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Prediction of modified Proctor compaction characteristics using Atterberg limit tests and gradation tests for laterite soils

Prévision des caractéristiques de compactage modifiées de Proctor à l'aide de tests limites et de tests de gradation Atterberg pour les sols en latérite

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ABSTRACT: Compaction is a vital process in any earthworks construction since it primarily increases the density of the soil. Technically, the laboratory determination of compaction parameters is laborious and time consuming in large earthwork constructions. In this paper, the prediction of these parameters of laterite also known as residual soil, which occur mostly in Ghana using Atterberg limit and gradation parameters, is presented. For the purpose of this study, 70 lateritic soils from Ghana were subjected to modified Proctor compaction, gradation and Atterberg limit tests according to ASTM standards. Subsequently, empirical models were developed between these parameters based on the test results and these can be used during the prefeasibility studies of projects in Ghana.

RÉSUMÉ: Le compactage est un processus essentiel dans toute construction de terrassement car il augmente principalement la densité du sol. Techniquement, la détermination en laboratoire des paramètres de compactage est laborieuse et prend du temps dans les grands travaux de terrassement. Dans cet article, on présente la prédiction de ces paramètres de la latérite, également connue sous le nom de sol résiduel, qui survient principalement au Ghana à l'aide des paramètres de limite et de gradation d'Atterberg. Pour les besoins de cette étude, 70 sols latéritiques du Ghana ont été soumis aux essais de compactage, de gradation et de limite d'Atterberg modifiés de Proctor conformément aux normes ASTM. Par la suite, des modèles empiriques ont été développés entre ces paramètres sur la base des résultats des tests et peuvent être utilisés lors des études de préfaisabilité de projets au Ghana.

Keywords: Lateritic soils; Ghana; modified Proctor; prediction; empirical model

1 INTRODUCTION

Due to the automobile invention in the 20th century, soil compaction investigations were initiated along the roads. Soil compaction is a means by which soil is modified through mechanical process, this is achieved by increasing the density of the soil by reducing the volume of air. Proctor, a pioneer in soil compaction established this fact in 1933.

During the construction of earth dams, roads, airfield pavements, landfill liners, etc compaction of the soil plays a very significant role. In order to increase the shear strength, minimize subsequent settlement of the soil mass under working loads, increases the slope stability of embankments, compaction of the soil must be properly carried out.

In the laboratory, soil compaction is conducted using the Proctor compaction test device. In the field, the compaction of the soil is achieved by different equipment with different compactive effort. The characteristics of the compaction test are optimum water content (w_{opt}) and maximum dry density or unit weight. (ρ_{dmax} or γ_{dmax}).

The modified Proctor test which is a better representative of the compactive effort used in the field was developed by the U.S. Army Corps of Engineers in 1958. In order to achieve higher shearing strength of the materials, modified Proctor test is employed.

Predictive models for the optimal characteristics of a modified Proctor tests are essential when there is time and cost restraint, large volume of materials and limited effort during construction of a project.

Simple tests like Atterberg limit tests and Gradation tests, especially, when these are known already from project reports, bibliographies, and from database of the engineering properties of quarried soil within the geographical area or soils of similar properties can be used to estimate the compaction characteristics.

The predicted maximum dry unit weight and optimum water content can be used for the preliminary design of the project.

There have been many studies done on this topic. Researchers such as (Joslin, 1959), (Ring et al, 1962), (Torrey, 1970), (Jeng & Strohm, 1976), (Wang & Huang, 1984), (Al-Khafaji, 1993), (Blotz et al, 1998), (Omar et al, 2003), (Gurtug & Sridharan, 2004), (Sridharan & Nagaraj, 2005), (Sivrikaya et al. 2008), (Ugbe, 2012), (Mujtaba et al. 2013), (Jyothirmayi et al. 2015), etc. did similar work on different types of soils. These models are applicable to particular soils or soils within a specific location.

2 MATERIALS AND METHOD

A total of 80 soil samples were selected from the Tarkawaian zone in Ghana. These samples were subjected to gradational tests, Atterberg limit tests and modified Proctor tests in accordance with ASTM standards. Out of the 80 samples, 70 were used for prediction purposes and the rest for validation. The statistical descriptive of the dependent (compaction characteristics) and independent variables (Atterberg limit tests and gradational parameters) for the 70 samples is shown in Table 1.

From the table, the maximum dry unit weight (γ_{dmax})of the samples ranges from 19.1kN/m^3 to 25.6kN/m^3; the optimum moisture content (w_{opt}) is between 6.3% and 14.5%. The highest liquid limit is 64 with the lowest being 24.4.

Table 1: Descriptive statistics of data for modified Proctor analysis

	Gravel (G) %	**Sand (S) %**	**FC %**	w_L %	w_P %	I_p %	γ_{dmax} **kN/m³**	w_{opt} %
N	*70*	*70*	*70*	*70*	*70*	*70*	*70*	*70*
Range	*44.1*	*57.5*	*70.1*	*39.6*	*27.4*	*40.2*	*6.5*	*8.2*
Minimum	*.9*	*11.0*	*10.1*	*24.4*	*11.8*	*.8*	*19.1*	*6.3*
Maximum	*45.0*	*68.5*	*80.2*	*64.0*	*39.2*	*41.0*	*25.6*	*14.5*
Mean	*17.102*	*34.512*	*48.386*	*48.438*	*21.665*	*26.784*	*22.905*	*9.578*
Std. Deviation	*12.7352*	*16.3672*	*18.7015*	*9.6964*	*5.8953*	*11.4124*	*1.7375*	*2.1147*
Variance	*162.186*	*267.887*	*349.747*	*94.019*	*34.755*	*130.243*	*3.019*	*4.472*
Skewness	*.569*	*.492*	*-.089*	*-.384*	*.941*	*-1.157*	*-.755*	*.763*
Kurtosis	*-.926*	*-1.198*	*-.965*	*-.718*	*.560*	*.163*	*-.345*	*-.448*

3 RESULTS AND DISCUSSIONS

In this study, MLR was carried out by using Minitab 17, a statistical software and Microsoft software was used in plotting the graphs. As previously said, the dependent variables are the compaction test properties and the independent variables are the Atterberg limit test: liquid limit (w_L), plastic limit (w_P), and plasticity index (I_p), and gradational parameters: gravel (G), sand (S), and Fines content (FC).

Mallows' Cp method and Analysis of Variance (ANOVA) are utilized in order to choose the best independent variable subset which will develop the most accurate regression model with minimum numerical noise. This method is used as a subsetting criterion in selecting a reduced model without overfitting problems.

Mallow's Cp statistic is specified by the formula:

$$C_p = \frac{SSE_p}{MSE_m} - (N - 2p) \tag{1}$$

Where C_p is Mallow's regression

SSE_p is the sum of squares of the residual error for the model with p parameters,

MSE_m is the mean square of the error for the model with all m predictors,

n is the sample size,

p is the number of selected independent variables

The independent variable subset which will be used for model development is estimated based on the following guidelines:

- if no large systematic error exists, then Cp ≈ p.
- if Cp >> p, then it indicates a sub-model with a large bias
- Consider a sub-model with small Cp and Cp ≈p.

The Mallow's Cp analysis result is as follows:

3.1 For Maximum dry unit weight

Subset regression for different variables for maximum dry unit weight is shown in Table 2.

Best Subsets Regression : γ_{dmax} versus *G*, *FC*, w_L, w_P and I_p.

Response is γ_{dmax} (kN/m^3)

Table 2. Subset regression for different variables for maximum dry unit weight

Variables	R-Sq	R-Sq(adj)	Mallows Cp	*SSE*	*G*	*FC*	w_L	I_p
1	69.6	69.2	25.7	0.964				X
1	34.0	33.1	133.2	1.422		X		
2	76.1	75.3	8.3	0.863			X	X
2	72.5	71.7	19.1	0.925		X		X
3	78.4	77.4	3.3	0.826		X	X	X
3	77.5	76.5	6.0	0.843	X		X	X
4	78.5	77.2	5.0	0.831	X	X	X	X

Although, the empirical equation involving for (4) variables has the highest R^2 value, the Mallows Cp and SSE are higher when compared to the best performing equations shown below which has the lowest Mallows Cp (3.3), lowest SSE (0.826), and second highest R^2 (78.4) which is very close to the highest (78.5) values;

$$\gamma_{\mathrm{dmax}} = 22.3 - 0.175\mathrm{FC} - 0.0842\mathrm{w_L} + 0.205\mathrm{I_p} \tag{2}$$

Where γ_{dmax}(kN/m) is the maximum dry unit weight

FC *(%)* is the fines content

w_L*(%)* is the liquid limit

I_p*(%)* is the plasticity index

SEE = 0.826185 *R-Sq* = 78.4% *R-Sq(adj)* = 77.4%

The model has a coefficient of determination (*R-Sq)* value of 0.784 (very good); this means that 78.4% of maximum dry unit weight can be estimated accurately using this empirical equation and *SEE* of 0.826.

It is also noticed from the *ANOVA* analysis that all the statistical parameters fall within the minimum limits thus the model can be used to accurately predict maximum dry unit weight.

3.2 For optimum moisture content

Subset regression for different variables for optimum moisture content is shown in Table 3.

Best Subsets Regression: w_{opt} versus *G, S, FC,* w_L, w_P and I_p

Response is w_{opt} (%)

Table 3: Subset regression for different variables for optimum moisture content

Variables	R-Sq	R-Sq(adj)	Mallows Cp	*SSE*	*G*	*FC*	w_L	I_p
1	65.0	64.4	17.1	1.261				X
1	34.2	33.2	90.1	1.728			X	
2	69.1	68.2	9.3	1.193			X	X
2	67.7	66.8	12.5	1.219		X		X
3	72.4	71.1	3.5	1.137		X	X	X
3	71.3	70.0	6.0	1.158	X		X	X
4	72.6	70.9	5.0	1.141	X	X	X	X

The empirical equation is;

$$w_{OPT} = 10.7 + 0.0209FC + 0.0814w_L - 0.229I_P \qquad (3)$$

Where w_{opt}(%) is the optimum moisture content
FC(%) is the fines content
w_L (%) is the liquid limit
I_p(%) is the plasticity index

SEE = 1.137 *R-Sq* = 72.4% *R-Sq(adj)* = 71.1%

The statistical strength of this model is very good since the *R-Sq* value is 0.724. This shows that 72.4% of optimum moisture content can be accurately predicted using Equation 3.

The final plots of the measured versus the predicted compaction characteristics parameters are shown in Figure 1 and 2 representing maximum dry unit weight and optimum moisture content respectively.

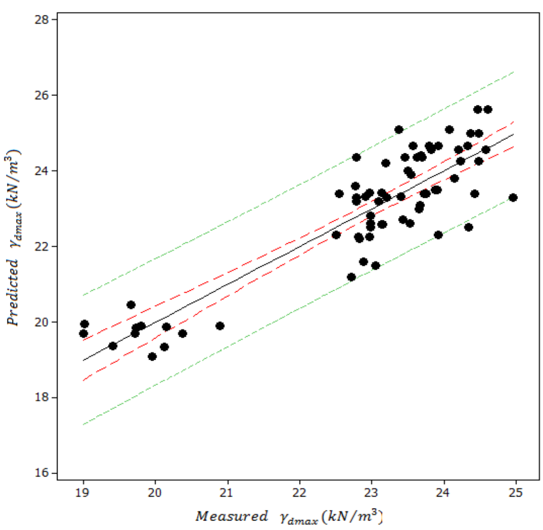

Figure 1: Comparison of predicted and measured γ_{dmax}

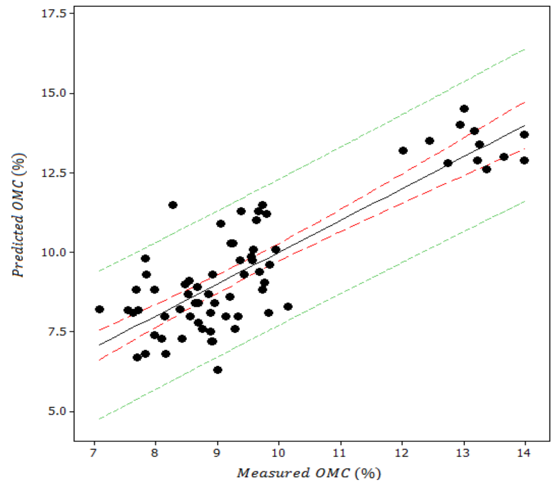

Figure 2: Comparison of predicted and measured w_{opt}

3.3 Validation of the developed models

The developed models were validated using a different set of data not seen by the model. Table 4 shows the results of the measured and the predicted γ_{dmax} and w_{opt}. The absolute error between them is also shown. Additionally, graphical representations of the validated model for γ_{dmax} and w_{opt} are shown in Figure 3 and 4 respectively. The *R-Sq* values are also shown and they show very high values which attest to the statistical strength of the models for γ_{dmax} and w_{opt}.

Table 3: Validation of modified Proctor compaction parameters models

Maximum Dry Unit Weight γ_{dmax} **(kN/m³)**			**Optimum Moisture Content** w_{opt} **(%)**		
Measured	Predicted	Abs. Error	Measured	Predicted	Abs.Error
20.6	21.10	0.497	11.7	11.60	0.101
23.1	22.40	0.699	10.9	10.24	0.661
21.8	22.07	0.272	11.8	10.39	1.411
22.3	22.89	0.593	10.3	9.66	0.643
21.1	20.51	0.593	12.3	12.53	0.225
24.5	23.79	0.710	8.7	8.61	0.087
22.6	22.14	0.456	10.4	10.35	0.052
22.9	22.15	0.249	10.8	10.30	0.503
23.1	22.60	0.495	10.1	9.84	0.259
22.9	22.89	0.008	10	9.47	0.531

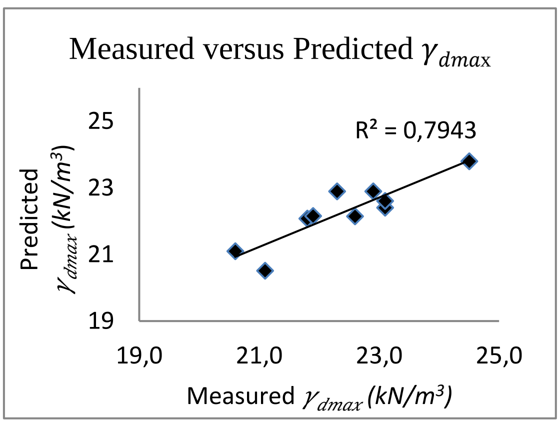

Figure 3: Predicted and measured γ_{dmax} for validation

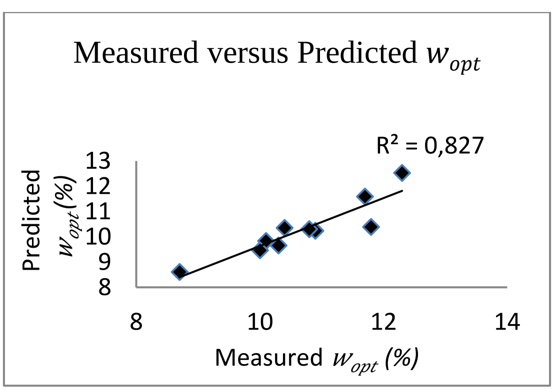

Figure 4: Predicted and measured w_{opt} for validation

4 CONCLUSIONS

In order to ensure the quality of compaction test carried out in the field, the compaction test parameters namely; maximum dry unit weight and optimum moisture content measured in the laboratory are dependable criteria. The proposed empirical models all have *R-Sq* values greater than 0.7 and the Standard Error of Estimate, *SEE* is less than 2 indicating the high statistical strength of the models. During the feasibility stages of any earthworks project that involves the use of lateritic soils, the proposed equations could be used to estimate the compaction test characteristics. It should be noted that these models do not serve as a replacement of field test hence testing should be done accordingly, they should only be used in preliminary design phase where there are limited time, financial limitations and large-scale testing.

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