**STRENGHT MODELLING OF SOIL GEOTECHNICAL PROPERTIES FROM INDEX PROPERTIES**

AFOLABI, Olumide Aderemi\* and AFOLAYAN, Olaniyi Diran\*

\*Graduate Student, Civil Engineering Department, University of Ibadan

Corresponding E-mail:olaniyiafolayanoy@gmail.com

**ABSTRACT**

This research work presents the strength models developed for class of soils encountered. An empirical, analytical model is developed to predict the CBR and shear stress of soil from its index properties and grade size, with a view to reducing time, efforts and cost usually incurred in determining this tests in the laboratory for future planning, design and construction projects.

Soil samples were collected from various locations in Ife central local government. The various and available index property tests such as the sieve analysis, Atterberg limit test, specific gravity test, were carried out and classification of each samples performed. Compaction test, California Bearing Ratio, triaxial test was also carried out with the Optimum Moisture Content (OMC), Maximum Dry Density (MDD), unsoaked California Bearing Ratio (CBR), internal angle of friction φ, cohesion c and shear stress determined. Regression models relating these index properties together were developed and tested to ascertain its effectiveness.

The study showed that about 44.4% of the soil mass of the Ife central local government is poorly graded soil with gravel followed by 33.3% of well graded soil with gravel. Linear and non-linear relationships were generated between various soils index and engineering properties through correlation analysis with a reliable coefficient of determination (R), poorly graded soil with gravel cannot be effectively correlated because of their weak coefficient of determination.

KEYWORDS: Strength models, Regression models, Linear and non-linear relationships

1. **INTRODUCTION**

Although not formally recognized and named until 1989, the concept of the correlation equations has long been applied to estimate soil properties that are difficult to determine. Many soil science agencies have their own (unofficial) rule of thumb for estimating difficult-to-measure soil properties. Probably because of the particular difficulty, cost of measurement, and availability of large databases, the most comprehensive research in developing correlation equations has been for the estimation of [water retention curve](http://en.wikipedia.org/wiki/Water_retention_curve) and [hydraulic conductivity](http://en.wikipedia.org/wiki/Hydraulic_conductivity).

The term correlation equation was coined by Bouma, [3] as translating data we have into what we need. The most readily available data come from [soil survey](http://en.wikipedia.org/wiki/Soil_survey), such as field morphology, [soil texture](http://en.wikipedia.org/wiki/Soil_texture), structure and pH. Correlation equations add value to this basic information by translating them into estimates of other more laborious and expensively determined soil properties. These functions fill the gap between the available soil data and the properties which are more useful or required for a particular model or quality assessment. Correlation equations utilize various [regression analysis](http://en.wikipedia.org/wiki/Regression_analysis) and [data mining](http://en.wikipedia.org/wiki/Data_mining) techniques to extract rules associating basic soil properties with more difficult to measure properties.

 The first correlation equation came from the study of [Briggs](http://en.wikipedia.org/wiki/Lyman_Briggs) and McLane [4]. They determined the wilting coefficient, which is defined as percentage [water content](http://en.wikipedia.org/wiki/Water_content) of a [soil](http://en.wikipedia.org/wiki/Soil) when the plants growing in that soil are first reduced to a wilted condition from which they cannot recover in an approximately saturated atmosphere without the addition of water to the soil, as a function of [particle-size](http://en.wikipedia.org/wiki/Soil_texture) as given in Equation 1

$Wilting coefficient = 0.01 + 0.12 + 0.57 $ (1)

With the introduction of the [field capacity](http://en.wikipedia.org/wiki/Field_capacity) (FC) and [permanent wilting point](http://en.wikipedia.org/wiki/Permanent_wilting_point) (PWP) concepts, research during the period 1950-1980 attempted to correlate particle-size distribution, [bulk density](http://en.wikipedia.org/wiki/Bulk_density) and organic matter content with water content at field capacity (FC), permanent wilting point (PWP), and [available water capacity](http://en.wikipedia.org/wiki/Available_water_capacity) (AWC). In the 1960s various papers dealt with the estimation of FC, PWP, and AWC, notably in a series of papers by Salter and Williams [13]. They explored relationships between texture classes and available water capacity, which are now known as class correlation equations. They also developed functions relating the particle-size distribution to AWC, now known as continuous correlation equations. They asserted that their functions could predict AWC to a mean accuracy of 16 %.

In the 1970s more comprehensive research using large databases was developed. A particularly good example is the study by Hall et al. [10] from soil in England and Wales; they established field capacity, permanent wilting point, available water content, and air capacity as a function of textural class, and as well as deriving continuous functions estimating these soil-water properties. In the USA, Gupta and Larson [9] developed 12 functions relating particle-size distribution and [organic matter](http://en.wikipedia.org/wiki/Soil_organic_matter) content to water content at potentials ranging from -4 kPa to -1500 kPa.

With the flourishing development of models describing soil hydraulic properties and computer modelling of soil-water and solute transport, the need for hydraulic properties as inputs to these models became more evident. Clapp and Hornberger [6] derived average values for the parameters of a power-function [water retention curve](http://en.wikipedia.org/wiki/Water_retention_curve), sorptivity and saturated [hydraulic conductivity](http://en.wikipedia.org/wiki/Hydraulic_conductivity) for different [texture classes](http://en.wikipedia.org/wiki/Soil_texture_classification). In probably the first research of its kind, Bloemen [1] derived empirical equations relating parameters of the Brooks and Corey hydraulic model to particle-size distribution.

Lamp and Kneib [11] from Germany introduced the term pedo function (PF), while Bouma and Van Lanen [2] used the term transfer function (PTF). To avoid confusion with the term transfer function used in soil physics and in many other disciplines, Bouma [3] later called it correlation equations. (A personal anecdote hinted that Arnold Bregt from Wageningen University suggested this term). Since then, the development of hydraulic Correlation equations has become a boom research topic, first in the US and Europe, South America, Australia and all over the world.

Although most Correlation equations have been developed to predict soil hydraulic properties, they are not restricted to hydraulic properties. Correlation equations for estimating soil physical, mechanical, chemical and biological properties have also been developed. In the process of carrying out Civil Engineering projects, it is necessary to carry out various soil tests to determine the soil properties either in the laboratory or on the field (In-situ). Some soil properties like the index properties are readily and easily obtained in the laboratory, however, direct measurements of other properties like the engineering properties including shear strength parameters, hydraulic conductivity, soil water characteristic curves and California Bearing ratios (CBR) are expensive, time consuming and labour intensive. Some methods or equations are developed to estimate the more difficult to obtain soil properties from soil properties that are easily obtained. These methods or equations are referred to as correlation equations” [15, 18].

There exists a lot of uncertainty in applying correlation equations to other soil conditions different from the soil conditions under which the correlation equations were developed because correlation equations are developed on the basis of a limited database. Thus, there is a need to understand the accuracy and the limit of the correlation equations developed. Considerable work has been performed developing such functions and testing such functions against databases of soil properties. Wagner et al. [16] evaluated eight well-known correlation equations used for estimation of soil hydraulic conductivity using detailed measurements of 63 German soil horizons and found that the PTF of Wösten [17] performed the best for predicting the unsaturated hydraulic conductivity.

***Methods of developing correlation equations***

There are basically two methods of developing correlation equations namely: the parametric and non-parametric methods. Parametric method includes the use of artificial neural network (ANN) and regression models. In some new applications, non-parametric methods have been successfully used. These techniques do not use any predefined mathematical functions, they work with similarities instead of fitting equations to data. Nemes et al. [12] introduced a relatively simple form of non-parametric lazy learning algorithm, called k-Nearest Neighbor algorithm (k-NN), to estimate soil hydraulic properties, and compared the results with a neural network model. If the soil properties to be estimated (e.g. Soil Moisture retention Capacity, SMRC parameters) appear in PTF’s as continuous functions of the other soil properties, the PTF’s are referred to as continuous.

***Study aim and Justification***

The aim of this research is to develop correlation equations for some selected soil samples in Ile-Ife, Nigeria in order to provide a guide that will assist in estimating some engineering properties of soil from some index soil properties.The major work in the development of correlation equations has been in the USA and Europe and therefore the soils used have been American or European [8, 18] as shown in Table 1. The physical properties of these soils are different from those of the soils found in the tropics [7]. Variations in easily measurable soil properties which are the key parameters for correlation equations, between the tropical and temperate soils cause direct inapplicability of the existing correlation equations to other areas [18].

The only available correlation equations developed using data from soils found in the tropics that seem applicable under Tanzanian conditions for estimating soil water retention capacity are those developed by Tomasella and Hodnett[14] in Brazil. Thus, in this project, these correlation equations will be developed and tested using data’s of independent variables such as clay content, moisture content, dry and bulk density etc obtained from test carried out on soil sample found in Ife Central Local Government, Osun State, Nigeria and statistical regression analysis of the measured soil physical properties will be carried out in order to come up with locally accurate correlation equations.

Table 1: The top 10 PTF producer countries. (Grant et al, 2006)

|  |  |  |
| --- | --- | --- |
| Countries  | No. of Papers (1991- August 2006) | Percentage of Total (284 papers) |
| USA | 83 | 29.2% |
| Germany | 47 | 16.55 |
| The Netherlands | 31 | 10.9% |
| Australia  | 30 | 10.6% |
| Canada  | 23 | 8.1% |
| France  | 19 | 6.7% |
| Brazil | 18 | 6.3% |
| Belgium | 15 | 5.3% |
| England | 14 | 4.9% |
| Italy  | 13 | 4.6% |

1. **MATERIALS AND METHOD**

***Background***

Various tests carried out range from tests involving the determination of both the independent and dependent variables. Independent variables are the index properties which are the moisture content, plastic limit, liquid limit, bulk density, silt content, sand content, clay content etc, while the dependent variables are the California Bearing Ratio (CBR), Unconfined Compressive Strength, permeability etc. The results from the tests will be used to develop pedo transfer/ correlation functions relating the dependent variables to the independent variables.

***Location of the Study Area***

The area from where the soil samples were collected for the laboratory test was at Ife Central local government area, Ile-Ife, Osun state, Nigeria. The local government has within it, the Obafemi Awolowo University which covers a considerable land area in the local government as shown in Fig. 1. The locations for the collection of soil samples were determined by means of a grid network on the Ife central local government map, which was followed as much as possible and divided into locations(A-J) as shown in Table 2. The map of the local government area was gridded at an interval of 5cm in both vertical and horizontal directions. This is to ensure that soil sampling is uniformly distributed over the whole local government area. The Global Positioning System (GPS) readings as shown in table 2 of the exact location of sample collection were recorded. The top soil will be scraped off to a depth of about 75 cm in order that the organic soil is gotten rid of.



Fig. 1: Map of Ife Central Local Government

Table 2: Sample reference and their locations

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sample | Position | Altitude | Trip | Track |
| A1(Road 1) | 07° 29.996”N |  004°31.499”E | 269m | 256Km | 123° |
| A2(Road 1) | 07° 30.017”N | 004°31.476”E | 269m | 250Km | 297° |
| B2(Road 1) | 07° 30.121”N | 004°31.545”E | 269m | 267Km | 039° |
| B1(Road 1) | 07° 30.107”N | 004°31.570”E | 269m | 265Km | 108° |
| B1(Road 1) | 07° 30.305”N | 004°31.669”E | 269m | 275Km | 045° |
| B2(Road 1) | 07° 30.308”N | 004°31.639”E | 273m | 269Km | 100° |
| C2(Road 1) | 07° 30.542”N | 004°31.527”E | 271m | 270Km | 352° |
| C1(Road 1) | 07° 30.563”N | 004°31.549”E | 268m | 270Km | 330° |
| D1(Road 1) | 07° 30.752”N | 004°31.429”E | 282m | 271Km | 114° |
| D2(Road 1) | 07° 30.743”N | 004°31.401”E | 283m | 271Km | 279° |
| E (Gbooro Village) | 07° 32.675”N | 004°30.835”E | 275m | 320Km | 321° |
| F (Arowooogun) | 07° 33.569”N | 004°31.930”E | 266m | 5.3Km | 038° |
| G (Akeredolu) | 07° 34.581”N | 004°33.913”E | 297m | 9.7Km | 105° |
| H(Olorunda) | 07° 34.330”N | 004°32.891”E | 286m | 13.5Km | 023° |
| J (Kajola) | 07° 33.823”N | 004°33.073”E | 291m | 14.9Km | 245° |
| J(Ibagbe) | 07° 34.985”N | 004°32.053”E | 306m | 17.3Km | 099° |
| K(Aregbe) | 07° 35.014”N | 004°31.372”E | 268m | 18.2Km | 073° |
| L(Olukotun) | 07° 34.516”N | 004°30.736”E | 251m | 19.8Km | 008° |
| M(Elegon) | 07° 33.530”N | 004°30.575”E | 264m | 21.8 Km | 193° |
| N(Agbe) | 07° 33.315”N | 004°30.306”E | 274m | 22.6Km | 280° |

***Materials Collection***

Eighteen (18) soil samples were collected from different locations in Ife Central local government in Osun state, south western Nigeria. The samples were collected along known roads in built up area at intervals which was decided by the length of the road from which the sample was collected. The Geographical Positioning System (GPS) gave the co-ordinates, height relative to mean sea level of each location where soil could be collected for future reference.

**Equipment for Laboratory Tests**

The equipments used for the laboratory tests are the California Bearing Ratio (CBR) machine, Triaxial testing machine, Unconfined Compression Machine, West Africa compaction moulds and rammer, constant and falling head permeameters. Drying oven capable of maintaining a temperature of 1050C to 1100C, Glass weighing bottle, weighing balance, scoop, corrosion-resistant container, palette knives or spatulas, Casagrande Apparatus, grooving tool and gauge, wash bottle or beaker, rod of length of 3 mm in diameter, Test sieves, An evaporating dish, Sieve brushes, Sodium hexametaphosphate, mechanical sieve shaker, tray, filter material, measuring cylinders, calibrated thermometer, stopclock, and Silicone grease or petroleum jelly.All the laboratory test are conducted in accordance to [5]

***Development of correlation equations***

In the development of correlation equations, the independent variables i.e. Atterberg limits, moisture content, optimum moisture content, maximum dry density etc was extrapolated to obtain the dependent variables such as the shear strength, California bearing ratio. Soil samples in the same classification were grouped and analysed together. The validity of each functions developed was verified by coefficient of determination (R²). If it is 1, there is a perfect correlation between the sample or if it is close to 1, there is a strong relationship between the estimated value and the actual value. The software used in determining these functions was MATLAB.

1. **RESULTS**

***Locations of the Collected Samples***

The locations of the collected samples are shown in Table 2. For example sample A1 indicates that the sample was collected from OAU campus along road 1at positions 07°29.996΄N and 03°39.499΄E respectively from the reference point, it also indicates that it is 269m above mean sea level and 256km trip collected at about 10:20am.

***Determination of index properties and classification of the soil sample***

 The index properties that were determined from the laboratory tests are the liquid limits, plastic limits, plasticity index. Particle size analysis was carried out using the wet sieving method in order to carry out the effective classification of the soil sample.

***Results of Atterberg limit test***

The table of values for the atterbergs limit is presented in Table 3, the sample number as stated in Table 2

Table 3: Sample numbers and Atterberg limit values

|  |  |  |  |
| --- | --- | --- | --- |
| SAMPLE NO | LIQUID LIMIT | PLASTIC LIMIT | PLASTICITY INDEX |
| A1 | 36.1 | 24.74 | 11.36 |
| A2 | 31.7 | 20.49 | 11.21 |
| B1 | 33 | 20.90 | 12.10 |
| B2 | 25.8 | 17.91 | 7.89 |
| C1 | 35.25 | 25.48 | 9.77 |
| C2 | 36.3 | 25.53 | 10.77 |
| D1 | 31.6 | 25.49 | 6.11 |
| D2 | 33.8 | 20.42 | 13.38 |
| E | 30.65 | 14.47 | 16.18 |
| G | 35 | 14.32 | 20.68 |
| H | 26.2 | 35.88 | -9.68 |
| I | 46 | 43.28 | 2.72 |
| J | 29 | 10.66 | 18.34 |
| K | 29.74 | 23.04 | 6.70 |
| L | 20.15 | 19.71 | 0.44 |
| M | 32.6 | 15.32 | 17.28 |
| N | 20.65 | 16.00 | 4.65 |
|  |  |  |  |

***Results of soil classification test***

The values resulting from sieving each of the samples were used in classifying the soil samples by using the AASHTO classification system and the USCS classification system are shown in Tables 4 and 5.

***Determination of Moisture Density relationship of soil samples***

The moisture density relationship involves the optimum moisture content and the maximum dry density which is usually determined by the compaction test. It was determined by taking the dry density value at the peak of the curve while the optimum moisture content was determined by taking the moisture content value at the peak of the curve. The sample numbers and the corresponding values of the MDD and OMC are shown in table 6.

Table 4: The AASHTO classification of soil samples

|  |  |
| --- | --- |
| SAMPLE NO | AASHTO CLASSIFICATION |
| A1 | A-2-6 |
| A2 | A-2-6 |
| B1 | A-2-6 |
| B2 | A-2-4 |
| C1 | A-2-4 |
| C2 | A-2-6 |
| D1 | A-2-4 |
| D2 | A-2-6 |
| E | A-2-6 |
| G | A-2-6 |
| H | A-3 |
| I | A-2-5 |
| J | A-2-6 |
| K | A-2-4 |
| L | A-2-4 |
| M | A-2-6 |
| N | A-2-4 |

***Determination of engineering properties of soil***

In this research, the engineering properties carried out are the California bearing ratio and the undrained triaxial test. Both tests were carried out as described in chapter three of this thesis. The needed values from the tri-axial tests are that of the cohesion C and the angle of internal friction Φ. The values are used to plot a stress-strain graph and Mohr circle which is drawn from a graph of shear strength against normal stress. Table 7shows the sample numbers with the corresponding values of C and Φ.

1. **DISCUSSIONS**

***Correlations between various soil properties***

The predominant soil types encountered during this project are A-2-6 and A-2-4 according to AASHTO classification and the SP (poorly graded sand with gravel) and SW (well graded sand with gravel) according to Unified Soil Classification System. It was deduced while generating the correlation for SP (poorly graded sand with gravel) that there exist no correlation between the various index properties obtained in this report and the shear strength of the sample. The functions obtained produced a very weak coefficient of determination

 (i.e R²< 0.5) which indicates a very weak relationship between the estimated value and the actual value on the y-axis.

Table 5: The USCS classification of soil samples

|  |  |
| --- | --- |
| **SAMPLE** | **UNIFIED CLASSIFICATION (USCS)** |
| A1 | SW-SC (well graded sand with clay and gravel (or silty clay and gravel) ) |
| A2 | SP(poorly graded sand with gravel) |
| B1 | SC (clayey sand with gravel) |
| B2 | SC-SM (silty clayey sand) |
| C1 | SC (clayey sand) |
| C2 | SP-SC (poorly graded sand with clay (or silty clay) |
| D1 | SW (well graded sand with gravel) |
| D2 | SP (poorly graded sand with gravel) |
| E | SW (well graded sand with gravel) |
| G | SW (well graded sand with gravel) |
| H | SP (poorly graded sand with gravel) |
| I | SW (well graded sand with gravel) |
| J | SP (poorly graded sand) |
| K | SW (well graded sand) |
| L | SP (poorly graded sand with gravel) |
| M | SP (poorly graded sand with gravel) |
| N | SP (poorly graded sand with gravel) |

***Correlations for A-2-6 soil classification***

Various correlations were developed for this type of soil classification using the optimum moisture content, maximum dry density, liquid limit, plastic limit, plasticity index to obtain the value for the CBR and shear strength of the soil. The samples used were A1, A2, and C2.

1. **Correlation between optimum moisture content, plasticity index, CBR and shear strength.**

CBR = 0.5(OMC)² + (OMC)(PI) + 0.5(PI)² - 24.31(OMC+PI) + 295.86

 (R2=1) (1)

Ʈ = 0.021(OMC)² + 0.042(OMC)(PI) + 0.021(PI)² - (OMC+PI) + 12.022

(R2=1) (2)

OMC is the optimum moisture content (in %); PI is the plasticity index; CBR in KN and shear strength in KN/m3.

1. **Correlation between CBR and maximum dry density.**

CBR= MDD [0.252(MDD) – 1] + 0.993

(R2=1) (3)

Table 6: The sample numbers and the OMC and MDD values

|  |  |  |
| --- | --- | --- |
| SAMPLE NO | OMC | MDD |
| A1 | 13.5 | 1.94 |
| A2 | 11.5 | 2.09 |
| B1 | 15.5 | 1.91 |
| B2 | 11.6 | 1.68 |
| C1 | 12.5 | 1.95 |
| C2 | 15 | 1.885 |
| D1 | 9 | 2.045 |
| D2 | 9 | 2.05 |
| E | 11.5 | 1.955 |
| F | 16.5 | 1.93 |
| G | 11.2 | 1.98 |
| H | 12.5 | 1.64 |
| I | 8.4 | 2.085 |
| J | 11.5 | 1.68 |
| K | 10.8 | 1.72 |
| L | 7 | 1.84 |
| M | 14 | 1.635 |
| N | 7.5 | 2.085 |

MDD is the maximum dry density in Mg/m3; CBR in KN.

1. **Correlation between shear strength, maximum dry density and optimum moisture content.**

Ʈ = 0.3441 (OMC)² + 0.6882 (MDD)(OMC) + 0.3441 (MDD)² - (OMC + MDD) + 7.65

(R2=1) (4)

Ʈ is the shear strength in KN/m3; MDD is the maximum dry density in Mg/m3; OMC is the optimum moisture content in %.

1. **Correlation between optimum moisture content, liquid limit, plasticity index, CBR and shear strength.**

CBR = 0.00858[OMC² + OMC(LL+PI) + LL² + LL(OMC+PI) + PI² + PI(OMC+LL)] – (OMC+LL+PI) +29.162

(R2=1) (5)

Ʈ = 0.00867[OMC² + OMC(LL+PI) + LL² + LL(OMC+PI) + PI² + PI(OMC+LL)] – (OMC+LL+PI) + 28.956

(R2=1) (6)

|  |  |  |
| --- | --- | --- |
| SAMPLE NO | Cohesion(KN/m2) | Angle of internal friction(φ°) |
| A1 | 54.9 | 13 |
| A2 | 37.7 | 23 |
| B1 | 19.5 | 17 |
| B2 | 25.8 | 25 |
| C1 | 10.9 | 33 |
| C2 | 32.3 | 35 |
| D1 | 20.9 | 15 |
| D2 | 38.1 | 23.5 |
| E | 22 | 13 |
| G | 21.1 | 14 |
| H | 37.7 | 23 |
| I | 21.6 | 13.5 |
| J | 25.5 | 29 |
| K | 73.5 | 4 |
| L | 37 | 26 |
| M | 39 | 22 |
| N | 37.7 | 23 |

Table 7: The values of cohesion and angle of internal friction of the soil samples

OMC is the optimum moisture content (in %); LL is the liquid limit; PI is the plasticity index; CBR in KN; Ʈ is the shear strength in KN/m3.

1. **Correlation between maximum dry density and shear strength.**

Ʈ = MDD [0.03995(MDD) – 1] + 6.74

(R2=1) (7)

MDD is the maximum dry density in Mg/m3; Ʈ is the shear strength in KN/m3.

***Correlations for well graded soil with gravel soil classification***

The samples used for this correlation are D1, G, I, and E and the properties considered include optimum moisture content, plasticity index, plastic limit, liquid limit, maximum dry density, D60 to obtain the shear strength only.

1. **Correlation between optimum moisture content, plastic limit and shear strength.**

Ʈ = 0.3295 (OMC+PL) [1- 0.129(OMC+PL)] + 29.74

(R2=0.970) (8)

OMC is the optimum moisture content (in %); PL is the plastic limit; Ʈ is the shear strength in KN/m3.

1. **Correlation between maximum dry density and D60.**

Ʈ = 2.0335 (MDD+D60) [0.0836(MDD+D60) – 1] + 41.37

(R2=0.965) (9)

MDD is the maximum dry density in Mg/m3; D60 is the diameter at 60% passing from grain size distribution (in mm); Ʈ is the shear strength in KN/m3.

1. **Correlation between liquid limit, plasticity index and optimum moisture content and shear strength.**

Ʈ = 0.4513(OMC+LL+PI) [0.00813(OMC+LL+PI) – 1] + 48.96

(R2=0.993) (10)

OMC is the optimum moisture content (in %); LL is the liquid limit; PI is the plasticity index; Ʈ is the shear strength in KN/m3.

1. **Correlation between optimum moisture content, maximum dry density and shear strength.**

Ʈ = 10.705(OMC+MDD) [1- 0.0420(OMC+MDD)] – 27.57

(R2=0.874) (11)

Ʈ is the shear strength in KN/m3; MDD is the maximum dry density in Mg/m3; OMC is the optimum moisture content in %.

***Correlations for A-2-4 soil classification***

Samples used include B2, C1, K. The maximum dry density, optimum moisture content, liquid limit, plastic limit and plasticity index are the properties used to obtain the shear strength in various combinations.

1. **Correlation between liquid limit, optimum moisture content and shear strength.**

Ʈ = 219.4e-0.025(LL+OMC)

(R2=0.863) (12)

LL is the liquid limit; OMC is the optimum moisture content (in %); Ʈ is the shear strength in KN/m3.

1. **Correlation between optimum moisture content, maximum dry density and shear strength.**

Ʈ = 443.6e-0.925(MDD+OMC)

(R2=0.966) (13)

Ʈ is the shear strength in KN/m3; MDD is the maximum dry density in Mg/m3; OMC is the optimum moisture content in %.

1. **Correlation between maximum dry density and shear strength.**

Ʈ = 426.1e-0.96MDD

(R2=0.954) (14)

MDD is the maximum dry density in Mg/m3; Ʈ is the shear strength in KN/m3.

1. **Correlation between plasticity index, optimum moisture content and shear strength.**

Ʈ = 38.23 – PI + OMC

(R2=0.888) (15)

OMC is the optimum moisture content; PI is the plasticity index; Ʈ is the shear strength in KN/m3.

1. **Correlation between liquid limit, optimum moisture content, plastic limit and shear strength.**

Ʈ = 14.973(LL + PL + OMC)[1 – 0.00828(LL+PL+OMC)] – 366.6

(R2=1) (16)

OMC is the optimum moisture content (in %); LL is the liquid limit; PL is the plastic limit; Ʈ is the shear strength in KN/m3.

1. **CONCLUSION**

The following conclusion are made from this research work with respect to the objectives of the research:

* About 44.4% of the soil mass of the Ife central local government is poorly graded soil with gravel followed by 33.3% of well graded soil with gravel;
* Linear and non-linear relationships have been generated between various soils index and engineering properties through correlation analysis with its coefficient of determination (R) obtained;
* Poorly graded soil with gravel cannot be effectively correlated as indicated by their weak coefficient of determination;
* Correlations between various soil properties provide a time saving means of obtaining some engineering properties without carrying out any test in the laboratory.
1. **RECOMMENDATIONS**
* More samples should be collected in order to have a wider range of values to work with so that a more detailed and accurate correlations/functions can be developed;
* More engineering property test such as consolidation test, permeability, slope stability test, pile load test etc should be carried in order to have a detailed functions for all engineering properties.

**REFERENCES**

1. Bloemen, G.W., (1977). *Calculation of capillary conductivity and capillary rise from grain size distribution.* ICW Wageningen nota no. 952, 962, 990, 1013.
2. Bouma, J. and van Lanen, H.A.J., (1986). *Transfer functions and threshold values: from soil characteristics to land qualities*. In: *Quantified land evaluation procedures*, Proceedings of the international workshop on quantified land evaluation procedures, 27 April - 2 May 1986. Washington, DC.
3. Bouma, J. (1989). *Using soil survey data for quantitative land evaluation.* Advances in Soil Science **9**: 177–213.
4. Briggs, L.J. and McLane, J.W.(1907). *The moisture equivalent of soils*. USDA Bureau of Soils Bulletin 45, 1-23.
5. British Standard Institution (1990). *Methods of test for Soils for Civil Engineering Purposes*, BS 1377, Part 1-8.
6. Clapp, R.B., Hornberger, G.M., (1978). *Empirical equations for some soil hydraulic properties.* Water Resources Research 14, 601-604.
7. FAO (1990). *Guidelines for Soil Profile Description*, Food and Agricultural Organization of the United Nations, Rome. pp 70.
8. Grant Tranter, B. Minasny and A. McBratney (2006). *Trends in correlation equations research.* Pedometron No. 20.
9. Gupta, S.C., and W.E. Larson. (1979). Estimating soil water retention characteristics from particle-size distribution, organic matter percent, and bulk density. Water Resource. Res. 15:1633–1635.
10. Hall, D.G.M., M.J. Reeve, A.I. Thomasson, and V.F. Wright. (1977). *Water retention, porosity and density of field soils.* Soil Surv. Tech. Monogr. 9. Rothamsted Experimental Station, Lawes Agricultural Trust, Harpenden, UK.
11. Lamp, J. and Kneib, W., (1981). *Zur quantitativen Erfassung und Bewertung von Pedofunktionen.* Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 32, 695-711.
12. Nemes, A., J.H.M. Wösten, A. Lilly and J.H. Oude Voshaar (1999). *Evaluation of different procedures to interpolate the cumulative particle-size distribution to achieve compatibility of soil databases.* Geoderma 90: 187-202.
13. Salter, P.J., Williams, J.B.,(1965). *The influence of texture on the moisture characteristics of soils. A critical comparison for determining the available water capacity and moisture characteristics curve of a soil*. Journal of Soil Science 16, 1-15. \
14. Tomasella, J. and Hodnett, M.G. (1998). *Estimating soil water retention characteristics from limited data in Brazilian Amazonia*. Soil Science, 163 (3): 190-202.
15. Tinsley M., Mayer U., Gerard F.(2003). *Comparison of pedo-transfer functions in a field situation.* Geophysical Research Abstracts, Vol. 5, 03452, 2003 European Geophysical Society 2003
16. Wagner, B., Tarnawski, V.R., Hennings, V., Müller, U., Wessolek, G., Plagge, R., (2001). *Evaluation of pedo-transfer functions for unsaturated soil hydraulic conductivity using an independent data set.* Geoderma, 102, 275−297.
17. Wösten, J.H.M., (1997). *Correlation equations to evaluate soil quality*. In: Gregorich, E.G., Carter, M.R. (Eds.), *Soil Quality for Crop Production and Ecosystem Health. Developments in Soils Science*, vol. 25, Elsevier, Amsterdam, pp. 221−245.
18. Young, M.D.B., Gowing, J.W., Hatibu, N., Mahoo, H.M.F. and Payton, R.W. (1999). *Assessment and development of correlation equations for Semi-Arid Sub-Saharan Africa*. Physics and Chemistry of the Earth –European Geophysical Society (B), Elsevier Science Ltd. 24: 845-849.