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ORIGINAL RESEARCH ARTICLE

# EFFECTS OF SOIL PROPERTIES AND OPERATIONAL VARIABLES ON THE COMPACTIBILITY OF A SANDY LOAM SOIL

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**ABSTRACT**

The evaluation of an empirical equation for the determination of degree of compaction of a sandy loam soil was carried out using seven soil physical properties and four compaction operational variables. The soil used was obtained from a borrow pit in Gombe. Five levels of compactive effort, E/A, using a drop-weight type compactor varying from 107.91 to 539.55 Nm was used to compact each of seven pairs of embankment and slice thicknesses (Z, z respectively) with Z varying from 210 to 450 mm and z from 30 to 210 mm. The developed empirical equation, $\pi_1 = G\pi_2^k$ in which π1 is the dimensionless degree of compaction and $\pi_2$ is a dimensionless combination of the soil properties and the compaction operational variables, has a very high coefficient of determination, $r^2$ varying from 98.8% to 98.9%. G and k are each polynomial functions of compactive effort per loading, $e_L$. that is, $G = \alpha_G e_L^2 + \beta_G e_L + \lambda_G$ and $k = \alpha_k e_L^2 + \beta_k e_L + \lambda_k$. The values of the respective α, β and λ are highly statistically significant at 99.95 confidence level. The "dependent" variables (G and k) are highly correlated at 99.95% confidence level of statistical significance with the "independent" variable ($e_L$). The multivariate expression of the degree of compaction obtained in this study shows that compaction depends, not only on cumulative compactive effort, E/A, but also on the compactive effort per loading ($e_L$), embankment and slice thicknesses (Z and z respectively) as well as on easy-to-measure soil properties (i.e. soil texture, soil uniformity coefficient, antecedent soil moisture and antecedent bulk density).



## 1.0 Introduction

Appropriate response of an engineering soil to compaction is one of the most important qualities sought in civil and agricultural engineering construction activities such as those in building foundations for canals, railroad and highway works, earth embankments and dams, airport runways, sanitary landfills and excavation for structures and retaining walls (Jack, 2007; Davis, 2008). Identification and measurement of the interactions of all relevant factors governing soil compaction still remain major challenges in geotechnics. This study seeks to address some of these challenges. The bulk density ($\rho_{bc}$) of a soil is a measure of soil's response to compaction through rolling, ramming, free falling loads or by consolidation. The degree of compaction or compactibility of a soil $C_d$ is a function of compactive energy (E), the area (A) of the soil on which energy is exerted, soil moisture content ($m_c$), density of water ($\rho_w$) in the soil, the mean soil particle size ($\varphi_{50}$), thickness of the compaction slice (z), the coarseness of the soil (C/F), where C is coarse fraction of the soil and F is fine fraction, soil's uniformity coefficient ($U_c = \varphi_{60}/\varphi_{10}$), the soil particle density ($\rho_s$), its antecedent bulk density ($\rho_{bc}$), acceleration due to gravity (g), and the time (t) of contact between the compacting load and the soil being compacted. By definition Cd is the ratio of the change in volume ($\Delta V = V_1 - V_2$) where $V_1$ is soil's original volume and $V_2$ is final soil volume after compaction to its original volume, $V_1$. A universal function of the type:

$$C_d = f[(E/A), t, C/F, m_c, \rho_w, z, \varphi_{50}, U_c, \rho_{bc}, \rho_s, g] \quad (1)$$

That simultaneously relates all the eleven independent variables believed to be influencing $C_d$ has not been successfully determined so far. The common practice has been to rely on case-specific model studies for a given project and apply the results to that project type only. That approach lacks the capacity for general application. The determination of the function "f" in Equation 1 is the main problem that requires solution or solutions.

The purpose of this study therefore is to evaluate the relationship between the degree of compaction and the easy-to-measure soil properties and compaction operational variables using a soil of given $\varphi_{50}$, C/F and $U_c$. Equation 1, implicitly incorporating eleven independent variables, is a robust function, which has a potential for wide applicability in soil engineering works, such as the construction of canals, roads and earth dams, provided the constituent variables are known and measurable.

Compaction is the process of increasing the density of a soil by packing the particles closer together with a reduction in the volume of air within the soil. Maximum compaction of a soil is achieved at the optimum moisture content of the soil (Timothy et al., 2012). This is the water content at which a maximum dry unit weight is reached (Craig, 1978; Sutton, 1986). Although this process involves the expulsion of air from the voids, the moisture content does not change significantly (Bell, 1993). Compaction results in increase in shear strength (Duncan, 1990). The increase in soil density according to Gray (2000) is as a result or consequence of compaction but not the goal. Density is used as a target in engineering soil compaction specifications. The purpose of compaction is to change engineering properties of a soil in a desirable direction. Optimally compacted materials display engineering properties that are substantially superior to the same materials in a loose state (Watson and Burnett, 1995; Werkmeister, 2003; Shestak et al., 2005).

Quality of compacted fill is influenced by inter-related factors such as soil type, thickness of compacting layer and the compactive effort. Soil characteristics including grain size ($\varphi_{50}$), gradation ($U_c$) and clay or fine content (C/F), play an important role in soil behaviour under compaction. In coarse-grained soils, there exists an inter-granular contact and compaction processes brings about re-arrangement of soil particle positions. The way in which these particles are arranged within the soil mass and the distribution of particle sizes throughout, will ultimately determine the degree of compaction and hence the density, stability and the bearing capacity of the soil. Therefore, the maximum compaction can be achieved by the best packing of well-graded soil where the fine grains fill the spaces between the large grains. However, surplus of fines can be detrimental by preventing inter-granular contact between coarse particles (Mosaddeghi et al., 2000; Shaqour, 2004).

Effective compaction of earth materials can be achieved by applying the proper mechanical energy to a soil layer of suitably specified optimum thickness. An optimised compactive effort may be described as one that results in obtaining the compaction required from making the correct number of falls or passes, over a layer of optimum thickness. In a field, an optimum thickness, 200 to 300 mm is normally recommended (Watson and Burnett, 1995). The thickness of the compacting layer varies with grain size and compactive effort. Generally, coarse-grained soils compact more readily than fine grained ones and hence the finer the particles the thinner the maximum layer to be compacted (Shaqour, 2004; SCH., 2005).

## 2. Materials and Methods

### 2.1 The Study Area

Gombe Metropolis is located between latitude 10° 0' N and 10° 20' N and longitude 11°01' E and 11° 19' E and lies in the stretch of Benue trough. It consists majorly two types of soils corresponding to the two geological formations from which they are derived; sandy soil found in the northwest underlain by keri keri formation and clayey soil which occurs to the south and southeast (Mbaya, 2012). Sandy loam soil could also be found in some parts of the metropolis, especially, in the north (Audu, 2014). Gombe Metropolis has two distinct climates: the dry season which begun from November to March and the rainy season, from April to October with an average rainfall of 969.7 mm (Yahaya, 2015).

### 2.2 Description of the Compaction Device

Figure 1 shows the sketch of the compaction device that was constructed and used for this study. As depicted, it consists of the following components: (a) Compactor and bearings; (b) Mould; (c) Removable Plate; and (d) Steel Rod.

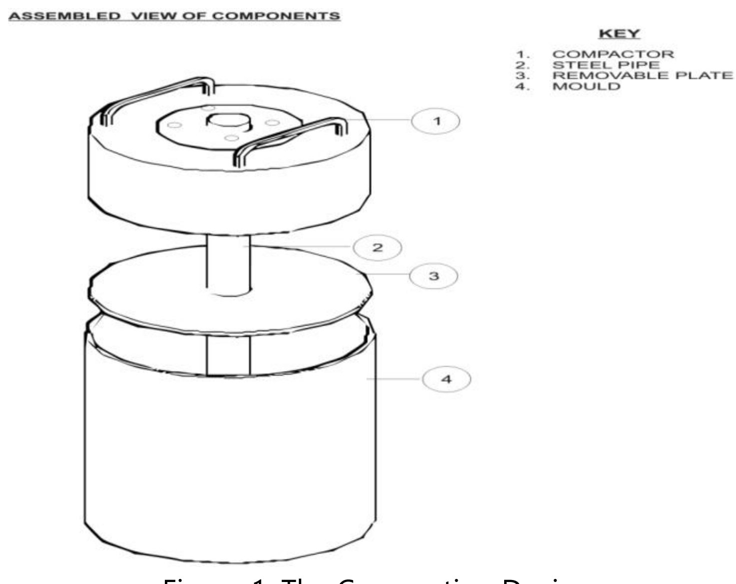


Figure 1: The Compaction Device



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#### 2.2.1 The Compactor and bearings

The compactor, cylindrical in shape, was constructed of concrete with cement, fines and coarse sand ratio of 1:2:4 by mixing 3.143 kg cement, 6.286 kg of fine sand and 12.571 kg of coarse sand with 2.2 litres of water and cured for 21 days, yielding 22 kg dry weight. The bearings were purchased. The cylindrical shaped compactor has a diameter of 305 mm and made 2 mm smaller than the diameter of the mould in order to allow its free in-and-out movement into the mould during compaction. The thickness of the compactor was 193 m with a circular hole at the centre to allow the steel rod to pass through and for the bearings to be situated inside as shown in Figure 1. The bearings slide along the steel rod up and down during compaction. This helps to reduce friction that may occur between the steel rod and the compactor during compaction process.

#### 2.2.2 The mould

This is also cylindrical in shape, and was constructed with 2 mm thick sheet metal according to the shape of the compactor. Its height was 500 mm and inner diameter was 307 mm, which was 2 mm larger than that of the compactor in order to allow free in-and-out movement of the compactor into it during the compaction process. It is built strong enough to withstand the pressure of the compacting force.

#### 2.2.3 The removable plate

This is of the same shape and diameter as the compactor and as the name implies, it is removable and constructed of the same material as the mould. It is placed at the base of the compactor to allow even distribution of compactive effort during the compaction process. It has a circular hole, 2 mm greater than the external diameter of the steel rod, at its centre, for the steel rod to pass through.

#### 2.2.4 The steel rod

This is a rigid, cylindrical structure placed vertically up at the bottom centre of the mould, passing through the drilled hole of the removable plate and the compactor, with an 85 mm thick (mahogany) wooden plate fixed at the base of the steel rod. The steel rod guides the compactor through the height of free fall during the compaction process. It was 1500 mm long.

### 2.3 Compaction Equipment

The compaction facilities consist of the fabricated compaction device shown in Figure 1 and moisture sprayer, sieves, pestle, scoop, knife, mixing pan, balances, drying oven, cans and polythene bags (Mann, 2006). Table 1 lists the specifications of the compaction equipment.

Table 1: Specifications of the Compaction Equipment

| S/N | Definition/Description | Quantity/value | Units |
|---|---|---|---|
| 1. | Cross sectional area | 0.07309 | $m^2$ |
| 2. | Weight | 215.82 | N |
| 3. | Height of drop | 0.5 | m |
| 4. | Height of mould | 0.5 | m |
| 5. | Height of rod | 1.5 | m |
| 6. | Diameter of compactor | 0.305 | m |
| 7. | Thickness of compactor | 0.193 | m |
| 8. | Diameter of mould | 0.324 | m |
| 9. | Cement : fine sand : coarse sand | 3.143 : 6.29 : 12.57 | kg |
| 10. | Water at 70% of the cement by wt. | 2.2 | litres |

**2.4 Soil Sample Preparation**

The soil used was obtained in Federal College of Education (Technical), Duku road, Gombe, Nigeria. It was air-dried, aggregates present in the sample were broken down gently, using pestle and mortar to maintain the natural size of the individual particles. Soil particles larger than 76.2 mm are gravels and were discarded as the soil was characterized and classified geotechnically according to the system adopted by AASHTO Standard No. M 145–91 (1995). The soil samples were then kept in polythene bags for compaction.

**2.5 Compaction Procedure**

A soil sample of 3.55 kg, whose physical characteristics such as texture was determined according to Braja (1986) was used to obtain uniformity coefficient and coefficient of curvature, particle density according to Blake (1965), bulk density according to Heed (1992), porosity by Nyle and Ray (1999) and moisture content by ASTM D 2216 (1998), was considered. The particle unit weight, bulk unit weight and unit weight of water were also calculated by multiplying the values of the particle density, bulk density and the moisture content by 9.81 $m/s^2$. The soil sample was then taken and spread evenly over a flat surface of area, A = 0.07309 $m^2$ in the mould, and its thickness, 30 mm was measured using a ruler placed vertically on the soil surface inside the mould. A compactor weight of 215.82 N was released from a height of 0.5 m, to drop one time on the soil layer; the new thickness was measured. Another soil "slice" (2 loadings), of thickness 30 mm was spread evenly on the previous slice, a new pre-compacted thickness was determined. Compactive effort was applied and a new compacted soil thickness was measured from which the new compaction was obtained. The above procedures were repeated until the desired "pavement" thickness of 210 mm was reached or slightly exceeded. The above procedures were repeated for 2, 3, 4 and 5 drops representing multiples of compacting energy per loading for the same soil thickness of 30 mm loaded in each case. The whole procedures were repeated for 60 mm, 90 mm and 120 mm, 150 mm, 180 mm and 210 mm soil thicknesses. From dimensional analysis, degree of compaction, $\pi_1 = \Sigma\Delta Z/Z$ and the governing variables, $\pi_2 = (E_c \varphi_{50} (C/F) U_c) \quad (A_{\gamma bc} z^3 S_e)$ for the 5 levels of compactive effort per loading was established. Multiple regression analysis was used to analyse the data to estimate the connection between



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degree of compaction, $\pi_1$ and the governing variables, $\pi_2$ and by how much. This provided an equation for the prediction and plotting of relationships. p-value and correlation coefficient were given to indicate the accuracy of the model.

## 3. Results and Discussions

Table 2 shows the results of the dry-sieving test which is used to obtain the grading curve (Figure 2) by plotting % passing versus sieve opening. From the hydrometer analysis, silt and clay particles were found to be 8% and 19%, respectively.

Table 2: Results of Sieve Analysis

| Sieve opening (mm) | Soil weight retained (g) | Soil weight passing (g) | Percent retained (%) | Percent passing (%) |
|---|---|---|---|---|
| 14 | 131.8 | 3868.2 | 3.295 | 96.705 |
| 5 | 267.3 | 3600.9 | 6.683 | 90.023 |
| 1.18 | 556.8 | 3044.1 | 13.920 | 76.103 |
| 0.3 | 2055.4 | 988.7 | 51.385 | 24.718 |
| 0.075 | 636.6 | 352.1 | 15.915 | 8.803 |
| Pan | 349.6 | 0.0 | 0.0 | 0.0 |

From the grading curve (Figure 2), $\varphi_{10}$ = 0.11, $\varphi_{30}$ = 0.34, $\varphi_{50}$ = 0.49 and $\varphi_{60}$ = 0.68, all φ values are in mm. From these data, Uniformity coefficient $U_c = \varphi_{60}/\varphi_{10}$ = 0.68/0.11 = 6.18 and the coefficient of curvature, $C_c = (\varphi_{30})^2/(\varphi_{60}\varphi 10)$ = (0.342)/0.68 x 0.11 = 0.1156/0.0748 = 1.55. According to Budhu (2004), a well graded soil is a soil with a uniformity coefficient ($U_c$) greater than 6 and coefficient of curvature ($C_c$) greater than 1 but less than 3. From the result of this analysis, the soil used was a well graded sandy loam soil and indicated that there was a wide spread of soil particle distribution of sand, silt and clay in the soil used, which is expected to compact well.

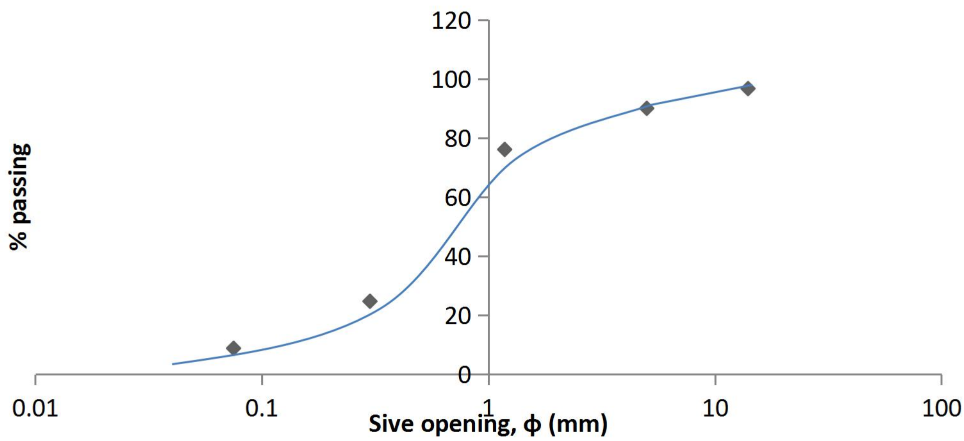


Figure 2: Percentage Soil Particle Size Distribution

Table 3 below shows the physical properties of the soil used in the study. From the Table, the energy deliverable per drop by the compactor of weight 215.82 N from a height of 0.5 m (i.e. 215.82 N x 0.5 m) was 107.91 N. The Table also shows that the coarse to fine fraction ratio (C/F)



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was 2.7 and uniformity coefficient was 6.18; the unit weight of soil particle; bulk soil and water were 26045.55, 15882.5 and 9810 $Nm^{-3}$ respectively. In table 4 column 8, the quantity of soil used for the compaction test was 1505 kg.

Table 3: Soil Physical Properties

| S/N | Item/Notation | Definition/Description | Quantity/Values | Units |
|---|---|---|---|---|
| 1. | Texture | Sandy loam | 1505 | kg |
| 2. | $\varphi_{50}$ | Mean particle diameter | 0.49 | mm |
| 3. | $U_c = \varphi_{60}/\varphi_{10}$ | Uniformity coefficient | 6.18 | - |
| 4. | C | Coarse fraction | 73% | - |
| 5. | F | Fine fraction | 27% | - |
| 6. | C/F | Coarse:fine ratio | 2.7 | - |
| 7. | $\gamma_{bc}$ | Initial antecedent unit weight | 15882.5 | $Nm^{-3}$ |
| 8. | $\gamma_s$ | Particle unit weight | 26045.55 | $Nm^{-3}$ |
| 9. | $\gamma_w$ | Unit weight of water | 9810 | $Nm^{-3}$ |

**3.1 Processed Compaction Data**

Table 4 shows the compaction test data for 7 levels of soil slice thicknesses, LST 1–7 and 5 levels of compactive effort per loading, LEL 1–5. According to the table, one drop of the compactor released an energy, $e_L$ of 107.91 Nm per loading or 755.37 Nm at the end of the 7th loading. Thus, the cumulative compactive effort, $E_c$, was 755.37 Nm achieving a cumulative soil compaction $\Sigma\Delta Z$ = 49.5 mm from Z = 210 mm thick of uncompacted soil at 15882.5 $Nm^3$ unit weight to a "pavement" of thickness Z′ = 160.5 mm at 19677.3 $Nm^{-3}$ unit weight. The last column shows the loading-by-loading computed degrees of compaction $\Delta Z/Z_\iota$ varying from 18.33% to 5.31% for LST = 1 and loading ι = 1 to ι = 7. Increasing values of $e_L$ at multiples of 107.91 Nm per loading carry similar information as described above.

Table 4: Test Data Record "Matrix" for 7 Levels of Soil Slice Thickness (LST) for the 1st Level of Compactive effort ($e_L$) per Loading

| LEL & eL | | | (1) 107.91 Nm/Loading | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| LST | z | Z | I | $E_c$ | ZI | ΔZ | m | $\gamma_{bc}$ | $S_e$ | $\Delta Z/ZI \times 10^2$ |
| 1 | 30 | 210 | 1 | 107.91 | 30.0 | 5.50 | 3.55 | 15882.5000 | 0.0469 | 18.3333 |
| | | | 2 | 215.82 | 54.5 | 6.00 | 7.10 | 17485.3000 | 0.0557 | 11.0092 |
| | | | 3 | 323.73 | 78.5 | 6.50 | 10.65 | 18209.2000 | 0.0608 | 8.2803 |
| | | | 4 | 431.64 | 102.0 | 7.00 | 14.20 | 18685.2130 | 0.0648 | 6.8627 |
| | | | 5 | 539.55 | 125.0 | 7.50 | 17.75 | 19058.8641 | 0.0682 | 6.0000 |
| | | | 6 | 647.46 | 147.5 | 8.00 | 21.30 | 19381.9568 | 0.0715 | 5.4237 |
| | | | 7 | 755.37 | 169.5 | 9.00 | 24.85 | 19677.3295 | 0.0748 | 5.3097 |
| | | | $m_c$ = 1.83% | | | | | | | |



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| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 60 | 300 | 1 | 107.91 | 60.0 | 8.50 | 7.10 | 15882.4737 | 0.0989 | 14.1667 |
| | | | 2 | 215.82 | 111.5 | 9.50 | 14.20 | 17093.2452 | 0.1123 | 8.5202 |
| | | | 3 | 323.73 | 162.0 | 11.00 | 21.30 | 17647.1930 | 0.1197 | 6.7901 |
| | | | 4 | 431.64 | 211.0 | 11.50 | 28.40 | 18065.3729 | 0.1260 | 5.4502 |
| | | | 5 | 539.55 | 259.5 | 12.00 | 35.50 | 18361.2412 | 0.1308 | 4.6243 |
| | | | $m_c$ = 3.86% | | | | | | | |
| 3 | 90 | 450 | 1 | 107.91 | 90.0 | 12.00 | 10.65 | 15882.4737 | 0.0551 | 13.3333 |
| | | | 2 | 215.82 | 168.0 | 13.50 | 21.30 | 17016.9361 | 0.0620 | 8.0357 |
| | | | 3 | 323.73 | 244.5 | 14.50 | 31.95 | 17538.9280 | 0.0658 | 5.9305 |
| | | | 4 | 431.64 | 320.0 | 15.00 | 42.60 | 17867.7829 | 0.0685 | 4.6875 |
| | | | 5 | 539.55 | 395.0 | 16.00 | 53.25 | 18093.9573 | 0.0704 | 4.0506 |
| | | | $m_c$ = 2.15% | | | | | | | |
| 4 | 120 | 360 | 1 | 107.91 | 120.0 | 14.50 | 14.20 | 15882.4737 | 0.0794 | 12.0833 |
| | | | 2 | 215.82 | 225.5 | 17.50 | 28.40 | 16903.7414 | 0.0883 | 7.7605 |
| | | | 3 | 323.73 | 328.0 | 18.00 | 42.60 | 17431.9833 | 0.0937 | 5.4878 |
| | | | $m_c$ = 3.10% | | | | | | | |
| 5 | 150 | 450 | 1 | 107.91 | 150.0 | 16.50 | 17.75 | 15882.4737 | 0.1207 | 11.0000 |
| | | | 2 | 215.82 | 284.0 | 17.00 | 35.50 | 16777.2609 | 0.1324 | 5.9859 |
| | | | 3 | 323.73 | 417.5 | 18.00 | 53.25 | 17118.8339 | 0.1374 | 4.3114 |
| | | | $m_c$ = 4.71% | | | | | | | |
| 6 | 180 | 360 | 1 | 107.91 | 180.0 | 18.50 | 21.30 | 15882.4737 | 0.2132 | 10.2778 |
| | | | 2 | 215.82 | 343.0 | 20.50 | 42.60 | 16669.6317 | 0.2311 | 5.9767 |
| | | | $m_c$ = 8.32% | | | | | | | |
| 7 | 210 | 420 | 1 | 107.91 | 210.0 | 19.00 | 24.85 | 15882.4737 | 0.1545 | 9.0476 |
| | | | 2 | 215.82 | 403.0 | 22.00 | 49.70 | 16552.4539 | 0.1654 | 5.4591 |
| | | | $m_c$ = 6.03% | | | | | | | |

$S_e = ((\gamma_{bc}/\gamma_w)/(1-(\gamma_{bc}/\gamma_s)))*m_c$, $m_c$=gravimetric dry weight soil moisture content, $\gamma_w$, $\gamma_s$ and $\gamma_{bc}$ are as given in Table 3.

Test data record matrix for 7 levels of soil slice thickness (LST) for the 2nd, 3rd, 4th and 5th levels of compactive effort ($e_L$) per loading convey the same trend of information with increasing relative magnitude of the coefficients in the polynomial function and power functions as the compactive effort increased.



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## 3.2 Dimensionless Degrees of Compaction Functions

### *3.2.1 The version of $\pi_1$ versus $\pi_2$ relationship*

Table 5: Input - Output Data for Computing $\pi_1$ and $\pi_2$

| LEL | | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| LST | $e_L$ , Nm | | 107.91 | 215.82 | 323.73 | 431.64 | 539.55 |
| 1 | z = 30, | Z = 210 | | | | | |
| | $S_e$ | | 0.0469 | 0.0469 | 0.0469 | 0.0469 | 0.0469 |
| | $E_c$ | | 755.37 | 1510.74 | 2266.11 | 3021.48 | 3776.85 |
| | ΣΔZ | | 49.5 | 59 | 63.5 | 69 | 71.5 |
| 2 | z = 60, | Z = 300 | | | | | |
| | $S_e$ | | 0.0989 | 0.0989 | 0.0989 | 0.0989 | 0.0989 |
| | $E_c$ | | 539.55 | 1079.1 | 1618.65 | 2158.2 | 2697.75 |
| | ΣΔZ | | 52.5 | 57.5 | 59.5 | 61.5 | 63.5 |
| 3 | z = 90, | Z = 450 | | | | | |
| | $S_e$ | | 0.0551 | 0.0551 | 0.0551 | 0.0551 | 0.0551 |
| | $E_c$ | | 539.55 | 1079.1 | 1618.65 | 2158.2 | 2697.75 |
| | ΣΔZ | | 71 | 80 | 85.5 | 87 | 92 |
| 4 | z = 120, | Z = 360 | | | | | |
| | $S_e$ | | 0.0794 | 0.0794 | 0.0794 | 0.0794 | 0.0794 |
| | $E_c$ | | 323.73 | 647.46 | 971.19 | 1294.92 | 1618.65 |
| | ΣΔZ | | 50 | 54 | 61 | 66 | 69.5 |
| 5 | z = 150, | Z = 450 | | | | | |
| | Se | | 0.1207 | 0.1207 | 0.1207 | 0.1207 | 0.1207 |
| | Ec | | 323.73 | 647.46 | 971.19 | 1294.92 | 1618.65 |
| | ΣΔZ | | 51.5 | 61.5 | 70 | 77 | 82 |
| 6 | z = 180, | Z = 360 | | | | | |
| | $S_e$ | | 0.2132 | 0.2132 | 0.2132 | 0.2132 | 0.2132 |
| | $E_c$ | | 215.82 | 431.64 | 647.46 | 863.28 | 1079.1 |
| | ΣΔZ | | 39 | 46 | 51 | 54.5 | 56.5 |
| 7 | z = 210, | Z = 420 | | | | | |
| | $S_e$ | | 0.1545 | 0.1545 | 0.1545 | 0.1545 | 0.1545 |
| | $E_c$ | | 215.82 | 431.64 | 647.46 | 863.28 | 1079.1 |
| | ΣΔZ | | 41 | 50.5 | 57.5 | 62.5 | 64.5 |

$\pi_1 = \Sigma\Delta Z/Z$; $\pi_2 = [U_c\varphi_{50}\,(C/F)/(A\gamma_{bc})](E_c/(S_e z^3))$; where z=Soil Slice Thickness, mm;
Z = Total Soil Thickness in mm to be compacted; $E_c$=Cumulative Compactive effort, Nm.

Table 5, derived from Table 4, contains the information required to compute the degree of compaction,



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$$\pi_1 = \Sigma\Delta Z/Z \quad (2)$$

and the governing variables,

$$\pi_2 = (E_c\varphi_{50}(C/F)U_c) \quad (A\gamma_{bc}z^3S_e) \quad (3)$$

for the 5 levels of compactive effort per loading. Here, the cumulative compactive efforts, Ec was used. The version of $\pi_1$ versus $\pi_2$ was discussed hereunder.

From Table 5, another table, Table 6 was derived to determine the version of the multivariate soil compaction function.

### *3.2.2 Function "weighted" by compactive effort per loading, $e_L$ and its use*

Each of the five pairs of columns in the main entries in Table 6 showing $\pi_1$ and $\pi_2$ also has its own unique characteristics namely, its magnitude of compactive effort per loading, $e_L$ in Nm/loading. This is reflected in the "best fit" regression curves, also power curves of the type:

$$\pi_1 = G\pi_2k$$

$$\pi_2 = \Delta Z = G(E_c\varphi_{50}(C/F)U_c)/(A\gamma_{bc}z^3S_e)b \quad (4)$$

Where: $\pi_1$ and $\pi_2$ are as defined in Table 7, "G" is the coefficient and "k" the exponent which took different values as MEL varied. As in section 3.2.3, G and k were regressed, but this time both on $e_L$ from 107.91 to 539.55 Nm/loading. Figures 3 to 7 derived from Table 6 show the coefficients "G", exponents "k", determination coefficients $r^2$ varying from 0.925 to 0.985, averaging 0.955 and each with its own "G" and "k" as listed in Table 7.

Table 6: The Values of $\pi_1$ (Y) and $\pi_2$ (X) for 7 Levels of Soil Slice Thickness (LST) and 5 Levels of Compactive effort per Loading (LEL)

| LEL | | | 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MEL = eL | | 107.91 | | 215.82 | | 323.73 | | 431.64 | | 539.55 | |
| | MST, mm | | | | | | | | | | | |
| LST | Z | Z | $\pi_1$x10$^4$ | $\pi_2$ | $\pi_1$x10$^4$ | $\pi_2$ | $\pi_1$x10$^4$ | $\pi_2$ | $\pi_1$x10$^4$ | $\pi_2$ | $\pi_1$x10$^4$ | $\pi_2$ |
| 1 | 30 | 210 | 2357 | 4201.466 | 2810 | 8402.932 | 3024 | 12604.400 | 3286 | 16805.860 | 3405 | 21007.330 |
| 2 | 60 | 300 | 1750 | 177.853 | 1917 | 355.705 | 1983 | 533.558 | 2050 | 711.410 | 2117 | 889.263 |
| 3 | 90 | 450 | 1578 | 94.613 | 1778 | 189.227 | 1900 | 283.840 | 1933 | 378.453 | 2044 | 473.066 |
| 4 | 120 | 360 | 1389 | 16.619 | 1500 | 33.237 | 1694 | 49.856 | 1833 | 66.475 | 1931 | 83.093 |
| 5 | 150 | 450 | 1144 | 5.597 | 1367 | 11.194 | 1556 | 16.791 | 1711 | 22.388 | 1822 | 27.985 |
| 6 | 180 | 360 | 1083 | 1.222 | 1278 | 2.445 | 1417 | 3.667 | 1514 | 4.890 | 1569 | 6.112 |
| 7 | 210 | 420 | 976 | 1.062 | 1202 | 2.124 | 1369 | 3.186 | 1488 | 4.249 | 1536 | 5.311 |

Notations:

$\pi_1 = \Sigma\Delta Z/Z$ for C/F = 2.7, A = 0.07308895m$^2$, $U_c$ = 6.18, $\varphi_{50}$ = 0.49 mm, $\gamma_{bc}$ = 15882.5 N,

$\pi_2 = E_c(C/F)\varphi_{50}U_c/(S_e\gamma_{bc}Az^3)$ becomes

$\pi_2 = ((C/F)\ \varphi_{50}U_c/A\gamma_{bc})(E_c/S_ez^3)) = 7.043325 \times 10^{-6}(E_c/S_ez^3)$.



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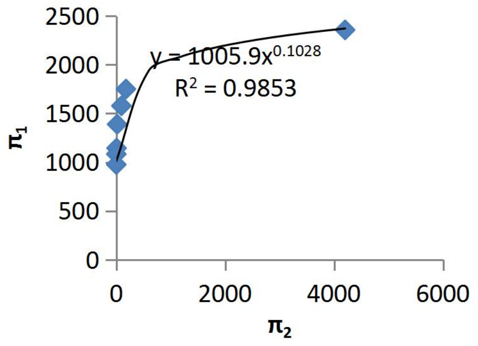


Figure 3: $\pi_1$ vs $\pi_2$ for 107.91 Nm compactive effort

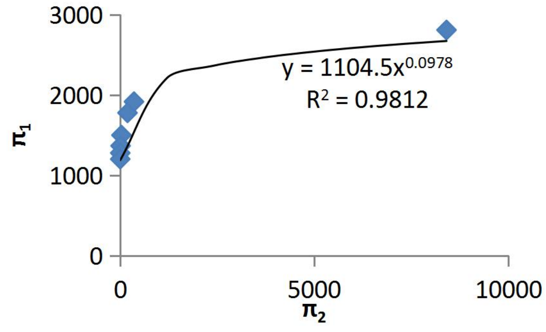


Figure 4: $\pi_1$ vs $\pi_2$ for 215.82 Nm compactive effort

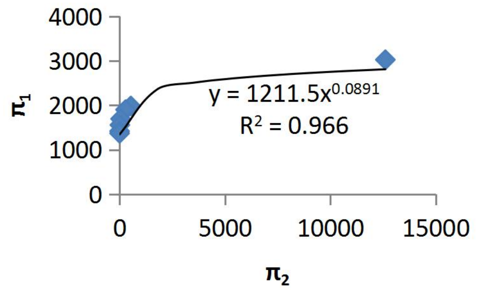


Figure 5: $\pi_1$ vs $\pi_2$ for 323.73 Nm compactive effort

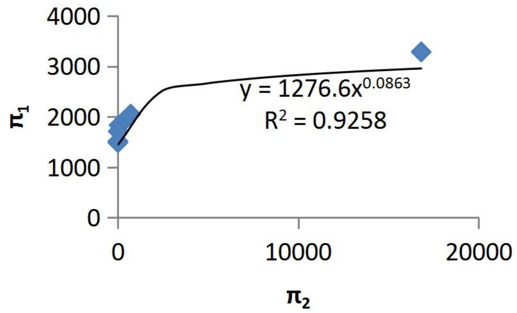


Figure 6: $\pi_1$ vs $\pi_2$ for 431.64 Nm Compactive effort

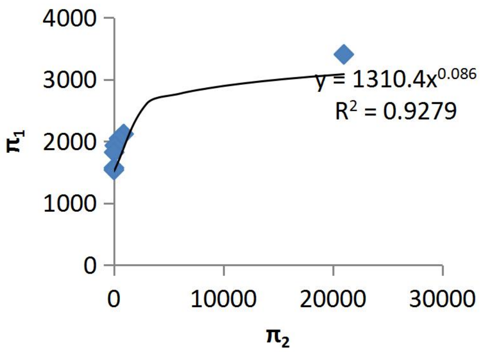


Figure 7: $\pi_1$ vs $\pi_2$ for 539.55 Nm compactive effort

Table 7: Power Function $\pi_1 = G\,\pi_2^k$, Coefficient "G", Exponent "k" Determination Coefficient $r^2$ and $e_L$ for the $e_L$-Governed Variations

| S/N | From Figures 3 – 7 | | | Compactive Effort per Loading |
|---|---|---|---|---|
| | "G" | "k" | $r^2$ | $e_L$, Nm |
| 1. | 1006 | 0.102 | 0.985 | 107.91 |
| 2. | 1104 | 0.097 | 0.981 | 215.82 |
| 3. | 1211 | 0.089 | 0.966 | 323.73 |
| 4. | 1276 | 0.086 | 0.925 | 431.64 |
| 5. | 1310 | 0.086 | 0.927 | 539.55 |



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With the data derived from Figures 3 to 7 and listed in Table 7 above, both "G" and "k" were regressed on eL as polynomial expressed in the following equations

$$G = \alpha_G e_L^2 + \beta_G e_L + \lambda_G \quad (5)$$

and shown in Figure 8, and

$$k = \alpha_k e_L^2 + \beta_k e_L + \lambda_k \quad (6)$$

shown in Figure 9

where:

$\alpha_G = -0.001$, $\beta_G = 1.398$, $\lambda_G = 862.4$, $r^2 = 0.996$ for "G"; and

$\alpha_k = 9\times10^{-8}$, $\beta_k = -1\times10^{-4}$, $\lambda_k = 0.112$, $r^2 = 0.975$ for "k".

Within the limits of dependability of $r^2$ from 0.975 to 0.996, equations (5) and (6) can be used to obtain best values for "G" and "k" for specified values of "$e_L$". From that, $\pi_1 = \Sigma\Delta Z/Z$ can be computed for specified values of the governing variables in $\pi_2$.

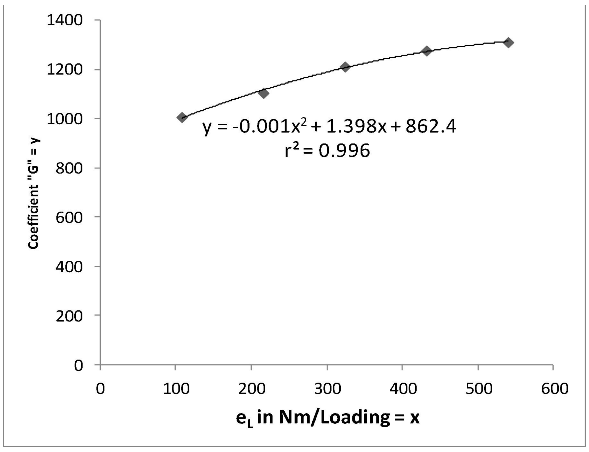


Figure 8: Coefficient "G" of $\pi_1$ versus $\pi_2$ against $e_L$

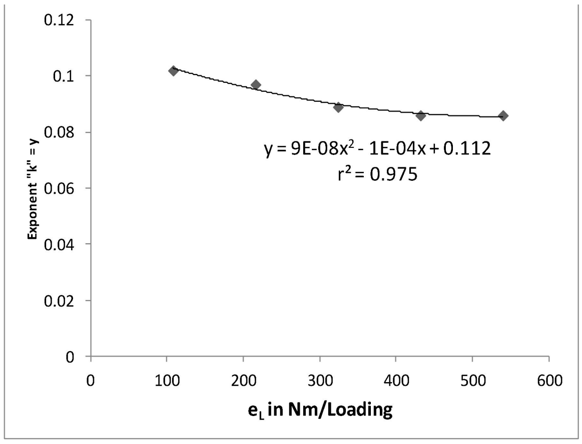


Figure 9: Exponent "k" of $\pi_1$ versus $\pi_2$ against $e_L$

### *3.2.3 Coefficient in the polynomials*

Table 8 shows the respective values of α, β and λ for G and k. The correlation coefficient of Y with X varied from 0.987 to 0.988 each indicating a high confidence level of statistical significance.

Table 8: The Polynomial Coefficients Data Matrix for Calculating the Coefficients and Exponents of Sandy Loam Soil Degree of Compaction Equation: $\pi_1 = G\pi_2 k$

| Function | | $Y = \alpha X^2+\beta X+\lambda$ | | | Correlation | |
|---|---|---|---|---|---|---|
| Y | X | A | B | Λ | R | t-test |
| G | $e_L$ | -0.001 | 1.398 | 862.4 | 0.988 | HS* |
| K | $e_L$ | $9\times10^{-8}$ | $-1\times10^{-4}$ | 0.112 | 0.987 | HS |

* = Highly significant at 99.95 Confidence Level.

### 3.3 Comparison of the Estimator with the Measured Values of Degree of Compaction

Table 9 shows the calculated values of the degree of compaction $(\pi_1)_c$ (i) $= G\pi_2^k$ and its corresponding ratio with measured value $(\pi_1)m = \Sigma\Delta Z/Z$.



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Table 9: Comparison of Estimated Values with Measured Value of Degree of compaction of Sandy Loam soil

| S/No | Variables | Validation Test | |
|---|---|---|---|
| | | 1 | 2 |
| 1. | Measured $\pi_1 = \Sigma\Delta Z/Z$ | 0.2357 | 0.2357 |
| 2. | $G\pi_2^k$ | 0.2167 | 0.1745 |
| 3. | Ratio, %100[$G\pi_2^k/(\Sigma\Delta Z/Z)$] | 97.79 | 97.98 |

From the above data, it is obvious that the function $G\pi_2^k$ estimated the degree of compaction of sandy loam soil accurately; G and k could be correlated significantly with $e_L$ in this study.

## 4. Conclusion

The foregoing has described a study of compaction behaviour of a sandy loam soil. Among many others, eleven quantifiable factors believed to be governing the compaction, $\Sigma\Delta V$ of the soil volume V have been identified and grouped to develop a multivariate compaction function using a "drop-weight" compactor designed and constructed for this study. From Table 8, G and k can be computed for use in estimating the degree of compaction $\pi_1 = \Sigma\Delta Z/Z = \Sigma\Delta V/V$ for any combination of the eleven governing factors encapsulated in $\pi_2$ as $\pi_1 = G\pi_2^k$. The other estimator $a\pi_2^b$ is weak. It needs more data from many other soils to characterize "a" and "b" more vigorously. Two validation test results show that the procedure is durable for a large number and a wide range of operating variables with respect to sandy loam soil and "drop-weight" compactor. The two estimators passed the t-test of statistical significance of correlation r of estimator with measured values of degree of sandy loam soil compaction.

The usefulness of the procedure is that one does not need to carry out trial compaction tests to know the degree of compaction of sandy loam soil from a given borrow site before knowing its response to a given set of operating conditions, provided the easy-to-measure variables in π2 are known.

## References

AASHTO 1995. Standard No. M – 145 – 191 in Soil Engineering Classification 2001. National Soil Survey Hand Book, 618. http://www.ohioagriculture.gov/pubs/curr/rules. Accesed 2nd January, 1999.

ASTM D1557 1990. Density and Unit Weight of Soil in Place by the Sand Cone Method. Pontificia Universidad Catolica del Ecuador. pp. 6

ASTM D-2216 1998. Laboratory Determination of Water Content of Soil and Rock. ASTM International, West Conshohocken, PA, USA. p. 12.

ASTM Standard D698 2007. Standard Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort, ASTM International, West Conshohocken, PA, DOI 10. Retrieved from http://www.astm/standards/D698.htm.Accessed 3rd February, 2013.

Audu, D. 2014. Evaluation of the Effects of Soil Properties and Compaction Operational Variables on the Compactibility of a Sandy Loam Soil. M. Sc. Thesis, Department of Agricultural and Environmental Resources Engineering, University of Maiduguri, pp. 41.



Corresponding author's e-mail address: danladimsh@gmail.com

Bell, FG. 1993. Engineering Treatment of Soils. E and IN Spon, an Imprint of Chapman and Hall, London, pp. 302.

Blake, GR. 1965. Particle Density. In: Black, C. A. Ed., Methods of Soil Analysis, Part I, Physical and Mineralogical Properties. American Society of Agronomy. Madison, Wisc. pp. 371-373.

Braja, MD. 1986. Soil Mechanics. 2nd Edition. Engineering Press, Russia. pp. 96.

Budhu. M. 2004. Soil Mechanics and Foundations. 3rd Edition. John Wiley and Sons: NY 2000. pp. 350-352.

Craig, RF. 1978. Soil Mechanics. Van Nostrand. Reinhold Ltd; London, pp. 317.

Davis, T. 2008. Geotechnical Testing, Observation, and Documentation. 2nd Edition, Reston, Virginia, American Society of Civil Engineers, pp. 25.

Duncan, JM. 1990. Soils and Foundations for Architects and Engineers. Van Nostrand Reinhold, New Delhi, India. pp. 361.

Gray, DH. 2000. Optimizing Soil Compaction. Balancing Engineering Requirements and Plant Growth Needs in Sloping and Erosion Control Works. http://www.Forester.net/ecm_0209_optimizing

Heed, RH. 1992. Manual of Soil Laboratory Testing. 2nd Edition. Pentech Press, London pp. 201-202.

Jack, E. and Liu, C. 2007. Soils and Foundations. 7th Edition. Prentice Hall. Retrieved from: http://en.wikipedia.org/w/index.php. Accessed 13th January, 2013.

Mann, G. 2006. Compaction Laboratory Exercise. CIVE 366.University of Washington.

http://www.ce.washington.ed/geotech/courses/cee366/Kramar/exercise Accessed 20th January, 2011.

Mbaya, LA. 2012. A Study of Inter-Relationships among Gully Variables in Gombe Town, Gombe State, Nigeria. Journal of Geography and Geology, 4(3): 1-6.

Mosaddeghi, M., Hajabbasi, M., Hemmat, A. and Afyuni, M. 2000. National Soil Survey Centre In Cooperation with the Soil Quality Institute, NRCS, USDA and the National Soil Tilth Laboratory, Agricultural Research Service (1996). Soil Quality Information Sheet. http://www. Ohioagriculture.gov/pubs/curr/rules

Nyle, CB. and Ray, RW. 1999. The Nature and Properties of Soils. 12th edition. Prentice Hall. pp. 118-125.

Shaqour, FM. 2004. Hydro-Compaction of Sand Fills. University of Jordan, Amman. pp. 6-8

Shestack, CJ. and Busse, MD. 2005. Compaction Alters Physical but not Biological Indices of Soil Health. Soil Science Society of America Journal, 69: 236-246.

Soil Compaction Handbook 2005. Soil Compaction-Soil Types, Methods and Compaction Techniques. http://www.concrete-catalog.com/soil_compaction

Sowers, GF. 1960. Introductory Soil Mechanics and Foundations. Geotechnical Engineering. McGraw-Hill, New York, pp. 99.

Sutton, BHC. 1986. Solving Problems in Soil Mechanics. John Wiley and Sons, New York. pp. 234. http://www.dnr.state.oh.us/water



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Timothy, D., Stark, F., Hangseok, C., Chulho, L. and Brian, Q. 2012. Compacted Soil Linear Interface Strength Importance. Journal of Geotechnical and Environmental Engineering, ASTM, 134(4): 544-550.

Yahaya, I. 2015. Analysis of Rainfall Variability in North-Eastern Nigeria. M. Sc. Thesis, Department of Geography, Bayero University, Kano, pp.73.

Watson, I. and Burnett, AD. 1995. Hydrology and Environmental Approach. Buchanam Books, Cambridge, pp.702.

Werkmeister, S. 2003. Permanent Deformation Behaviour of Unbound Granular Materials in Pavement Construction. M. Sc. Thesis in University of Technology, Dresden, Germany, 10th February, 2013. pp.79



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