growth and development base for plants which usually exist on the surface of the earth while the Geologist defines soil as a substance possessing organic matter, within the thin root zone and sustains the growth of crops and trees. The Engineer's view of the soil depends on the degree of cementation as a result of inherent minerals, air and water and the degree of weathering of parent rocks as well. Soil includes widely different materials ranging from boulders, sand, gravels, silts and clays having particle sizes between the ranges of (200 mm - 0.002 mm). It is important to note that soils are natural materials and as such they are complex, they are materials that are not isotropic like other engineering materials (cement, steel etc.) and thus do not always exhibit the properties desired for construction purposes. Due to this, soil property differs not only from one location to another but also among the horizons of a given profile. These characteristics should, however, be kept in mind when handling soils (Gadzama et al, 2018).

Due to their complex nature and variable properties, modification of soils at the site to improve their engineering properties is essential (Horpibulsuk et al, 2013).

Laterites are soils that can be found at different places in the world especially at the tropics where the temperature favours their formation (Kumar et al, 2016). Nigeria which is one of the tropical countries of the world have wide resources of laterites. Among the soils commonly used for construction in south-eastern Nigeria, laterites have found enormous utilization because it is cheap and readily available. The soils are used for foundation construction in roads, buildings, bridges (Nnochiri, 2017).

In road construction for instance, it is often imperative to improve the shear strength of the soil through the improvement of its density in proportion to the expected wheel load. The improvement of soil density can be made possible through an intentional/beneficial alteration of soil physical and/or chemical properties often know as soil stabilization. Among the different means of soil stabilization, compaction which is an aspect of mechanical soil stabilization is one of the commonest. Impact compaction is usually done in the laboratory under controlled conditions using various sizes of mould and rammer (Arora, 2014). Laboratory compaction usually serves as control for field compaction. It is undoubtable that the inherent/index properties of laterites would definitely affect the response of a soil to compaction. One of such important index properties is the fines content of soils.

Osinubi et al (2012) reported that several researchers have worked on the effect of fines on different engineering properties of soils. Researches have shown that fines content affects the compression and compaction behavior of soils, the instability and strength of soils which are desirable properties for soils to be used as highway materials.

A work on the effects of index properties of soils upon their compaction characteristics carried out by Dash (n.d.) showed that particular gradation or plasticity characteristics gave the maximum dry density (MDD) or minimum optimum moisture content (OMC).

Arvelo (2004) in his investigation of the effects of the soil properties on the MDD obtained from the standard proctor test showed that well-graded sands have higher MDD than poorly graded sands when the soils have the same fines content. It was shown that plastic fines tend to increase the MDD.

Sivrikaya et al (2017) developed reliable models based on some soil index parameters which included gravel content, sand content, fines content, liquid limit and plasticity index together with compaction energy to predict MDUW and OMC. Sivrikaya et al (2017) recommended the development and use of the similar models for preliminary design where there are time and financial constraints.

Reviewed literatures have shown that important relationship exist between compaction parameters and index properties. It is necessary to examine these relationships for some selected lateritic soils in the tropical region to aid construction experts in this region. Based on the outcome of the reviewed literatures, the objectives of this study would be to show that the compactive effort and fines content: sand content ratio can be used to predict the compaction characteristics of coarse-grained lateritic and to show that the third order polynomial function can be used to describe the moisture-unit weight relationship.

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2. MATERIALS AND METHODS

2.1. Materials

The materials used for the work are nine (9) lateritic soils collected from nine popular borrow sites in Anambra State, Nigeria located at Agu Awka 1 (A), Agu Awka 2 (B), Nawfia (C), Awkuzu Nkwelle (D), Awkuzu Ifite 1 (E), Awkuzu Ifite 2 (F), Ring Road 1 (G), Ring Road 2 (H), Nteje (I). The soil samples were collected in a disturbed state using shovels and packaged in airtight polythene bag to prevent moisture loss.

2.2. Methods

Three compaction energies were used for the soils. These include:

British Standard Light (BSL) (BS 1377-4:1990): BSL gives a compaction energy of 605.89 kN/m^3 to the soil and involves compaction of the soil in 1000 cubic centimetre mould. The soil is compacted in 3 layers, given each layer 27 uniform blows using 2.5 kg rammer that falls through 0.3048 m height.

West African Standard (WAS) (Ola, 1989): WAS gives a compaction energy of 1008.71 kN/m^3 to the soil and involves compaction of the soil in 1000 cubic centimetre mould as well. The soil is compacted in 5 layers, given each layer 10 uniform blows using 4.5 kg rammer that falls through 0.457 m height.

British Standard Heavy (BSH) (BS 1377-4:1990): BSH gives a compaction energy of 2723.53 kN/m^3 to the soil and involves compaction of the soil in 1000 cubic centimetre mould. The soil is compacted in 5 layers, given each layer 27 uniform blows using 4.5kg rammer that falls through 0.457 m height.

The British Standard compaction procedures are according to BS 1377-4-1990 while the West African method is according to the work of Ola (1989).

The analysis of results was carried out using graphs, descriptive statistics, correlation, regression analysis, analysis of variance (ANOVA) and third order polynomial. Third order polynomial (Howell et al, 1997) can be defined by Equation 1

$$Y_d = Aw^3 + Bw^2 + Cw + D \quad (1)$$

Where Y_d is the dry unit weight, w is the moisture content and A, B, C, and D are constants resulting from the fitting process. Even though second order polynomial and fourth order polynomial could also be used, they have shortcomings which significantly affect the accuracy of the results (Howell et al, 1997). Thus third order polynomial equation is more reasonable to examine the relation between the compaction parameters.

3. RESULTS AND DISCUSSION

Table 1 shows the index properties of the soil samples that were tested. The specific gravity of the soils range from 2.42 to 2.59. According to guide for specific gravity of solids determination (ASTM D 854-92), the specific gravities of some porous soils or soils infested with much organic matter usually fall below 2.6 while tropical iron-rich laterite are expected to have specific gravity range of 2.75 – 3.0. Even though our soil samples were collected as laterites and falls in class SC which should be good soils for engineering purposes, their specific gravity values (2.42 – 2.59) are all below 2.6. This shows that the soils contains organic matter and/or porous materials. Thus, these soils would need to be stabilized before they can be used as highway materials. The gravel percentage of these soils are quite low with majority falling below 1%. The percentage of gravel would not have effect on the soil's behaviour because percentage of sand usually control soils classified under SM-SC (USCS). Based on the USCS class, the values of these soils as subgrade or subbase when not subject to frost action fall between poor to fair. They are also fairly stable to be used as embankment materials based on USCS.

Table 1: Index and compaction characteristics of the soils

Properties	A	B	C	D	E	F	G	H	I
Natural Moisture Content (%)	10.10	9.30	6.50	7.62	9.11	5.79	9.14	9.03	8.29
Specific gravity	2.58	2.48	2.55	2.51	2.59	2.49	2.42	2.46	2.42
Liquid Limit (%)	34.70	51.30	28.00	40.50	24.40	20.90	24.60	23.60	22.25
Plasticity Limit (%)	17.84	32.55	15.98	19.49	13.37	8.58	14.4	13.21	5.78
Plasticity Index (%)	16.86	18.75	12.02	21.01	11.03	12.32	10.20	10.39	6.47
Gravel (%)	0.05	0.14	0.00	0.04	0.08	0.00	1.28	6.68	0.00

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Sand (%)	54.31	63.93	80.21	69.87	64.05	74.72	64.30	65.56	72.25
Fine and Clay (%)	45.64	35.93	19.79	30.09	35.87	25.28	34.42	27.76	27.75
MDUW (BSL)	19.40	18.07	19.00	19.28	18.85	19.45	18.85	18.84	19.39
MDUW (WAS)	19.30	18.80	18.97	20.03	19.30	19.71	18.18	19.18	19.76
MDUW (BSH)	20.20	20.46	20.10	20.20	19.65	20.31	19.85	19.95	20.21
OMC (BSL)	13.00	13.80	12.80	12.40	12.40	11.80	13.60	11.50	12.00
OMC (WAS)	12.00	12.30	10.40	11.50	11.20	9.80	13.40	12.40	10.10
OMC (BSH)	10.00	11.20	8.40	9.50	9.40	9.00	9.20	8.80	9.60
Soil Class (USCS)	SC	SM	SC	SC	SC	SC	SC	SC	SC
Soil Class (AASHTO)	**A-6(4)**	**A-7-5(2)**	**A-2-6(0)**	**A-7-6(2)**	**A-6(0)**	**A-2-6(0)**	**A-2-6(0)**	**A-2-6(0)**	**A-2-6(0)**

3.1 Alternative way of estimating Maximum Dry Unit Weight and Optimum Moisture Content of soils using third order polynomial

Maximum dry unit weight (MDUW) and optimum moisture content (OMC) is usually obtained by reading off from a compaction curve (graph) the highest point which represent MDUW and the corresponding moisture content which is the OMC. Due to the irregularity of the curve as a result of likely experimental errors, the values gotten from normal graph may not give perfect representation of the soil MDUW and corresponding OMC at which this can be achieved. An alternative method of determining the parameters by fitting the curves to third order polynomial was sought. Table 2 shows the results of MDUW and OMC obtained from normal graph and third order polynomial together with the coefficient of determination (R^2) for results from third order polynomial.

Table 2: Error between MDUW/OMC determined from normal graph and third order polynomial fit

			A	B	C	D	E	F	G	H	I
BSL	**Graph**	**MDUW (kN/m³)**	19.40	18.07	19.00	19.28	18.85	19.45	18.85	18.84	19.39
		OMC (%)	13.00	13.80	12.80	12.40	12.40	11.80	13.60	11.50	12.00
	Third order polynomial	**MDUW (kN/m³)**	20.02	18.01	18.95	18.69	19.95	19.39	20.78	18.81	19.31
		OMC (%)	14.14	15.15	12.76	13.59	13.76	11.43	14.93	11.09	11.36
		R^2	**0.9074**	**0.9855**	**0.9987**	**0.8912**	**0.9374**	**0.9988**	**0.9157**	**0.9999**	**0.9970**
	Error in MDUW (Graph minus Polynomial)		**-0.62**	**0.06**	**0.05**	**0.59**	**-1.10**	**0.06**	**-1.93**	**0.03**	**0.08**
	Error in OMC (Graph minus Polynomial)		**-1.14**	**-1.35**	**0.04**	**-1.19**	**-1.36**	**0.37**	**-1.33**	**0.41**	**0.64**
WAS	**Graph**	**MDUW (kN/m³)**	19.30	18.80	18.97	20.03	19.30	19.71	18.18	19.18	19.76
		OMC (%)	12.00	12.30	10.40	11.50	11.20	9.80	13.40	12.40	10.10
	Third order polynomial	**MDUW (kN/m³)**	18.66	18.74	18.93	19.36	19.26	19.78	17.64	18.98	19.72
		OMC (%)	13.81	12.60	10.77	10.69	10.76	9.75	13.86	11.16	9.65
		R^2	**0.7298**	**1**	**0.9997**	**0.9099**	**0.9925**	**0.9992**	**0.8673**	**0.9615**	**1**
	Error in MDUW (Graph minus Polynomial)		**0.64**	**0.06**	**0.04**	**0.67**	**0.04**	**-0.07**	**0.54**	**0.20**	**0.04**
	Error in OMC (Graph minus Polynomial)		**-1.81**	**-0.30**	**-0.37**	**0.81**	**0.44**	**0.05**	**-0.46**	**1.24**	**0.45**
BSH	**Graph**	**MDUW (kN/m³)**	20.20	20.46	20.10	20.20	19.65	20.31	19.85	19.95	20.21
		OMC (%)	10.00	11.20	8.40	9.50	9.40	9.00	9.20	8.80	9.60
	Third	**MDUW (kN/m³)**	20.24	20.47	20.09	20.09	19.65	20.33	19.82	19.88	20.17

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	order polynomial	**OMC (%)**	9.59	10.49	9.31	9.49	9.99	8.81	8.92	8.72	9.51
		R^2	**0.9977**	**0.9895**	**0.9873**	**1**	**0.9977**	**1**	**1**	**0.9997**	**1**
	Error in MDUW (Graph minus Polynomial)		**-0.04**	**-0.01**	**0.01**	**0.11**	**0.00**	**-0.02**	**0.03**	**0.07**	**0.04**
	Error in OMC (Graph minus Polynomial)		**0.41**	**0.71**	**-0.91**	**0.01**	**-0.59**	**0.19**	**0.28**	**0.08**	**0.09**

More than 70% of the error differences for MDUW are below 0.5 which represent about 2.6% error on the average while for OMC more than 50% error differences are below 0.5 which represent about 4.65% error on the average. This shows that there is close association between results obtained from normal graph and those obtained from third order polynomial (Figures 1-6). The R^2 – values obtained from third polynomial fit has lowest value of 0.7298 while 89% of all the values are above 0.9. This shows that third order polynomial fit could be more reliable.

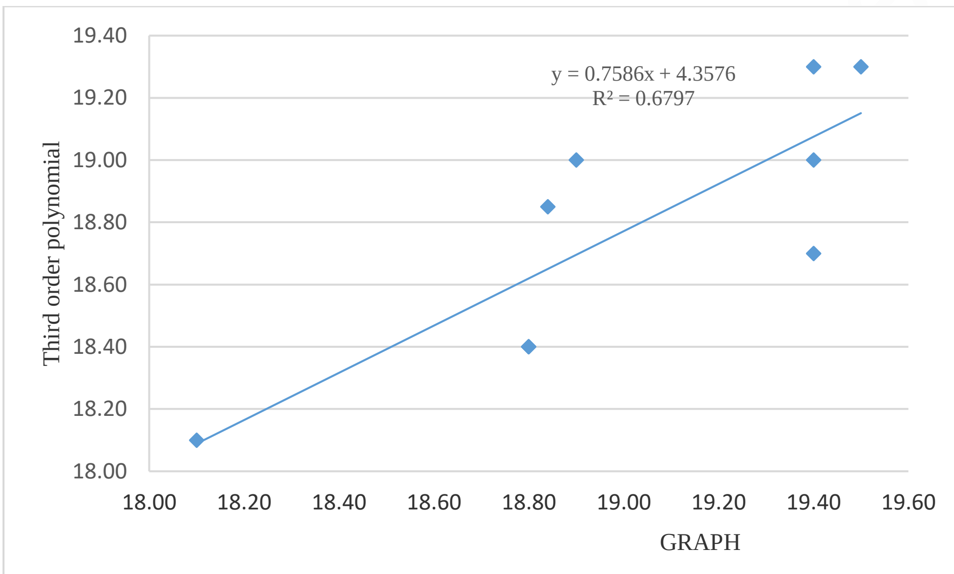

Figure 1: Maximum dry unit weight of third order polynomial versus graph for BSL

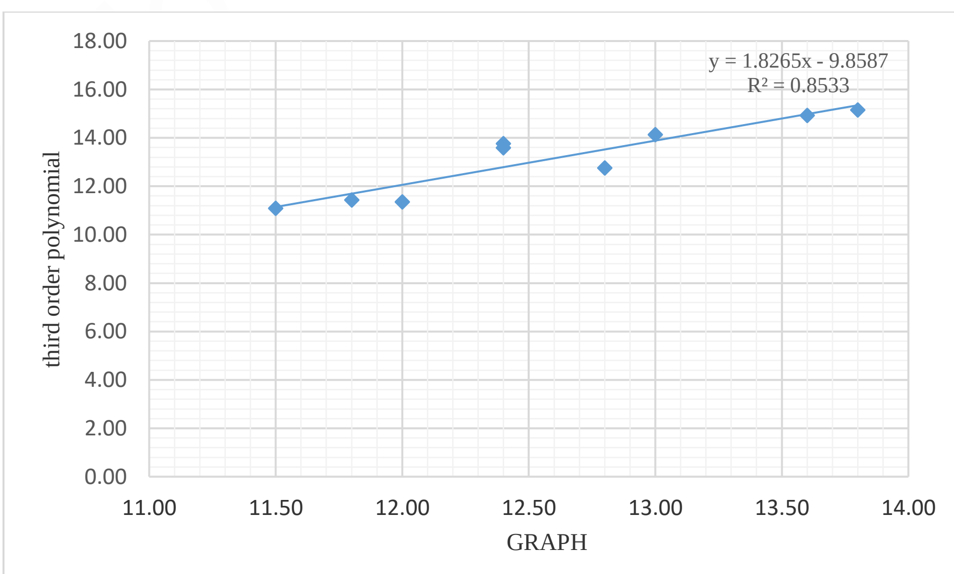

Figure 2: Optimum moisture content of third order polynomial versus graph for BSL

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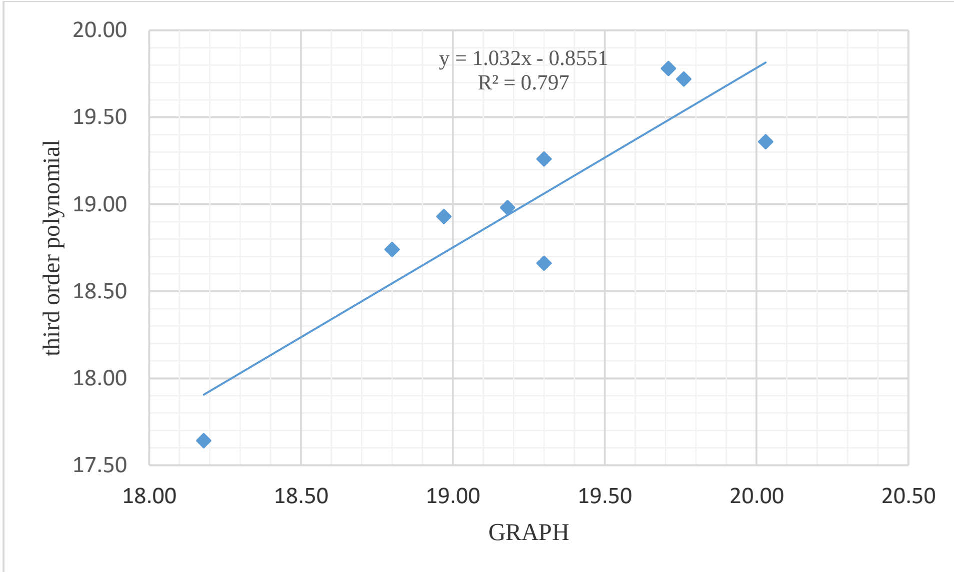

Figure 3: Maximum dry unit weight of third order polynomial versus graph for WAS

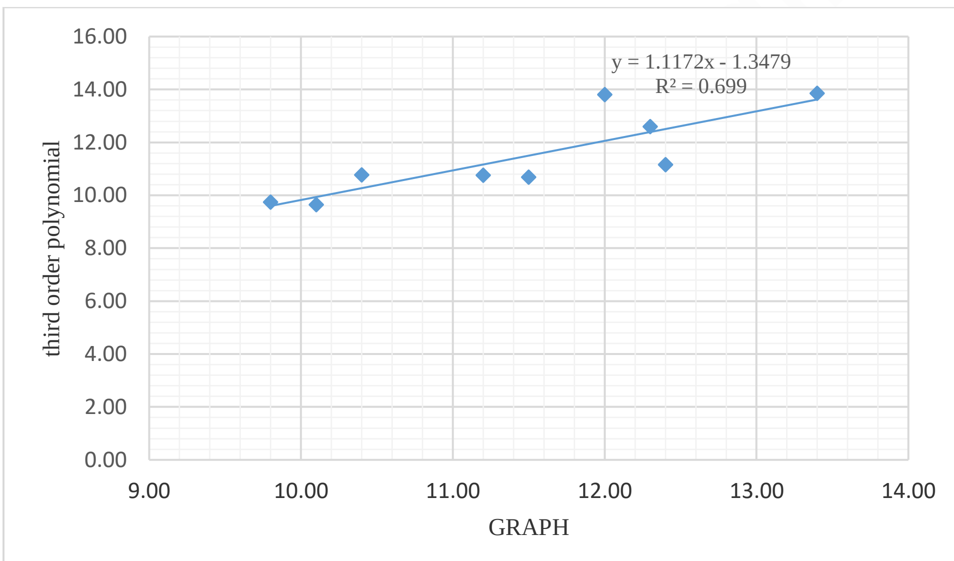

Figure 4: Optimum moisture content of third order polynomial versus graph for WAS

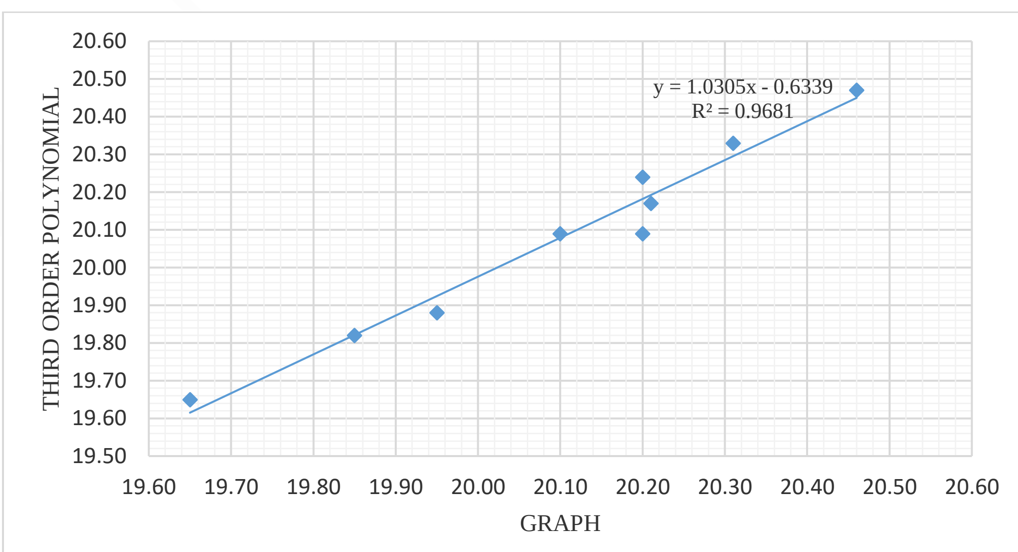

Figure 5: Maximum dry unit weight of third order polynomial versus graph for BSH

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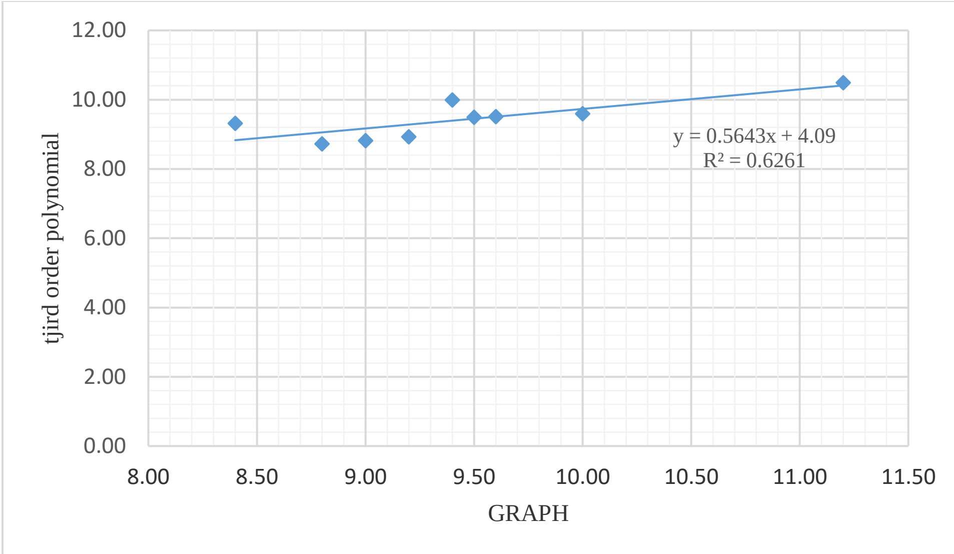

Figure 6: Optimum moisture content of third order polynomial versus graph for BSH

Figures 1-6 show that there is close association between MDUW and OMC obtained from normal graph and those obtained from third order polynomial. For MDUW (BSL, WAS and BSH), R^2 = 0.6797, 0.797 and 0.9681 respectively. For OMC (BSL, WAS and BSH), R^2 = 0.8533, 0.699 and 0.6261 respectively. It have been proven that a relationship exists between the values obtained from graphical plots and third order polynomial while the R^2 of compaction curve using third order polynomial also indicates that it would be more reliable to use third order polynomial to obtain compaction characteristics of soils.

3.2 Relationship between MDUW/OMC and Compaction energy

Several authors have proven that significant relationship exist between MDUW/OMC and compaction energy. This relationship have been employed to develop models to predict to MDUW/OMC (Benson et al, 2000; Jesmani et al, 2008; Tenpe and Kaur, 2015; Jayan and Sankar, 2015; Ratnam and Prasad, 2019). This is also true for the soil used in this research based on high values of coefficient of correlation shown in Table 3.

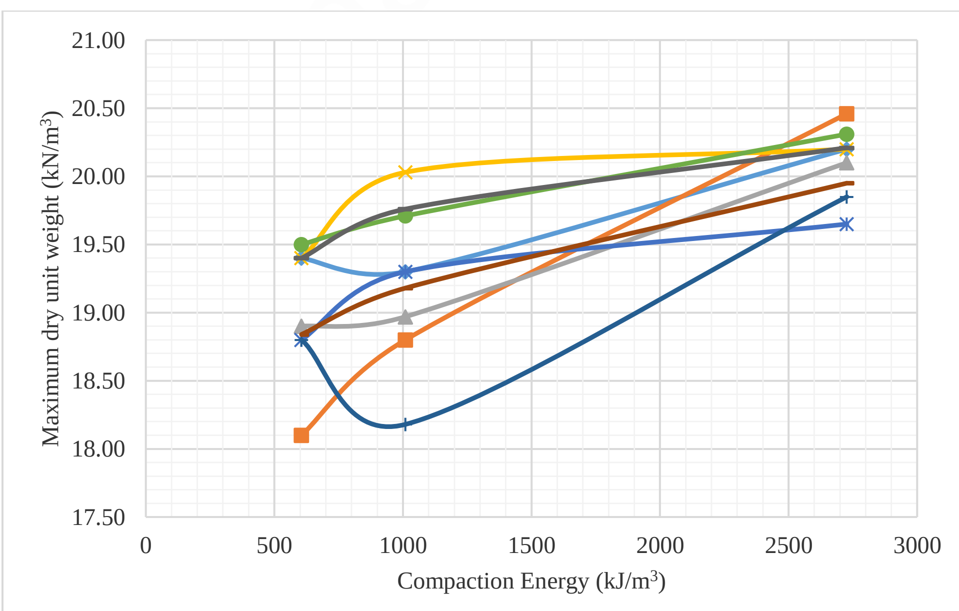

Figure 7: Maximum dry unit weight versus compaction energies

Figures 7 and 8 show the relationship between MDUW/OMC and E while Table 3 shows the R^2 obtained from these relationships. The significant R^2 values stands to prove that the results of the findings of the authors above are also true for these soils and thus the compaction energies can be used to develop models to predict the compaction characteristics.

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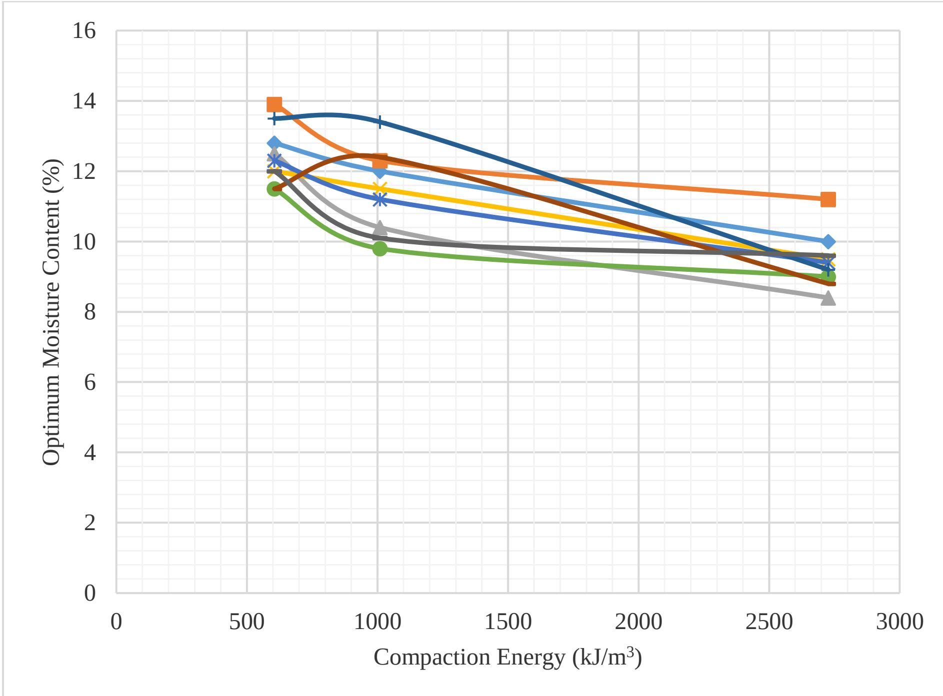

Figure 8: Optimum moisture content versus compaction energies

Table 3: Coefficient of determination for relationship between MDUW/OMC and E

Samples	MDUW/E	OMC/E
A	0.9225	0.9899
B	0.9874	0.8111
C	0.9836	0.8778
D	0.6206	0.9999
E	0.815	0.9587
F	0.9948	0.7285
G	0.721	0.9746
H	0.9849	0.8314
I	0.9241	0.6164

3.3 Descriptive statistics of Index and compaction properties

Table 4 shows the descriptive statistics for compaction characteristics and index properties of soils.

Table 4: Description statistics for the index properties with compaction characteristics

Description	NMC	SG	FC	SC	LL	PL	PI	d_{50}	BSL (MDUW)	WAS (MDUW)	BSH (MDUW)	BSL (OMC)	WAS (OMC)	BSH (OMC)
Mean	8.32	2.50	31.39	67.69	30.03	16.80	13.23	0.28	19.01	19.25	20.10	19.32	19.01	20.08
Standard Error	0.47	0.02	2.51	2.51	3.40	2.22	1.56	0.03	0.15	0.19	0.08	0.28	0.22	0.09
Median	9.03	2.49	30.09	65.56	24.60	15.78	12.02	0.25	19.00	19.30	20.20	19.31	18.98	20.09
Standard Deviation	1.42	0.06	7.52	7.53	10.21	6.67	4.67	0.08	0.44	0.56	0.25	0.83	0.65	0.26
Sample Variance	2.02	0.00	56.62	56.77	104.30	44.51	21.78	0.01	0.19	0.31	0.06	0.69	0.42	0.07
Kurtosis	-0.34	-1.27	0.61	0.42	1.13	4.42	-0.60	-2.04	1.91	0.40	0.02	-0.03	1.73	-0.57
Skewness	-0.82	0.17	0.46	-0.05	1.36	1.77	0.50	0.15	-1.24	-0.56	-0.59	0.27	-1.03	-0.26

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Range	4.31	0.17	25.85	25.90	30.40	23.97	14.54	0.20	1.38	1.85	0.81	2.77	2.14	0.82
Minimum	5.79	2.42	19.79	54.31	20.90	8.58	6.47	0.18	18.07	18.18	19.65	18.01	17.64	19.65
Maximum	10.10	2.59	45.64	80.21	51.30	32.55	21.01	0.38	19.45	20.03	20.46	20.78	19.78	20.47
Sum	74.88	22.50	282.53	609.20	270.25	151.20	119.05	2.49	171.13	173.23	180.93	173.91	171.07	180.74
Count	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
Coefficient of variation (%)	15.73	2.41	24.99	11.49	41.50	42.27	38.85	32	2.32	2.90	1.24	4.30	3.42	1.29
Confidence Level (95.0%)	1.09	0.05	5.78	5.79	7.85	5.13	3.59	0.06	0.34	0.43	0.19	0.64	0.50	0.20

The sample size used in this work is nine (9) which is quite small. Thus, kurtosis and skewness would not be used to access them because they depend on and improve with sample size (McNeese, 2016). Furthermore, the information given on the samples by measures of location and dispersion are adequate to describe the statistics (Wheeler, 2011). The interest on the coefficient of variation (cov) is on the dependent variables (MDUW/OMC). The coefficient of variations range from 1.29 to 4.30. This shows that there is no high risk in predicting MDUW/OMC using the index properties because the dispersion of the data points around the mean is quite low.

3.4 Correlation matrix of Index and Compaction properties

Table 5 shows the correlation matrix between the index properties and compaction properties using Rank Spearman correlation tool. The Spearman's rho measures the strength of association between two variables in a single value -1 and +1 known as the correlation coefficient. If the correlation coefficient appears on the right side of zero (0), it shows that there is a positive correlation, thus, rise in one variable is followed by rise in the other variable. On the other hand, if the correlation coefficient appears on the left side of zero, it indicates negative correlation, thus rise in one variable is followed by fall in the other variable. A correlation coefficient of zero shows there is no relationship existing between the variables.

Table 5: Correlation Matrix for the index properties with compaction characteristics

Correlation Coefficient	NMC	SG	FC	SC	GC	LL	PL	PI	d_{50}	MDUW (BSL)	OMC (BSL)	MDUW (WAS)	OMC (WAS)	MDUW (BSH)	OMC (BSH)
NMC (%)	1.000	.025	.899**	-.950**	.661	.483	.383	.033	-.167	-.570	.698*	-.460	.700*	-.134	.633
SG	.025	1.000	.274	-.192	-.221	.293	.142	.527	.444	.098	.072	.202	-.276	-.210	.008
FC (%)	.899**	.274	1.000	-.966**	.513	.521	.412	.269	.042	-.416	.593	-.156	.513	-.101	.748*
SC (%)	-.950**	-.192	-.966**	1.000	-.661	-.483	-.333	-.217	.050	.502	-.571	.301	-.633	.109	-.667*
GC (%)	.661	-.221	.513	-.661	1.000	.237	-.051	-.119	-.390	-.727*	.282	-.587	.915**	-.434	.068
LL (%)	.483	.293	.521	-.483	.237	1.000	.900**	.683*	.033	-.400	.706*	-.276	.467	.126	.483
PL (%)	.383	.142	.412	-.333	-.051	.900**	1.000	.583	.083	-.196	.639	-.050	.217	.377	.650
PI (%)	.033	.527	.269	-.217	-.119	.683*	.583	1.000	.267	.136	.176	.192	-.017	.452	.350
d_{50} (%)	-.167	.444	.042	.050	-.390	.033	.083	.267	1.000	-.145	.143	.100	-.567	.276	.200
MDUW (BSL) kN/m^3	-.570	.098	-.416	.502	-.727*	-.400	-.196	.136	-.145	1.000	-.618	.765*	-.655	.368	-.111
OMC (BSL) %	.698*	.072	.593	-.571	.282	.706*	.639	.176	.143	-.618	1.000	-.658	.471	-.004	.471
MDUW (WAS) kN/m^3	-.460	.202	-.156	.301	-.587	-.276	-.050	.192	.100	.765*	-.658	1.000	-.636	.273	.176
OMC (WAS) %	.700*	-.276	.513	-.633	.915**	.467	.217	-.017	-.567	-.655	.471	-.636	1.000	-.360	.133
MDUW (BSH) kN/m^3	-.134	-.210	-.101	.109	-.434	.126	.377	.452	.276	.368	-.004	.273	-.360	1.000	.485
OMC (BSH) %	.633	.008	.748*	-.667*	.068	.483	.650	.350	.200	-.111	.471	.176	.133	.485	1.000

*correlation significant at 0.05 (2-tailed) **correlation significant at 0.01 (2-tailed)

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The results of the correlation matrix shows high correlation between compaction characteristics and some index factors or among some index factors as well. Correlation coefficients without * or ** are not statistically significant. Correlation coefficient with * shows that there is 95% confidence of the results while those with ** shows that there is 99% confidence of the results.

3.5 Analysis of variance (ANOVA) on sample CE for MDUW/OMC

Tables 6 and 7 shows the ANOVA for compaction characteristics and compactive effort. For the MDUW and OMC, there is significant relationship between the two parameters and compactive effort since P-value < 0.05 and F > F crit in both cases.

Table 6: Analysis of variance on maximum dry unit weight /compactive effort

Source of Variation	df	F	P-value	F crit
Maximum Dry Unit Weight	8	2.566	0.0517	2.591
Compactive Effort	2	23.825	2E-05	3.634

From Table 6, the p-value (0.00002) for the compactive effort is less than 0.05 and the calculated F statistic is much larger than the value of Fcrit. This implies that the compactive effort would be significant in predicting the MDUW of soils.

Table 7: Analysis of variance on maximum dry unit weight /compactive effort

Source of Variation	df	F	P-value	F crit
Optimum Moisture Content	8	0.381	0.91518	2.591
Compactive Effort	2	5.542	0.01483	3.634

From Table 7, the p-value (0.01483) is also less than 0.05 and the calculated F statistic is larger than the value of Fcrit. This implies that the compactive effort would also be significant in predicting the OMC of soils.

3.6 Regression analyses

This section examines how the various index properties of the soils relate to compaction characteristics based on regression analysis. The significant p-values in each case except the derived variables in some cases show that there is significant relationship between compaction parameters and the variables. The regression analysis in Tables 14 to 17 would be viable because the p-values of all the variables are significant.

Table 8: Regression analysis of MDUW with log E, SC and PP

Property	Variables	Co-efficient	Standard error	t-statistics	p-value
MDUW	Intercept	10.4383	1.1238	9.2886	9.6333E-10
	Log E (kNm/m^3)	1.7272	0.2916	5.9238	2.9971E-06
	Sand (%)	0.0479	0.0077	6.1975	1.4822E-06
	PP	0.0010	0.0005	2.0295	0.0528
OMC	Intercept	34.1497	2.2732	15.0226	2.4879E-14
	Log E (kNm/m^3)	-4.9768	0.5898	-8.4380	6.4170E-09
	Sand (%)	-0.1127	0.0156	-7.2099	1.1735E-07
	PP	4.3926E-06	0.0010	0.0042	0.9967

Table 9: Regression analysis of MDUW with E, SC and PM

Property	Variables	Co-efficient	Standard error	t-statistics	p-value
MDUW	Intercept	11.09485	1.0376	10.6924	5.1658E-11
	Log E (kNm/m^3)	1.7272	0.2986	5.7845	4.3004E-06
	Sand (%)	0.03856	0.0059	6.5657	5.8153E-07
	PM	0.0005	0.0003	1.6488	0.1112
OMC	Intercept	34.0011	2.04697	16.6104	2.3157E-15
	Log E (kNm/m^3)	-4.9768	0.5890	-8.4489	6.2601E-09

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	Sand (%)	-0.1124	0.01158	-9.7015	3.9696E-10
	PM	0.0001	0.00058	0.2585	0.79803

Table 10: Regression analysis of MDUW with E, SC and GM

Property	Variables	Co-efficient	Standard error	t-statistics	p-value
MDUW	Intercept	12.4754	1.2086	10.3226	1.0901E-10
	Log E (kNm/m^3)	1.7272	0.3036	5.6885	5.5185E-06
	Sand (%)	0.0533	0.0134	3.9732	0.0005
	GM	-0.0567	0.0426	-1.3319	0.1944
OMC	Intercept	33.8400	2.3449	14.4312	6.3462E-14
	Log E (kNm/m^3)	-4.9768	0.5891	-8.4477	6.2769E-09
	Sand (%)	-0.1185	0.0260	-4.5512	0.0001
	GM	0.02016	0.08258	0.2442	0.8090

Table 11: Regression analysis of MDUW with E, SC and FC

Property	Variables	Co-efficient	Standard error	t-statistics	p-value
MDUW	Intercept	5.6094	3.4000	1.6498	0.111
	Log E (kNm/m^3)	1.7272	0.2952	5.8504	3.6247E-06
	Sand (%)	0.0942	0.0315	2.9901	0.0060
	Fines (%)	0.0682	0.0371	1.8376	0.0776
OMC	Intercept	36.8550	6.7698	5.444	1.0452E-05
	Log E (kNm/m^3)	-4.9768	0.5878	-8.4661	6.0179E-09
	Sand (%)	-0.1385	0.06271	-2.2081	0.03626
	Fines (%)	-0.03078	0.07388	-0.4166	0.6804

Table 12: Regression analysis of MDUW with E and PP

Property	Variables	Co-efficient	Standard error	t-statistic	p-value
MDUW	Intercept	14.4721	1.4149	10.2881	8.7316E-11
	Log E (kNm/m^3)	1.7272	0.4503	3.8354	0.0007
	PP	-0.0011	0.0006	-1.9116	0.06659
OMC	Intercept	24.6569	3.1494	7.8292	2.0339E-08
	Log E (kNm/m^3)	-4.9768	1.0024	-4.9650	3.3457E-05
	PP	0.0051	0.0013	3.9140	0.0006

Table 13: Regression analysis of MDUW with E and PM

Property	Variables	Co-efficient	Standard error	t-statistic	p-value
MDUW	Intercept	13.767	1.5271	9.0153	1.2499E-09
	Log E (kNm/m^3)	1.7272	0.4777	3.6156	0.00121
	PM	0.0002	0.0005	0.4913	0.62721
OMC	Intercept	26.2121	3.9716	6.5999	4.4266E-07
	Log E (kNm/m^3)	-4.9768	1.2424	-4.006	0.00044
	PM	0.0009	0.0012	0.7384	0.4667

Table 14: Regression analysis of MDUW with E and GM

Property	Variables	Co-efficient	Standard error	t-statistic	p-value
MDUW	Intercept	10.7678	1.4052	7.6627	3.0531E-08
	Log E (kNm/m^3)	1.7272	0.3777	4.5726	9.6037E-05

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	GM	0.0951	0.0234	4.0708	0.0004
OMC	Intercept	37.6352	2.8828	13.0552	3.5227E-13
	Log E (kNm/m^3)	-4.9768	0.7749	-6.4224	7.0063E-07
	GM	-0.3171	0.0479	-6.6189	4.2152E-07

Table 15: Regression analysis of MDUW with E and FC

Property	Variables	Co-efficient	Standard error	t-statistic	p-value
MDUW	Intercept	15.3789	1.07022	14.3699	3.6196E-14
	Log E (kNm/m^3)	1.7272	0.3358	5.1428	2.0755E-05
	Fines (%)	-0.0409	0.0077	-5.3023	1.35297E-05
OMC	Intercept	22.48997	2.0031	11.2273	1.1201E-11
	Log E (kNm/m^3)	-4.9768	0.6286	-7.91696	1.6441E-08
	Fines (%)	0.1296	0.01444	8.9778	1.3615E-09

Table 16: Regression analysis of MDUW with E and SC

Property	Variables	Co-efficient	Standard error	t-statistic	p-value
MDUW	Intercept	11.5909	1.0242	11.3174	9.3632E-12
	Log E (kNm/m^3)	1.7272	0.30795	5.6087	5.9674E-06
	Sand (%)	0.0373	0.006	6.2092	1.2215E-06
OMC	Intercept	34.1546	1.9249	17.7439	2.0679E-16
	Log E (kNm/m^3)	-4.9768	0.5788	-8.5988	3.2594E-09
	Sand (%)	-0.1128	0.01128	-9.9966	1.4303E-10

Table 17: Regression analysis of MDUW with CE and FC/SC

Property	Variables	Co-efficient	Standard error	t-statistic	p-value
MDUW	Intercept	14.5864	0.8849	16.4836	1.28495E-15
	Log E (kNm/m^3)	1.7272	0.2853	6.0535	1.83765E-06
	FC/SC (%)	-0.9347	0.1330	-7.0259	1.4913E-07
OMC	Intercept	25.1399	1.6469	15.2650	8.4163E-15
	Log E (kNm/m^3)	-4.9768	0.5310	-9.3721	5.6012E-10
	FC/SC (%)	2.7547	0.2476	11.1261	1.3717E-11

3.6.1 Regression analysis results using root mean square error (RMSE)

Tables 18 and 19 presents the regression analysis results using root mean square error (RMSE). RMSE is a statistical tool used to examine the relationship between two important parts of a model (predicted and actual values) by measuring the differences between them. RMSE is always non-negative and a value of 0 (always never achieved in practice) would indicate a perfect fit to the data but lower values of RMSE are better than higher ones. The purpose of the two tables are to select the best predictive models based on Adjusted R^2, overall F and RMSE (minimum).

Table 18: Regression analysis of MDUW with three variables and showing the RMSE

Property	Variables	R^2	Adjusted R^2	Overall F	Standardized Residual N (μ, σ)	RMSE
MDUW	Log E, Sand, PP	0.7597	0.7320	27.4060	7.8086E-15, 1	0.4032
	Log E, Sand, PM	0.7480	0.71895	25.7287	1.06951E-14, 1	0.4129
	Log E, Sand, GM	0.7395	0.7094	24.5975	7.79006E-15, 1	0.4198
	Log E, Sand, FC	0.7537	0.7252	26.5169	9.41284E-15, 1	0.40826
OMC	Log E, Sand, PP	0.8656	0.8501	55.8104	1.20459E-15,1	0.8156
	Log E, Sand, PM	0.8659	0.8505	55.9761	1.06951E-14,1	0.81456
	Log E, Sand, GM	0.8659	0.8504	55.9582	1.07692E-15,1	0.81467
	Log E, Sand, FC	0.8664	0.8511	56.2408	2.43324E-15,1	0.81290

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In Table 18, the RMSE are closer to zero and adjusted R^2 is quite significant. This shows that MDUW can be predicted with combination of either of the variables above with some level of confidence. The adjusted R^2 is also significant but the RMSE is higher than what is obtainable with MDUW. This shows that prediction of OMC from the combination of variables above can come with some levels of error.

Table 19: Regression analysis of MDUW with two variables and showing the RMSE

Property	Variables	R^2	Adjusted R^2	Overall F	Standardized Residual N (μ, σ)	RMSE
MDUW	Log E, PP	0.40482	0.36074	9.18231	6.0100E-15,1	0.63461
	Log E, PM	0.33025	0.28064	6.65688	1.10548E-14,1	0.67319
	Log E, GM	0.58127	0.55025	18.73997	9.58493E-15,1	0.52294
	Log E, FC	0.66897	0.64444	27.28143	1.17995E-14,1	0.47328
	Log E, SC	0.72168	0.70107	35.00572	8.30817E-15,1	0.433962
	Log E, FC/SC	0.76108	0.74338	43.00428	1.30137E-14,1	0.40208
OMC	Log E, PP	0.59684	0.56698	19.9854	-1.31006E-15,1	1.41252
	Log E, PM	0.3806	0.33472	8.2953	2.36848E-16,1	1.75082
	Log E, GM	0.75905	0.7412	42.5287	-1.53211E-15,1	1.09198
	Log E, FC	0.84144	0.8297	71.6393	-4.6819E-16,1	0.8858
	Log E, SC	0.86559	0.85563	86.9353	-4.90349E-16,1	0.81560
	Log E, FC/SC	0.88685	0.8785	105.8132	-4.37428E-15,1	0.7483

In Table 19, the combination of E/PP, E/PM and E/GM to predict MDUW would not give satisfactory results due to low values of adjusted R^2 and high values of RMSE. However, with E/FC, E/SC and E/ (FC/SC), the prediction could be done with some level of accuracy. Also, the combination of E/PP, E/PM and E/GM to predict OMC would not give satisfactory results due to low values of adjusted R^2 and high values of RMSE. However, with E/FC, E/SC and E/ (FC/SC), the prediction could be done with some level of accuracy.

4. CONCLUSION

Alternative method of determining compaction parameters (MDUW/OMC) based on third order polynomial was sought. Eighty-nine (89) % of the R^2 values obtained through the compaction curve of the alternative method are greater than 0.9 which is quite significant. The relationship between MDUW/OMC and compactive effort (E) were also significant with average values of R^2 being 0.884 and 0.865 for MDUW and OMC respectively. Correlation matrix and descriptive statistics between MDUW/OMC and index properties/derived variables also show some levels of association among them. ANOVA and regression analysis between MDUW/OMC and compactive effort/some index properties/derived variables show significant relationship in most cases with p-value < 0.05. Thus, these index parameters and derived variables can be used to develop models to predict MDUW/OMC with minimum error. Based on the results of the findings, it can be drawn that third order polynomial can be used to determine MDUW/OMC of soils with greater accuracy than using normal graph. Index properties such as sand content (SC), fines content (FC), fines-sand content ratio (FC/SC) can be used together with compactive effort to develop models to predict MDUW/OMC. However, more accurate models would be developed with the combination of three variables than two variables.

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