

DEVELOPMENT OF QUASI-EMPIRICAL MODEL FOR PREDICTING DEGREE OF SOIL COMPACTION

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ABSTRACT

This study developed a model, $\pi_1 = a\pi_2^b$ for predicting the degree of soil compaction using compaction operational variables such as compactive energy (E), area (A) of the soil on which E is exerted, the thickness of the compaction slice (z), and acceleration due to gravity (g); and soil index properties such as soil moisture content (m_c), antecedent soil bulk density (ρ_{bc}), soil particle density (ρ_s), mean soil particle size (ϕ_{50}), soil's uniformity coefficient ($U_c = \phi_{60}/\phi_{10}$), the density of water (ρ_w) in the soil and coarseness of the soil (C/F), where C is a coarse fraction of the soil and F is a fine fraction, using three soil classes namely, laterite, non-cohesive and cohesive soils obtained from Iwontu community, near Ilorin, Kwara State. A function of the type $C_d = f[(E/A), t, z, g, m_c, \rho_{bc}, \rho_s, \phi_{50}, U_c, \rho_w, C/F]$ that relates all the thirteen independent dimensional variables believed to be influencing C_d have 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 aim of the study therefore was to use all the variables influencing compaction to develop a quasi-empirical model that can be used to predict the degree of soil compaction. Seven levels of compactive efforts, using a drop-weight type compactor varying from 147.15 to 1030.05 Nm were used to compact five pairs of embankment and slice thicknesses, Z and z respectively, with Z varying from 140 to 700 mm and z from 20 to 100 mm. Dimensional analysis was carried out on all the governing variables to make them dimensionless and expressed in functional forms. A functional relationship, f , of the dimensionless terms, $\pi_1 = Y$ and $\pi_2 = X$ was established for the soils of the known values of π_2 . Five (5) type functions namely linear, power, exponential, polynomial and logarithmic were considered to establish the best-fit function; and the power function gave the highest value of the coefficient of determination, R^2 , varying from 98.8% to 98.9%. Validation tests were carried out and the model estimated the soil degree of compaction with more than 75% accuracy. It is recommended that further studies of different sub-soils under different conditions will be required to strengthen the applicability of the model. The model is important especially when there are financial restraints, short timeframes, or unavailability of compaction test equipment, particularly in early design stages and preliminary studies, before appropriate soil sampling and field investigation can be conducted; thus saving substantial time and financial resources.

Keywords: Empirical model, Soil compaction, Degree of compaction, Soil index properties

1 INTRODUCTION

The establishment of an empirical model for predicting the degree of soil compaction involves several soil variables and compactor operational variables [1]. To make good decisions in the face of so many unavoidable uncertainties [2] says it is essential to understand the variables that influence soil behaviour in the best possible way, as well as to conceive mathematical models capable of representing and predicting the degree of compaction for field performance of geotechnical structures. Determining soil compaction variables in a laboratory is a crucial step in controlling the field compaction of earthworks such as embankments [3]. However, during the early stage of a project,

considerable time and effort can be saved through the use of empirical models [4, 5], which can be extremely helpful provided the compaction variables are known. Soil index properties are those upon which the identification and classification steps of soil are based; this includes soil moisture content (m_c), antecedent soil bulk density (ρ_{bc}), soil particle density (ρ_s), mean soil particle size (ϕ_{50}), soil's uniformity coefficient ($U_c = \phi_{60}/\phi_{10}$), the density of water (ρ_w) in the soil and coarseness of the soil (C/F), where C is a coarse fraction of the soil and F is a fine fraction. The compaction operational variables such as compactive energy (E), area (A) of the soil on which E is exerted, time (t) of contact between the compacting load and the soil being compacted, the thickness of the compaction slice (z), and acceleration due to gravity (g) are determined through very time-consuming laboratory tests during laboratory compaction test. This makes the establishment of predicting models highly desirable and remarkably useful [6, 7]. To effectively generate the aforementioned data that seems to influence soil degree of compaction, a compaction device developed by [8] was used. This device is capable of providing the soil variables and compactor operational variables needed to establish the model. The essence of dropping the proctor device is because, in the Proctor compaction procedure (i) it is manually operated (ii) a drop of the hammer does not cover the whole surface of the soil specimen (iii) it accommodates only a specific soil thickness (117 mm) and (iv) a maximum of 3 (in standard Proctor) or 5 (in modified Proctor) slices can be compacted and this is not sufficient enough to generate the data required for investigating the degree of soil compaction especially in embankments such as landfills, dams, road embankments, and so on, which usually involves several numbers of layers to be compacted. The compaction device adopted has the same operational principle as the Proctor device except that the device (i) is mechanically operated to save time, energy and cost, (ii) accommodates cumulatively 7 slices of 100 mm thick and (iii) uses 5 different soil thicknesses from 20 to 100 mm that yielded the variables believed to influence soil compaction and the data generated were used in establishing the model. Functionally, the degree of compaction (C_d) of soil is a function of compaction operational variables and soil variables. A function of the type:

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

that relates all the thirteen independent dimensional variables believed to be influencing C_d have 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. Determining the function "f" in the Equation is the problem that requires a solution. Considering this gap, a simplified empirical model to predict soil degree of compaction was developed. Application of the model can save valuable resources especially when there are financial constraints and limited time.

2 LITERATURE REVIEW

Many types of earth construction such as roads, railways, embankments, retaining walls, dams and airport runways, require man-placed soils or fills. Soil compaction is one of the mechanical efforts to bring the soil grains together; however, the grain volume does not change [9]. Soil compaction is the method of mechanically increasing the density of soil by reducing the volume of air. It is the process in which stress applied to soil causes densification as air is displaced from the pores between the soil grains. Compaction brings homogenous soil mass having improved soil properties [10]. In geotechnical engineering, there are roads, parking lots, buildings, walls, dams, etc. used to facilitate different activities, but few years of usage, there appear potholes in the roads, sinkholes in the parking lots and cracking or settling in foundations, excess seepage through dam embankments and so on. Very often, it is a result of a poorly compacted embankment or base. There are indications that much attention is focused on structures while the condition of the ground beneath is frequently neglected. This can cause a myriad of problems in farm structures and the environment [11]. Understanding soil and compacting it appropriately for structures to sit on may prevent cost overruns, call-backs, accidents due to collapse, etc. [12]. The development of a model for estimating the degree of compaction involves several soil and compactor operational variables. To make good decisions in the face of so many unavoidable uncertainties, says it is essential to understand the variables that influence soil behaviour in the best possible way, as well as to conceive a mathematical model capable of representing and estimating the degree of soil compaction for field performance of geotechnical structures [1, 2].

2.1 Collection and Characterization of Soil Samples

Three soil samples with different mean soil particles diameter, (ϕ_{50}), coarseness factor (C/F) and uniformity coefficient (U_c) were considered for this study. The soil samples were obtained in Iwonte town, near Ilorin, Kwara State, at a depth of 0.5 m to exclude the upper organic soils which are mostly not used for engineering purposes due to their compressibility. The soil samples were packed into bags and labelled accordingly, then taken to the soil mechanics laboratory at Kwara State University, Malete and characterized by testing the index properties. Particles larger than 76.2 mm were discarded as they were rocks.

2.2 Determination of Soil Index Properties

Determination of soil texture using sieves was carried out following the procedure according to [13] to segregate the coarse materials (gravels and sands) from the fine (silts and clays) components of the soil samples. The sieve number, sieve opening, percentage retained and percentage of the soil passing each sieve opening were indicated. The soil sample passing the number 200 sieve i.e. the one accumulated in the clay pan was removed and used to determine the percentages of clay and silt in the soil. The standard hydrometer test was performed on the fine materials left on the sieve pan [14, 15]. A curve of the percent of the soil finer than the diameter (ϕ) was drawn. From the curve, ϕ_{10} , ϕ_{30} , ϕ_{50} and ϕ_{60} were determined to obtain the uniformity coefficient, $U_c = \phi_{60}/\phi_{10}$ and coefficient of curvature, $C_c = (\phi_{30})^2/(\phi_{60}\phi_{10})$, which describes the soil's suitability to compaction. The determination of particle density was carried out using the pycnometer method according to [16]; bulk density, according to [17]; porosity, according to [18, 19, 20] and moisture content, according to [21].

2.3 Equipment and Compaction Procedure

The compaction equipment/tools consist of a compaction device, moisture sprayer, set of sieves (2.0, 0.6, 0.3, 0.15, 0.075 and 0.01 mm), pestle and mortar, scoop, knife, mixing pan, balances (sensitivity 0.01), drying oven (110°C), cans and polythene bags [22]. The compaction procedure involves taking 1 kg of soil of predetermined physical characteristics and spread evenly over a flat surface of area 0.0314 m² in the mould to a thickness of 20 mm. A compactive effort was released from a height of 0.5 m and dropped 3 times on the soil layer, and a new thickness was measured. Another soil "slice" (2 loadings), of the same thickness was spread evenly on the previous slice, and a new pre-compacted thickness was determined. Compactive effort was applied, and a new compacted soil thickness was measured from which further compaction was obtained. Loading continued up to the desired "pavement" thickness, Z of 140 mm was reached. The above steps were repeated for 6, 9, 12, 15, 18 and 21 drops representing multiples of compacting energy per loading for the same soil thickness of 20 mm loaded in each case; the whole steps were repeated for 40, 60, 80 and 100 mm slice thicknesses. The same was repeated for the other two soil classes.

2.4 Analysis and Criteria for Selecting Best-Fit

Dimensional analysis was applied to make all the terms of the governing variables dimensionless; these dimensionless variables were grouped and expressed in functional forms. A functional relationship, f, of the dimensionless terms, $\pi_1 = Y$ and $\pi_2 = X$ were established from regression exercise for the soils of the known values of π_2 . Five (5) common type functions namely linear, power, exponential, polynomial and logarithmic were applied; the power function established the best-fit function with the highest coefficient of determination, R^2 , and was selected and applied.

3 RESULTS AND DISCUSSION

Table 1 shows the specifications of the compactor used in the study. From the Table, the energy deliverable per drop by the compactor of weight 294.3N and from a height of 0.5m was 147.15 Nm while the cross-sectional area was 0.0314m². The mould height was 0.7m to accommodate at least seven soil slices of 0.1m thick.

Table 1. Compactor Operational Variables and Specifications

| S/N | Variables | Symbols/Notations | Values | Units |
|-----|-----------------------------|--------------------|---------------------|------------------|
| 1 | Compactive energy (W x h) | E | 294.3 x 0.5 = 147.5 | Nm |
| | Weight | W = mg = 30 x 9.81 | 294.3 | N |
| | Height of drop | H | 0.5 | m |
| 2 | Cross-sectional area | A | 0.0314 | m ² |
| 3 | Time of contact | T | Instantaneous | s |
| 4 | Slice thickness | Z | 0.02 to 0.1 | m |
| 5 | Acceleration due to gravity | g | 9.81 | m/s ² |

Table 2 shows the results of the index properties and Fig. 1 shows the grading curves. From hydrometer analysis, silt was found to be 7.09, 12.03 and 31.00 and clay was 20.4, 16.02 and 27.05 while from sieve analysis, sand was found to be 72.5, 71.93 and 41.91 for the three soil samples A, B and C respectively. The Table also shows the coarse to fine fraction (C/F) for the soil samples to be 2.64, 1.16, 0.73 and uniformity coefficients, $U_c = \phi_{60}/\phi_{10}$ to be 6.57, 6.43, 48.89 respectively. The bulk densities of the soil samples were 1590.84, 1511.29 and 1479.48 kgm⁻³ for soil samples A, B and C respectively. These results agree with those presented by [23].

Table 2. Soil Variables/Properties

| S/N | Variables | Notations | Samples | | | Units |
|------------------------|-----------------------------|--|----------|---------|----------|-------------------|
| | | | A | B | C | |
| 1 | Soil moisture content | m_c | 11 | 10 | 11.5 | % |
| 2 | Bulk Density | ρ_b | 1590.84 | 1511.29 | 1479.48 | kgm ⁻³ |
| 3 | Specific Gravity | G_s | 2669.12 | 2592.0 | 2704.36 | kgm ⁻³ |
| 4 | Mean particle size | ϕ_{50} | 0.17 | 0.6 | 0.16 | mm |
| 5 | Uniformity coefficient | $U_c = \phi_{60}/\phi_{10}$ | 6.57 | 6.43 | 48.89 | - |
| | | ϕ_{10} | 0.035 | 0.14 | 0.0045 | mm |
| | | ϕ_{60} | 0.23 | 0.9 | 0.22 | mm |
| 6 | Coarse-to-fine ratio | C/F | 2.64 | 1.16 | 0.73 | - |
| | Fine fraction (Silt + Clay) | F | 27.49 | 46.2 | 58.05 | % |
| | | Silt | 7.09 | 27.8 | 31.00 | % |
| | | Clay | 20.4 | 18.4 | 27.05 | % |
| Coarse fraction (Sand) | C | 72.5 | 53.7 | 41.91 | % | |
| 7 | Coefficient of curvature | $C_c = (\phi_{30})^2/(\phi_{60}\phi_{10})$ | 2.435 | 1.269 | 14.545 | - |
| | | ϕ_{30} | 0.14 | 0.4 | 0.12 | mm |
| 8 | Particle unit weight | γ_s | 2669.12 | 2592.53 | 2704.36 | Nm ⁻³ |
| 9 | Consistency | LL | 22 | - | 42 | % |
| | | PL | 10.50 | - | 13.41 | % |
| | | PI = LL-PL | 11.50 | - | 28.6 | - |
| 10 | Porosity | n | 40.4 | 41.69 | 44.57 | % |
| 11 | Texture | - | SCL | SL | CL | - |
| 12 | Unit weight before com | γ_{bc} | 15606.11 | 14825.8 | 14513.68 | Nm ⁻³ |

From the grading curve (Figure 1), $\phi_{30} = 0.14, 0.4$ and 0.12 and the coefficient of curvature, $C_c = (\phi_{30})^2/(\phi_{60}\phi_{10}) = 2.44, 1.27, 14.55$ for the samples A, B and C respectively. According to [24], well-graded soil is soil with a uniformity coefficient (U_c) greater than 6 and a coefficient of curvature (C_c) greater than 1 but less than 3. From the results, the soil samples A and B were well-graded sandy clay loam and sandy loam soil respectively and indicated that there was a widespread soil particle distribution of sand, silt and clay in the samples, which compacted well, giving high-density values; while sample C was clay loam, and is poorly graded and was difficult to compacted giving lower density values. Specific gravity was found to be 2669.12, 2592.0 and 2704.36 for soil samples A, B and C respectively. This gives an idea about the suitability of the soils as construction material because higher values give more strength for roads and foundations; but clay, even with high value, is not suitable for foundations because it is difficult to compact and gives lower density values [25].

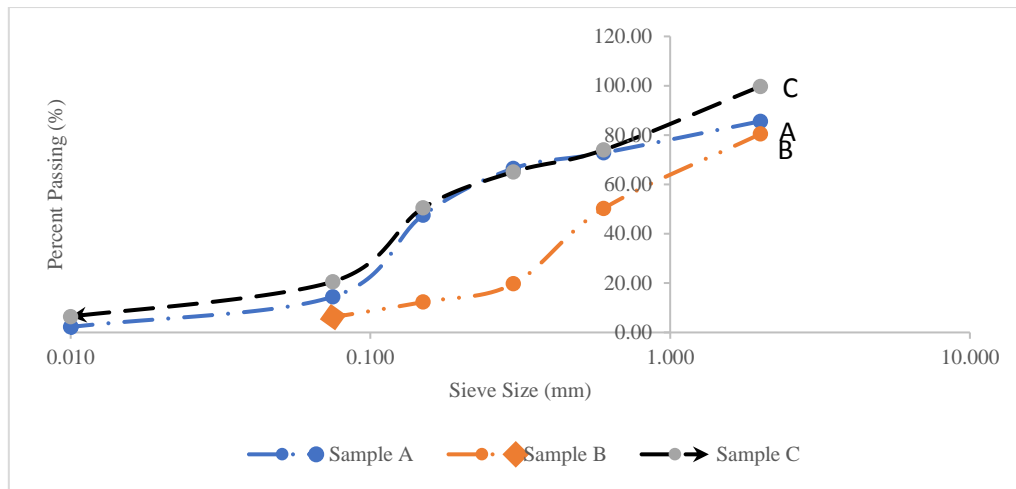


Figure 1. Grading Curves

Consistency test results such as liquid and plastic limits were also measured. The liquid limit of samples A and C were 22 and 42% (Figure 1) while the plastic limits were 10.5 and 13.41% and the plasticity index was 11.5 and 28.6% respectively (Table 2). Sample B is sandy and its liquid and plastic limits cannot be determined because the soil cannot be held together at any moisture content due to the high proportion of coarse fraction in the sample [26]. The plastic limit is an important soil property. Earth roads are easily usable at this water content. Excavation work and agricultural cultivation can be carried out with the least effort with soils at the plastic limit [27, 28].

3.1 Development of the Model

Table 3 contained test data record matrix for the 5 levels of soil slice thickness (20, 40, 60, 80 and 100 mm) for 7 levels of compactive efforts (147.15, 194.3, 441.45, 588.6, 735.75, 882.9 and 1030.05 Nm) while Table 4, derived from Table 3, contained the information required to compute the degrees of compaction, $\pi_1 = \Sigma \Delta Z / Z$ and the governing variables, $\pi_2 = [(C/F)U_c \phi_{50} E_c / A \gamma_{bc} S_e z^3]$. The versions of π_1 versus π_2 were discussed hereunder. From Table 4, another table (Table 5) was derived for the model development.

Table 3. Test Data Record Matrix for 5 Levels of Soil Slice Thickness (LST) for the 1st Level of Compactive Effort (e_L) Per loading at 11% moisture content for Sample A

| LEL and e_L | | (1) 147.15 Nm/Loading | | | | | | | | | | |
|---------------|----|-----------------------|---|---------|--------|------------|--------|-------|---------------|--------|------------------------------|--|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | |
| LST | z | Z | L | E_c | Z_l | ΔZ | C_c | m | γ_{bc} | S_e | $10^2 \times \Delta Z / Z_l$ | |
| 1 | 20 | 140 | 1 | 147.15 | 0.0200 | 0.0035 | 0.0035 | 1.00 | 15606.11 | 0.2723 | 17.5000 | |
| | | | 2 | 294.30 | 0.0365 | 0.0040 | 0.0075 | 2.00 | 17102.59 | 0.3172 | 10.9589 | |
| | | | 3 | 441.45 | 0.0525 | 0.0040 | 0.0115 | 3.00 | 17835.55 | 0.3450 | 7.6190 | |
| | | | 4 | 588.60 | 0.0685 | 0.0045 | 0.0160 | 4.00 | 18226.11 | 0.3619 | 6.5693 | |
| | | | 5 | 735.75 | 0.0840 | 0.0050 | 0.0210 | 5.00 | 18578.70 | 0.3787 | 5.9524 | |
| | | | 6 | 882.90 | 0.0990 | 0.0050 | 0.0260 | 6.00 | 18916.50 | 0.3963 | 5.0505 | |
| | | | 7 | 1030.05 | 0.1140 | 0.0055 | 0.0315 | 7.00 | 19165.40 | 0.4104 | 4.8246 | |
| 2 | 40 | 280 | 1 | 147.15 | 0.0400 | 0.0045 | 0.0045 | 2.00 | 15606.11 | 0.2723 | 11.2500 | |
| | | | 2 | 294.30 | 0.0755 | 0.0050 | 0.0095 | 4.00 | 16536.27 | 0.2985 | 6.6225 | |
| | | | 3 | 441.45 | 0.1105 | 0.0050 | 0.0145 | 6.00 | 16947.81 | 0.3118 | 4.5249 | |
| | | | 4 | 588.60 | 0.1455 | 0.0065 | 0.0210 | 8.00 | 17161.36 | 0.3192 | 4.4674 | |
| | | | 5 | 735.75 | 0.1790 | 0.0065 | 0.0275 | 10.00 | 17436.99 | 0.3293 | 3.6313 | |
| | | | 6 | 882.90 | 0.2125 | 0.0070 | 0.0345 | 12.00 | 17625.72 | 0.3365 | 3.2941 | |
| | | | 7 | 1030.05 | 0.2455 | 0.0075 | 0.0420 | 14.00 | 17799.23 | 0.3435 | 3.0550 | |
| 3 | 60 | 420 | 1 | 147.15 | 0.0600 | 0.0050 | 0.0050 | 3.00 | 15606.11 | 0.2723 | 8.3333 | |
| | | | 2 | 294.30 | 0.1150 | 0.0060 | 0.0110 | 6.00 | 16284.64 | 0.2910 | 5.2174 | |
| | | | 3 | 441.45 | 0.1690 | 0.0065 | 0.0175 | 9.00 | 16621.89 | 0.3012 | 3.8462 | |
| | | | 4 | 588.60 | 0.2225 | 0.0075 | 0.0250 | 12.00 | 16833.56 | 0.3080 | 3.3708 | |
| | | | 5 | 735.75 | 0.2750 | 0.0080 | 0.0330 | 15.00 | 17024.85 | 0.3145 | 2.9091 | |
| | | | 6 | 882.90 | 0.3270 | 0.0085 | 0.0415 | 18.00 | 17181.04 | 0.3199 | 2.5994 | |
| | | | 7 | 1030.05 | 0.3785 | 0.0090 | 0.0505 | 21.00 | 17317.21 | 0.3248 | 2.3778 | |
| 4 | 80 | 560 | 1 | 147.15 | 0.0800 | 0.0070 | 0.0070 | 4.00 | 15606.11 | 0.2723 | 8.7500 | |

| | | | | | | | | | | | |
|---|-----|-----|---|---------|--------|--------|--------|-------|----------|--------|--------|
| | | | 2 | 294.30 | 0.1530 | 0.0075 | 0.0145 | 8.00 | 16320.11 | 0.2920 | 4.9020 |
| | | | 3 | 441.45 | 0.2255 | 0.0085 | 0.0230 | 12.00 | 16609.61 | 0.3008 | 3.7694 |
| | | | 4 | 588.60 | 0.2970 | 0.0090 | 0.0320 | 16.00 | 16814.66 | 0.3074 | 3.0303 |
| | | | 5 | 735.75 | 0.3680 | 0.0090 | 0.0410 | 20.00 | 16963.16 | 0.3124 | 2.4457 |
| | | | 6 | 882.90 | 0.4390 | 0.0100 | 0.0510 | 24.00 | 17063.63 | 0.3158 | 2.2779 |
| | | | 7 | 1030.05 | 0.5090 | 0.0105 | 0.0615 | 28.00 | 17169.79 | 0.3195 | 2.0629 |
| 5 | 100 | 700 | 1 | 147.15 | 0.1000 | 0.0085 | 0.0085 | 5.00 | 15606.11 | 0.2723 | 8.5000 |
| | | | 2 | 294.30 | 0.1915 | 0.0090 | 0.0175 | 10.00 | 16298.81 | 0.2914 | 4.6997 |
| | | | 3 | 441.45 | 0.2825 | 0.0095 | 0.0270 | 15.00 | 16572.86 | 0.2997 | 3.3628 |
| | | | 4 | 588.60 | 0.3730 | 0.0100 | 0.0370 | 20.00 | 16735.77 | 0.3048 | 2.6810 |
| | | | 5 | 735.75 | 0.4630 | 0.0105 | 0.0475 | 25.00 | 16853.25 | 0.3087 | 2.2678 |
| | | | 6 | 882.90 | 0.5525 | 0.0110 | 0.0585 | 30.00 | 16947.81 | 0.3118 | 1.9910 |
| | | | 7 | 1030.05 | 0.6415 | 0.0110 | 0.0695 | 35.00 | 17029.27 | 0.3146 | 1.7147 |

$S_e = ((\gamma_{bc}/\gamma_w)/(1-(\gamma_{bc}/\gamma_s)) \times m_c$; m_c = Gravimetric moisture content; $\gamma_w, \gamma_s, \gamma_{bc}$ are as given in Table 2

Table 4. Input-Output Data for Computing π_1 and π_2 for the three Soil Samples A, B and C

| LST | Soil Slice | LEL e_L | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|-----|--------------|------------------|---------|--------|---------|--------|---------|--------|---------|
| | | | 147.15 | 294.30 | 441.45 | 588.60 | 735.75 | 882.90 | 1030.05 |
| 1. | z=20, Z=140 | S_e | 0.41 | 0.47 | 0.56 | 0.7 | 1.02 | 1.18 | 1.51 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.0315 | 0.037 | 0.0435 | 0.05 | 0.057 | 0.059 | 0.0615 |
| 2 | z=40, Z=280 | S_e | 0.34 | 0.36 | 0.38 | 0.38 | 0.42 | 0.43 | 0.45 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.042 | 0.0475 | 0.054 | 0.056 | 0.064 | 0.0675 | 0.071 |
| 3 | z=60, Z=420 | S_e | 0.32 | 0.33 | 0.34 | 0.35 | 0.35 | 0.36 | 0.37 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.0505 | 0.0555 | 0.0615 | 0.0665 | 0.063 | 0.073 | 0.076 |
| 4 | z=80, Z=560 | S_e | 0.32 | 0.33 | 0.33 | 0.34 | 0.34 | 0.35 | 0.35 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.0615 | 0.0675 | 0.071 | 0.076 | 0.082 | 0.084 | 0.088 |
| 5 | z=100, Z=700 | S_e | 0.31 | 0.32 | 0.32 | 0.33 | 0.34 | 0.34 | 0.34 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.0695 | 0.0775 | 0.0815 | 0.0875 | 0.094 | 0.0955 | 0.0975 |
| 1. | z=20, Z=140 | S_e | 0.32 | 0.35 | 0.38 | 0.40 | 0.43 | 0.44 | 0.45 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.025 | 0.031 | 0.036 | 0.038 | 0.04 | 0.041 | 0.042 |
| 2 | z=40, Z=280 | S_e | 0.32 | 0.33 | 0.36 | 0.39 | 0.41 | 0.42 | 0.45 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.052 | 0.059 | 0.066 | 0.073 | 0.0775 | 0.0805 | 0.0845 |
| 3 | z=60, Z=420 | S_e | 0.30 | 0.31 | 0.32 | 0.34 | 0.36 | 0.37 | 0.37 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.066 | 0.073 | 0.079 | 0.086 | 0.096 | 0.098 | 0.099 |
| 4 | z=80, Z=560 | S_e | 0.29 | 0.29 | 0.30 | 0.31 | 0.32 | 0.32 | 0.32 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.076 | 0.08 | 0.085 | 0.092 | 0.099 | 0.105 | 0.106 |
| 5 | z=100, Z=700 | S_e | 0.28 | 0.29 | 0.30 | 0.31 | 0.32 | 0.33 | 0.33 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.086 | 0.099 | 0.109 | 0.113 | 0.131 | 0.134 | 0.138 |
| 1. | z=20, Z=140 | S_e | 0.30 | 0.33 | 0.35 | 0.37 | 0.38 | 0.38 | 0.39 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.019 | 0.0265 | 0.0315 | 0.0355 | 0.036 | 0.0365 | 0.0375 |
| 2 | z=40, Z=280 | S_e | 0.31 | 0.32 | 0.34 | 0.36 | 0.38 | 0.39 | 0.40 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.043 | 0.0505 | 0.059 | 0.068 | 0.074 | 0.077 | 0.0785 |
| 3 | z=60, Z=420 | S_e | 0.30 | 0.30 | 0.32 | 0.33 | 0.34 | 0.35 | 0.35 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.055 | 0.0615 | 0.077 | 0.0775 | 0.0865 | 0.091 | 0.092 |
| 4 | z=80, Z=560 | S_e | 0.29 | 0.29 | 0.30 | 0.30 | 0.31 | 0.31 | 0.32 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.0635 | 0.0665 | 0.074 | 0.078 | 0.0905 | 0.093 | 0.0945 |
| 5 | z=100, Z=700 | S_e | 0.29 | 0.29 | 0.30 | 0.30 | 0.31 | 0.32 | 0.32 |
| | | E_c | 1030.05 | 2060.1 | 3090.15 | 4120.2 | 5150.25 | 6180.3 | 7210.35 |
| | | $\Sigma\Delta Z$ | 0.076 | 0.081 | 0.099 | 0.101 | 0.113 | 0.119 | 0.127 |

Table 5 (A). The values of π_1 and π_2 for 5 levels of soil slice thickness and 7 levels of compactive effort per loading of sample A

| LEL | | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | |
|-----|-----|-----|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| eL | | | 147.15 | | 294.3 | | 441.45 | | 588.6 | | 735.75 | | 882.9 | | 1030.05 | |
| LST | z | Z | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 |
| 1 | 20 | 140 | 0.225 | 1885.5 | 0.2643 | 3289.6 | 0.3107 | 4141.3 | 0.3571 | 4417.4 | 0.4071 | 3789.5 | 0.4214 | 3930.8 | 0.4393 | 3583.7 |
| 2 | 40 | 280 | 0.15 | 284.2 | 0.1696 | 536.9 | 0.1929 | 762.85 | 0.2 | 1017.2 | 0.2286 | 1150.4 | 0.2411 | 1348.4 | 0.2536 | 1503.2 |
| 3 | 60 | 420 | 0.1202 | 89.45 | 0.1321 | 173.5 | 0.1464 | 252.65 | 0.1583 | 327.2 | 0.15 | 409 | 0.1738 | 477.2 | 0.181 | 541.7 |
| 4 | 80 | 560 | 0.1098 | 37.75 | 0.1205 | 73.2 | 0.1268 | 109.8 | 0.1357 | 142.1 | 0.1464 | 177.7 | 0.15 | 207.1 | 0.1571 | 241.6 |
| 5 | 100 | 700 | 0.0993 | 19.95 | 0.1107 | 38.65 | 0.1164 | 58 | 0.125 | 75 | 0.1343 | 90.95 | 0.1364 | 109.2 | 0.1393 | 127.3 |

Notations: $\pi_1 = \Sigma \Delta Z / Z$ and for $C/F = 2.6363$, $A = 0.0314 \text{ m}^2$, $U_c = 6.571$, $\phi_{50} = 0.17$, $\gamma_{bc} = 15606.11 \text{ Nm}^{-3}$; $\pi_2 = E_c(C/F)\phi_{50}U_c / (S_e \gamma_{bc} A z^3)$ becomes $\pi_2 = ((C/F)\phi_{50}U_c / A \gamma_{bc})(E_c / S_e z^3) = 0.006x(E_c / S_e z^3)$

Table 5 (B). The values of π_1 and π_2 for 5 levels of soil slice thickness and 7 levels of compactive effort per loading of sample B

| LEL | | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | |
|-----|-----|-----|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| eL | | | 147.15 | | 294.3 | | 441.45 | | 588.6 | | 735.75 | | 882.9 | | 1030.05 | |
| LST | z | Z | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 |
| 1 | 20 | 140 | 0.1786 | 3863.1 | 0.2214 | 7063.9 | 0.2571 | 9759.4 | 0.2714 | 12361.9 | 0.2857 | 14374.2 | 0.2929 | 16857.1 | 0.3 | 19229.5 |
| 2 | 40 | 280 | 0.1857 | 482.9 | 0.2107 | 936.5 | 0.2357 | 1287.7 | 0.2607 | 1584.9 | 0.2768 | 1884.4 | 0.2875 | 2207.5 | 0.3018 | 2403.7 |
| 3 | 60 | 420 | 0.1571 | 152.6 | 0.1738 | 295.4 | 0.1881 | 429.2 | 0.2048 | 538.6 | 0.2286 | 635.9 | 0.2333 | 742.5 | 0.2357 | 866.2 |
| 4 | 80 | 560 | 0.1357 | 66.6 | 0.1429 | 133.2 | 0.1518 | 193.2 | 0.1643 | 249.2 | 0.1768 | 301.8 | 0.1875 | 362.2 | 0.1893 | 422.5 |
| 5 | 100 | 700 | 0.1229 | 35.3 | 0.1414 | 68.2 | 0.1557 | 98.9 | 0.1614 | 127.6 | 0.1871 | 154.5 | 0.1914 | 179.8 | 0.1971 | 209.8 |

Notations: $\pi_1 = \Sigma \Delta Z / Z$ and for $C/F = 1.1598$, $A = 0.0314 \text{ m}^2$, $U_c = 6.429$, $\phi_{50} = 0.6$, $\gamma_{bc} = 14825.8 \text{ Nm}^{-3}$; $\pi_2 = E_c(C/F)\phi_{50}U_c / (S_e \gamma_{bc} A z^3)$ becomes $\pi_2 = ((C/F)\phi_{50}U_c / A \gamma_{bc})(E_c / S_e z^3) = 0.0096x(E_c / S_e z^3)$

Table 5 (C). The values of π_1 and π_2 for 5 levels of soil slice thickness and 7 levels of compactive effort per loading of sample C

| LEL | | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | |
|-----|-----|-----|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| eL | | | 147.15 | | 294.3 | | 441.45 | | 588.6 | | 735.75 | | 882.9 | | 1030.05 | |
| LST | z | Z | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 |
| 1 | 20 | 140 | 0.1357 | 5351.3 | 0.1893 | 9729.6 | 0.2250 | 13760.5 | 0.2536 | 17355.6 | 0.2571 | 21123.6 | 0.2607 | 25348.3 | 0.2679 | 28814.7 |
| 2 | 40 | 280 | 0.1536 | 647.3 | 0.1804 | 1254.2 | 0.2107 | 1770.7 | 0.2429 | 2229.7 | 0.2643 | 2640.4 | 0.2750 | 3087.3 | 0.2804 | 3511.8 |
| 3 | 60 | 420 | 0.1310 | 198.2 | 0.1464 | 396.4 | 0.1833 | 557.4 | 0.1845 | 720.7 | 0.2060 | 874.4 | 0.2167 | 1019.3 | 0.2190 | 1189.2 |
| 4 | 80 | 560 | 0.1134 | 86.5 | 0.1188 | 173.0 | 0.1321 | 250.8 | 0.1393 | 334.5 | 0.1616 | 404.6 | 0.1661 | 485.5 | 0.1688 | 548.7 |
| 5 | 100 | 700 | 0.1086 | 44.3 | 0.1157 | 88.6 | 0.1414 | 128.4 | 0.1443 | 171.2 | 0.1614 | 207.1 | 0.1700 | 240.8 | 0.1814 | 280.9 |

Notations: $\pi_1 = \Sigma \Delta Z / Z$ and for $C/F = 0.7271$, $A = 0.0314 \text{ m}^2$, $U_c = 48.89$, $\phi_{50} = 0.16$, $\gamma_{bc} = 14513.68 \text{ Nm}^{-3}$; $\pi_2 = E_c(C/F)\phi_{50}U_c / (S_e \gamma_{bc} A z^3)$ becomes $\pi_2 = ((C/F)\phi_{50}U_c / A \gamma_{bc})(E_c / S_e z^3) = 0.0125x(E_c / S_e z^3)$

3.2 Regression of π_1 on π_2

Figure 2 drawn with data from Table 6 shows the regression of π_1 on π_2 as $\pi_1 = a\pi_2^b = a[E_c\varphi_{50}(C/F)U_c/AY_{bc}z^3S_e]^b$ with its regression statistics, $r^2 = 0.69$. Applying a “t-test” to the regression statistics, a t_r -value of 15.22 was obtained from $t_r = \sqrt{((N-2)r^2/(1-r^2))} = 15.22$, where $N = 105$, $df = N-2 = 103$. This “ t_r ” is more than four times the tabled value of “ t ” at 103 degrees of freedom and $\alpha = 0.05\%$ or 99.95% confidence according to [29].

Table 6. Unweighted Regression of π_1 versus π_2 for Samples A, B and C

| S/No | SAMPLE A | | SAMPLE B | | SAMPLE C | |
|------|----------|---------|----------|---------|----------|---------|
| | π_1 | π_2 | π_1 | π_2 | π_1 | π_2 |
| 1 | 0.23 | 1885.5 | 0.18 | 3863.1 | 0.14 | 5351.3 |
| 2 | 0.26 | 3289.6 | 0.22 | 7063.9 | 0.19 | 9729.6 |
| 3 | 0.31 | 4141.3 | 0.26 | 9759.4 | 0.23 | 13760.5 |
| 4 | 0.36 | 4417.4 | 0.27 | 12361.9 | 0.25 | 17355.6 |
| 5 | 0.41 | 3789.5 | 0.29 | 14374.2 | 0.26 | 21123.6 |
| 6 | 0.42 | 3930.8 | 0.29 | 16857.1 | 0.26 | 25348.3 |
| 7 | 0.44 | 3583.7 | 0.30 | 19229.5 | 0.27 | 28814.7 |
| 8 | 0.15 | 284.2 | 0.19 | 482.9 | 0.15 | 647.3 |
| 9 | 0.17 | 536.9 | 0.21 | 936.5 | 0.18 | 1254.2 |
| 10 | 0.19 | 762.9 | 0.24 | 1287.7 | 0.21 | 1770.7 |
| 11 | 0.20 | 1017.2 | 0.26 | 1584.9 | 0.24 | 2229.7 |
| 12 | 0.23 | 1150.4 | 0.28 | 1884.4 | 0.26 | 2640.4 |
| 13 | 0.24 | 1348.4 | 0.29 | 2207.5 | 0.28 | 3087.3 |
| 14 | 0.25 | 1503.2 | 0.30 | 2403.7 | 0.28 | 3511.8 |
| 15 | 0.12 | 89.5 | 0.16 | 152.6 | 0.13 | 198.2 |
| 16 | 0.13 | 173.5 | 0.17 | 295.4 | 0.15 | 396.4 |
| 17 | 0.15 | 252.7 | 0.19 | 429.2 | 0.18 | 557.4 |
| 18 | 0.16 | 327.2 | 0.20 | 538.6 | 0.18 | 720.7 |
| 19 | 0.15 | 409.0 | 0.23 | 635.9 | 0.21 | 874.4 |
| 20 | 0.17 | 477.2 | 0.23 | 742.5 | 0.22 | 1019.3 |
| 21 | 0.18 | 541.7 | 0.24 | 866.2 | 0.22 | 1189.2 |
| 22 | 0.11 | 37.8 | 0.14 | 66.6 | 0.11 | 86.5 |
| 23 | 0.12 | 73.2 | 0.14 | 133.2 | 0.12 | 173.0 |
| 24 | 0.13 | 109.8 | 0.15 | 193.2 | 0.13 | 250.8 |
| 25 | 0.14 | 142.1 | 0.16 | 249.2 | 0.14 | 334.5 |
| 26 | 0.15 | 177.7 | 0.18 | 301.8 | 0.16 | 404.6 |
| 27 | 0.15 | 207.1 | 0.19 | 362.2 | 0.17 | 485.5 |
| 28 | 0.16 | 241.6 | 0.19 | 422.5 | 0.17 | 548.7 |
| 29 | 0.10 | 20.0 | 0.12 | 35.3 | 0.11 | 44.3 |
| 30 | 0.11 | 38.7 | 0.14 | 68.2 | 0.12 | 88.6 |
| 31 | 0.12 | 58.0 | 0.16 | 98.9 | 0.14 | 128.4 |
| 32 | 0.13 | 75.0 | 0.16 | 127.6 | 0.14 | 171.2 |
| 33 | 0.13 | 91.0 | 0.19 | 154.5 | 0.16 | 207.1 |
| 34 | 0.14 | 109.2 | 0.19 | 179.8 | 0.17 | 240.8 |
| 35 | 0.14 | 127.3 | 0.20 | 209.8 | 0.18 | 280.9 |

where $\pi_1 = \Sigma\Delta Z/Z$ and $\pi_2 = [(C/F)U_c\varphi_{50}E_c/AY_{bc}S_ez^3]$

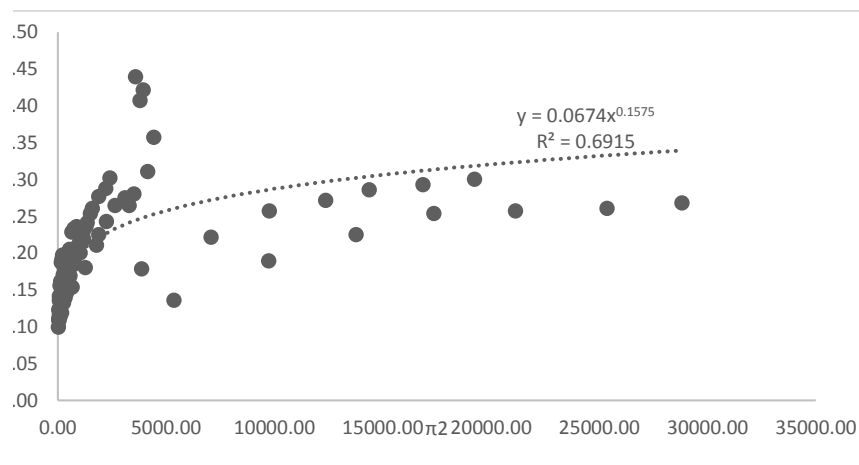


Figure 2. π_1 versus π_2 of Data for Regression of Samples A, B, and C

That means that the correlation of $r = \sqrt{(0.692)} = 0.832$, is highly significant. [30] performed regression analysis with multiple variables to predict compaction parameters such as the bulk density and they concluded that there is indeed a direct linear relationship between index properties and compaction.

Table 7. Coefficient “a”, Exponent “b” for $a\pi_2^b$ Model

| S/No | Soil Samples | Coefficient a | Exponent b | Det. Coeff. R ² | Correlation t-Test |
|------|--------------|------------------|---------------|-------------------------------|-----------------------|
| 1 | A, B, C | 0.0674 | 0.1575 | 0.69 | HS |

Highly significant at 99.95 Confidence Level

Table 8. The Developed Model

| Samples | Coefficient a | Exponent b | Estimator | The Model |
|---------|------------------|---------------|------------|------------------------|
| A, B, C | 0.0674 | 0.1575 | $a\pi_2^b$ | $0.0674\pi_2^{0.1575}$ |

Hence, the developed model is $\pi_1 = 0.0674\pi_2^{0.1575}$ where $\pi_2 = 0.0674[(C/F)U_c\phi_{50}E_c/A\gamma_{bc}S_eZ^3]$.

3.3 Validation

Table 9 is a list of information required to validate the model while Table 10 shows the computation sequence for estimating the model and its corresponding ratios with measured value $(\pi_1)_m$. The values of the coefficient ‘a’ and exponent ‘b’ were obtained from the regression curve in Fig. 3. The model estimated the degree of compaction with 75% accuracy.

Table 9. Degree of Compaction Function Validation Test Information

| Variables | Symbols | Units | Sample A | | Sample B | | Sample C | |
|---|------------------|------------------|----------|----------|----------|---------|----------|----------|
| | | | 1 | 2 | 1 | 2 | 1 | 2 |
| Soil Variables | | | | | | | | |
| Coarse fraction | C | - | 72.50 | 72.50 | 53.7 | 53.7 | 42.10 | 42.10 |
| Fine fraction | F | - | 27.49 | 27.49 | 46.2 | 46.2 | 57.89 | 57.89 |
| Coarseness | C/F | - | 2.64 | 2.64 | 1.16 | 1.16 | 0.73 | 0.73 |
| Mean particle size | ϕ_{50} | m | 0.17 | 0.17 | 0.6 | 0.6 | 0.16 | 0.16 |
| Uniformity coefficient (ϕ_{60}/ϕ_{10}) | U_c | - | 6.57 | 6.57 | 6.43 | 6.43 | 48.89 | 48.89 |
| Grain particle unit weight | γ_s | Nm ⁻³ | 2669.12 | 2669.12 | 2592.53 | 2592.53 | 2704.36 | 2704.36 |
| Gravimetric moisture content | m_c | % | 9.5 | 13 | 9 | 11 | 10 | 13 |
| Pre-compaction bulk unit weight | γ_{bc} | Nm ⁻³ | 15606.11 | 15606.11 | 14825.8 | 14825.8 | 14513.68 | 14513.68 |
| Degree of water saturation | $S_e(\theta/P)$ | - | 0.32 | 0.39 | 0.31 | 0.34 | 0.28 | 0.34 |
| New Compactor Variables | | | | | | | | |
| Mass | m | kg | 30 | 30 | 30 | 30 | 30 | 30 |
| Drop Height | h | m | 0.4 | 0.6 | 0.4 | 0.6 | 0.4 | 0.6 |
| Compactive Effort per Drop (mgh) | E | Nm | 117.72 | 176.58 | 117.72 | 176.58 | 117.72 | 176.58 |
| Cross-Sectional Area | A | m ² | 0.0314 | 0.0314 | 0.0314 | 0.0314 | 0.0314 | 0.0314 |
| New Operational Variables | | | | | | | | |
| Pre-compaction soil slice thickness per loading | | | | | | | | |
| Number of loading (Z/z) | L | - | 7 | 5 | 7 | 5 | 7 | 5 |
| Pre-compaction soil thickness | Z | m | 0.21 | 0.25 | 0.21 | 0.25 | 0.21 | 0.25 |
| Number of drops per loading | N_d | - | 2 | 4 | 2 | 4 | 2 | 4 |
| Compactive Effort per Loading (EN_d) | e_L | Nm | 235.44 | 706.32 | 235.44 | 706.32 | 235.44 | 706.32 |
| Cumulative Compactive Effort (e_{cL}) | E_c | Nm | 1648.08 | 3531.6 | 1648.08 | 3531.6 | 1648.08 | 3531.6 |
| Measured Cumulative Compaction | $\Sigma\Delta Z$ | m | 0.0445 | 0.0410 | 0.0425 | 0.0465 | 0.0390 | 0.0545 |

Table 10. Computation of Estimated $(\pi_1)_c$ and Comparison with Measured $(\pi_1)_m$ using the Model, $a\pi_2^b$

| Steps | Variables | Sample A | | Sample B | | Sample C | |
|-------|---|----------|--------|----------|--------|----------|---------|
| | | 1 | 2 | 1 | 2 | 1 | 2 |
| 1 | $\pi_2 = (C/F)\phi_{50}U_cE_c/(\gamma_{bc}AS_ez^3)$ | 1159.92 | 453.92 | 1890.14 | 847.67 | 2725.45 | 1077.27 |
| 2 | a | 0.0398 | 0.0398 | 0.0881 | 0.0881 | 0.073 | 0.073 |
| 3 | b | 0.2524 | 0.2524 | 0.1271 | 0.1271 | 0.131 | 0.131 |
| 4 | Calculated | 2362 | 1864 | 2298 | 2075 | 2058 | 1822 |
| 5 | Measured | 2119 | 1640 | 2024 | 1860 | 1857 | 2180 |
| 6 | Ratio (%) $100[a\pi_2^b/(\Sigma\Delta Z/Z)]$ | 96.60 | 107.74 | 109.29 | 104.78 | 126.12 | 92.84 |

4 CONCLUSIONS

The coefficient ‘a’ and exponent ‘b’ were computed for use in estimating the degree of compaction, $\pi_1 = \Sigma\Delta Z/Z = \Sigma\Delta V/V$ for any combination of the thirteen governing factors encapsulated in π_2 as $\pi_1 = a\pi_2^b = 0.0674[(C/F)U_c\phi_{50}E_c/AY_{bc}S_ez^3]^{0.1575}$, where ‘a’ = 0.0674, ‘b’ = 0.1575 and $\pi_2 = [(C/F)U_c\phi_{50}E_c/AY_{bc}S_ez^3]$. Two validation test results showed that the procedure is durable for a wide range of operating variables and a “drop-weight” compactor. Though the problem of soil compaction cannot completely be estimated, a significant value can be estimated and applied for proper geotechnical activities as the model passed the t-test of statistical significance of correlation. The usefulness of this model is that one does not need to carry out trial compaction tests during preliminary design stages of earth structures to know the degree of compaction of soils from a given borrow site before knowing its response to a given set of operating conditions, provided the measurable variables in π_2 are known. It could also be useful when a laboratory compaction device is not available. The model can save valuable resources, especially when there are financial constraints and limited time.

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