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A Laboratory Investigation into the Effect of Confinement on the Dynamic Cone Penetration Index of a Lateritic Soil for Field Compaction Verification

by

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MASTER OF SCIENCE

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CERTIFICATION

I hereby declare that this submission is my own work towards the MSc and that, to the best of my knowledge, it contains no material previously published by another person, nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BS	British Standards
CBR	California Bearing Ratio

Dc	Cone Diameter
DCP	Dynamic Cone Penetrometer
Dm	Mould Diameter
DPI	Dynamic Cone Penetration Index
E_m	Existing Moisture
Es	Specific Energy
LC	Level of Compaction
ρ_{bulk}	Bulk Density
ρ_d	Dry Density
ρ_{dmax}	Maximum Dry Density
RSD	Relative Standard Deviation
USCS	Unified Soil Classification System
W_{opt}	Optimum Water Content
W_R	Required Water Content

ABSTRACT

The compaction quality control process may be simplified by introducing the Dynamic Cone Penetrometer (DCP) as a compaction verification tool. To use the DCP for this purpose requires a field calibration exercise. The calibration parameters κ, and λ and the magnitudes of the dynamic cone penetration index (DPI) are known to be influenced by many factors including soil type, density and moisture content. Due to the sensitivity of these parameters to the soil factors, a new calibration test has to be performed whenever there is a change in the material source. However, in-situ calibration test is tedious and time consuming and tend to decrease the attractiveness of compaction verification using DCP. To overcome this challenge, in-mould DCP is proposed. However, the influence of confinement provided by compaction moulds needs to be examined and quantified in order that the laboratory determined parameters may be used in the field. This research investigated the influence of horizontal confinement provided by the in-mould DCP on the DPI of a lateritic soil. The lateritic soil were compacted at the optimum water content using the modified AASHTO in seven moulds of nominal diameters of 100mm, 150mm, 200mm, 300mm, 400mm, 500mm and 600mm. For each mould, three levels of compaction ranging from 80% to 100% were performed. This was followed by conducting the in-mould DCP test with a DCP equipment of hammer mass 8kg in accordance with ASTM D 6951-03. From the study, it was found out that, for a given mould diameter, the DPI (mm/blow) reduced with increasing dry density. The effect of confinement was observed to increase as the mould diameters increases but from 500mm, the effect of confinement was insignificant. For the 500mm diameter mould the effect of confinement increases the DPI value in the CBR mould by 2.2. A relationship was developed between level of laboratory compaction and DPI that may be used for field compaction verification.

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CHAPTER 1: INTRODUCTION

1.1 Background Study

Residual soils such as laterites and lateritic soils have been a source of good pavement material in tropical countries for a long time. This is because they are readily available and relatively cheap. However, the satisfactory performance of road pavements built with these materials depend on the quality control measures taken during the construction phase. High levels of compaction which are associated with higher strength and minimum deformation lead to durable pavement layers. In road pavement construction, compaction quality control is typically done based on the ASTM Test Method for Laboratory Compaction Characteristics of Soil using Modified Effort of ASTM D 1557-91. The procedure for verifying the level of compaction is done by determining the in-place dry density achieved in the field and then comparing this value with the maximum dry density obtained in the laboratory using the Modified Proctor specification. There are several test methods that are used to determine the in-place dry unit weight and water content. These include sand cone (ASTM D 1556-90), rubber balloon (ASTM D 2167-94), drive cylinder (ASTM D 2937-94) and nuclear-moisture density gauge (ASTM D 2922-96).

For pavement quality control testing, the sand cone test and the nuclear gauge tests are the most applicable in Ghana. The nuclear gauge test is used mostly on large projects that are well funded. This is because it is hazardous and requires the use of highly trained personnel in protective clothing to operate. The sand cone method, however, is simple to operate and the commonest method preferred on low-volume roads. However, one key disadvantage of the sand cone method, aside being destructive to the pavement layers, is that, it is tedious and also requires a means of determining the water content of the compacted material on site so that the dry density can be determined quickly. This slows down the quality control operations beyond the desirable rate. Consequently, the quality control operation may not be done at all on small projects. The challenge with the water content may be overcome by the use of approximate but rapid methods such as the Speedy Moisture Tester (ASTM D 494489) and the Microwave Oven Method (ASTM D 4643-91). However, the whole compaction quality control process may be simplified by introducing the Dynamic Cone Penetrometer (DCP) as a verification tool for the levels of compaction being achieved on site.

The DCP is a simple hand-held device that provides a rapid, easy-to-operate, easy-to-understand and a non-destructive method for determining the strength profile of flexible pavements or the subgrade due to its ability to provide a continuous record of relative soil strength with depth. The DCP has been widely used by many agencies primarily to estimate the California Bearing Ratio (CBR) in-situ (Kleyn, 1975; Gabr et al., 2000). It has also been used to estimate the elastic modulus back calculated from the falling weight deflectometer test (De Beer, 1991; Cheng et al., 2001; Abu-Farsakh et al., 2005; Ampadu and Okang, 2011). Another application of the DCP is its use to predict the dry density achieved in lateritic soils in-situ (George et al., 2009; Jjuuko et al., 2015). It has also been proposed as a compaction verification tool (Gabr et al., 2000; Ampadu and Arthur, 2006).

1.2 Problem Statement

As a rapid compaction verification tool, Ampadu and Arthur (2006) proposed Equation (1.1) as the relationship between the level of compaction (LC) and the penetration per blow known as the dynamic cone penetration index (DPI).

$$\log(\mathrm{LC}) = \kappa - \lambda \log(\mathrm{DPI}) \qquad (1.1)$$

However, the calibration equation was determined in-situ and therefore the determination of the parameters of the equation also have to be done from in-situ testing. In the field, the calibration parameters κ, and λ and the magnitudes of the DPI are known to be influenced by many factors including soil type, (gradation and Plasticity Index), density and moisture content. Due to the sensitivity of these parameters to the soil factors, a new calibration test has to be performed whenever there is a change in the material source. However, in-situ calibration test is tedious and time consuming and tend to decrease the attractiveness of compaction verification using DCP.

However, the major problem with using results in the laboratory is that they are influenced by the confinement effect of the mould. Previous studies on the effect of confinement on the DPI by Gabr et al., (2001) and Nguyen and Mohajerani (2012, 2015) show that the confinement in the compaction mould (in this case in the CBR mould) has tremendous influence on the DCP test results when compared with those obtained in the field using the same penetrometer on the same soil. This study therefore seeks to investigate the influence of confinement provided by the mould on the DCP test results. The study will help develop a calibration equation from laboratory test that can be applied in the field.

1.3 Objective of Study

This study is part of a larger study which has the overall objective of developing in-mould DCP calibration equation for field application. It seeks to quantify the influence of horizontal confinement provided by the mould during inmould DCP test on the dynamic cone penetrometer index (DPI) of a lateritic soil.

The Specific objectives are to:

1. obtain the index and compaction characteristics of the lateritic soil.
2. manufacture moulds of different diameters spanning a range large enough to study the effect of confinement on DPI

3. perform in-mould DCP tests on the lateritic soil in these moulds at different dry densities and establish the relationship between the mould diameter and DPI.
4. investigate the effect of the different dry densities on the DPI values at the optimum moisture content.
5. establish a calibration equation between the DPI and the relative level of compaction.

1.4 Justification

The satisfactory performance of road pavements built with lateritic material depends on the compaction quality control measures taken during the construction phase. The compaction quality control process may be simplified by introducing the Dynamic Cone Penetrometer (DCP) as a compaction verification tool. However, the use of the DCP as a compaction verification tool requires a calibration equation which currently is established only in the field. But field calibration is tedious and time consuming so if the calibration can be carried out in the laboratory, then it will greatly simplify the compaction verification process, since laboratory testing is simple and rapid. It will then promote the use of the DCP for compaction verification and contribute towards facilitating compaction quality control and thus greatly improve the quality of earthworks.

1.5 Scope of Work

This research is a laboratory test conducted using one soil type (lateritic). The lateritic soil was compacted in varying mould diameters at levels of compaction between 80% and 100% of Modified AASHTO. Diameters for the compaction mould ranged from 100mm, 150mm, 200mm, 300mm, 400mm, 500mm and 600mm. The DCP equipment with 8kg hammer was used for this laboratory study.

CHAPTER 2: LITERATURE REVIEW

2.1 Lateritic Soils

2.1.1 Definitions of laterites

The soil name "laterite" was used by Buchanan (1807) to describe reddish, ferruginous, vesicular, unstratified and porous material found in Malabar, India. Since then many authors have defined laterites based on their properties such as the hardening property, chemical composition, mode of formation etc. For instance, Alexander and Cady (1962) defined laterite as "highly weathered material, rich in secondary oxides of iron, aluminium, or both. It is nearly void of bases and primary silicates, but it may contain large amounts of quartz and kaolinite. It is either hard or capable of hardening on exposure to wetting and drying". Gidigasu (1976) defined laterites as all reddish residual and non-residual tropically weathered soils which generally form a chain of materials forming from decomposed rock through clay to sesquioxide-rich crust. In the same year, the 6th Regional Conference for Africa on its special session on pedogenic materials said laterites are materials containing a minimum of about 50% of the cementing material (iron and aluminium oxides) and lateritic soils applies to materials containing less than 50% of the cementing material.

2.1.1.1 Formation of Laterites

Laterite is described as highly weathered and altered residual soils formed by the in-situ weathering and decomposition of rocks under tropical condition (Blight, 1997). The presence of the residual soils, mainly in the tropical and subtropical regions of the world, suggests that there are certain soil forming factors required for the formation and its abundance. These are the climate, vegetation, topography and parent rock.

The climate shapes the stratigraphy of the soil with regards to the depth of deposition of salts, the degree of surface desiccation and/or saturation (Gidigasu, 1988). Charman (1988) describes the climate requirement for the formation of laterites in a region as being a mean annual temperature of around 25^0 C with warm and wet periods. He suggested that the minimum annual rainfall required for laterite formation is generally 750mm and the higher the rainfall above this value, the greater is the leaching effect, which removes the silica, reduces the silica sesquioxide (S/R) ratio and, therefore, increases the proportion of gibbsite ($Al(OH)_3$). In the tropics, the occurrence of high vegetation covers reduces the rate of evaporation but provides organic matter for the formation of dissolved acids which give the low pH environment that accelerates weathering.

Gidigasu (1972) explained the formation of laterites in three stages. The weathering process begins when during the high and low temperatures, the activity of expansion and contraction results in cracks in the parent rock. The surface cracks serve as conduits for run-off water which percolates along the fractured zones. The water gets mixed with the unstable parent minerals in the rock. This chemically active water decomposes the rocks by making it permeable and isolates them into blocks of fresh materials. At this stage (primary weathering), the primary minerals are transformed to clay minerals especially those belonging to the kaolinite group.

In the second stage (secondary or laterisation), there is partial or complete leaching of bases and combined silica and the leaching effect is as a result of the extent and nature of the chemical weathering of the primary minerals. This leads to the crystallising out of the residue of oxides and hydroxides of the laterite constituents. The combined effect of upward suction of moisture to the surface in the dry season and drainage of rainwater over the gentle and moderate relief of the tropics remove the dissolved minerals (silica) of the parent rock in solution. The oxides of iron and aluminium (sesquioxides) remain in-situ because they have high resistance to leaching. The silica released in solution is transported away by the large amount of water percolating through the weathering zone. This results in relative accumulation of sesquioxides.

The last stage involves the dehydration and desiccation of hydrated colloids forming concretionary particles. Hence, laterite is predominantly found in low topographical reliefs of gentle crests and plateaus with little or no erosion of the surface cover. Figure 2.1 adopted after Ampadu (2015) shows the influence of the topography in the formation of laterite. The predominant minerals of the iron oxide are the limonite for lower slopes, goethite upper slopes and hematite for hill top. The predominant mineral for the oxides of aluminium at the summit of the hill is Gibbsite ($Al_2O_3 \cdot 3H_2O$).

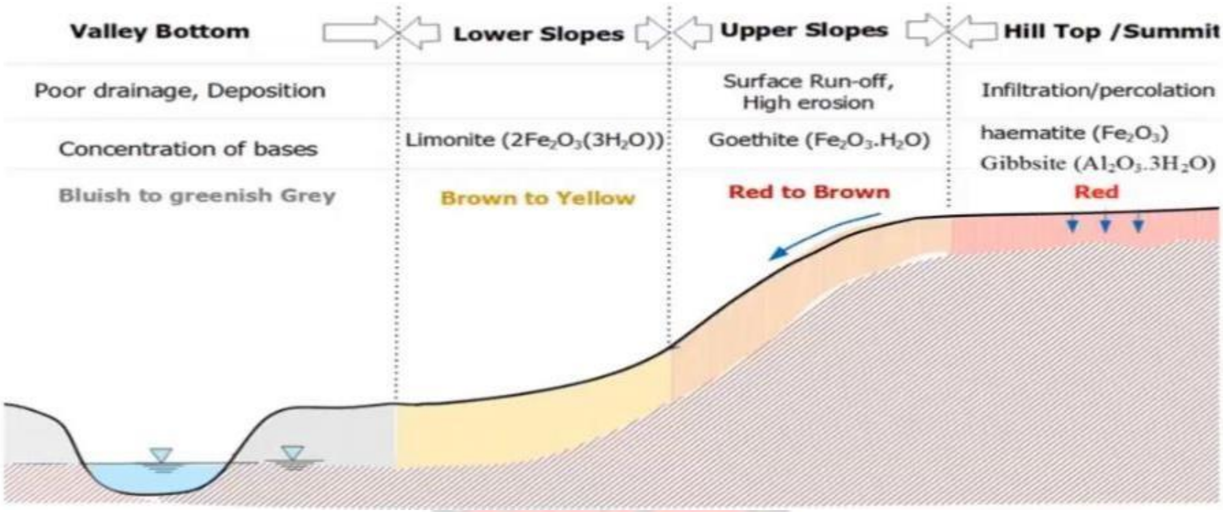


Figure 2.1: Topography and laterite formation (after Ampadu, 2015).

2.1.2 Characteristics of Laterites

By their mode of formation, laterites and lateritic soils are rich in iron and aluminium oxides. These oxides provide characteristic bonding between the soil particles. Manipulation and drying of these lateritic soils can lead to breakage of and/or irreversible changes in these bonds.

The Atterberg limits test are determined on completely remolded soil. However, due to the nature of formation of laterites, there exist strong microstructure between the particles. Therefore the use of conventional procedures unlike for temperate soils, may not entirely de-structure the soil hence yielding non

reproducibility of results. For lateritic soils, the type of pretreatment given to the soil prior to testing affect outcome of the results. The pretreatment include method of drying and degree of de-structuring (mixing time). The degree of mixing lead to a physical breakdown in the concretionary structures and results in inconsistent values in plasticity. Ampadu et al. (2015) suggested a mixing time of 45mins to produce reproducible results for plasticity index results as opposed to the conventional time of

10 mins in BS 1377-90. Similar effects of mixing on the Atterberg limits were reported by various authors such as Lyon Associates Inc (1971) and Abebaw (2005). The results of Atterberg limits test are sensitive to the method of drying prior to testing. Ampadu et al. (2015) reported that the drying method (as received (NMC), air dried (AD), oven dried (OD)) can influence the results. In the study, NMC samples, gave the highest Plasticity Index values while for normal levels of manipulation, OD samples gave the lowest values. Findings from the study affirms the recommendation in both ASTM D 4318-98 and BS 1377-1990 that pre-test drying of any form should not be used for lateritic soils for Atterberg limit determination. However, given the need to ensure that sample preparation procedures model as much as possible conditions pertaining to the field, with activities such as winning and stockpiling leading to some amount of air –drying of the materials; pretreatment procedure of air drying best models the field condition (De Graft Johnson and Bhatia, 1969).

2.2 Soil Compaction

Satisfactory performance of lateritic materials in road construction has been reported (Gidigasu and Dogbey, 1980). A key requirement of using lateritic soil is to ensure the material is well compacted. Compaction of soil is the process by which the solid particles are packed more closely together, usually by mechanical means, thereby increasing the dry density of the soil. The densification achieved depends on the degree of compaction applied and on the amount of water present in the soil (BS 1377: Part 4: 1990). The objective of the soil compaction test is to reduce the sensitivity of strength and volume changes to environmental changes, especially those affected by moisture. The compaction process also tends to increase the strength and bearing capacity and reduce the compressibility and permeability of the soil. The principal types of compaction efforts that are currently used in compaction test are the impact, the kneading and the vibratory types.

2.2.1 Field Compaction

Compactive effort may be by static, vibratory or combination of both. Static force relies on the dead weight of the equipment to apply downward force on the soil surface consequently compressing the soil particles. This approach is best suited for upper soil layers. Two examples of static compaction are kneading and pressure. Vibratory force however, uses mechanically driven force to create a downward pressure in addition to the equipment's static weight. This means different types of compaction are best suited for different soil types and conditions. As such based on the materials being compacted, a certain amount of force must be used because of the underlying density and moisture characteristics of different soil types as shown in

Figure 2.2.

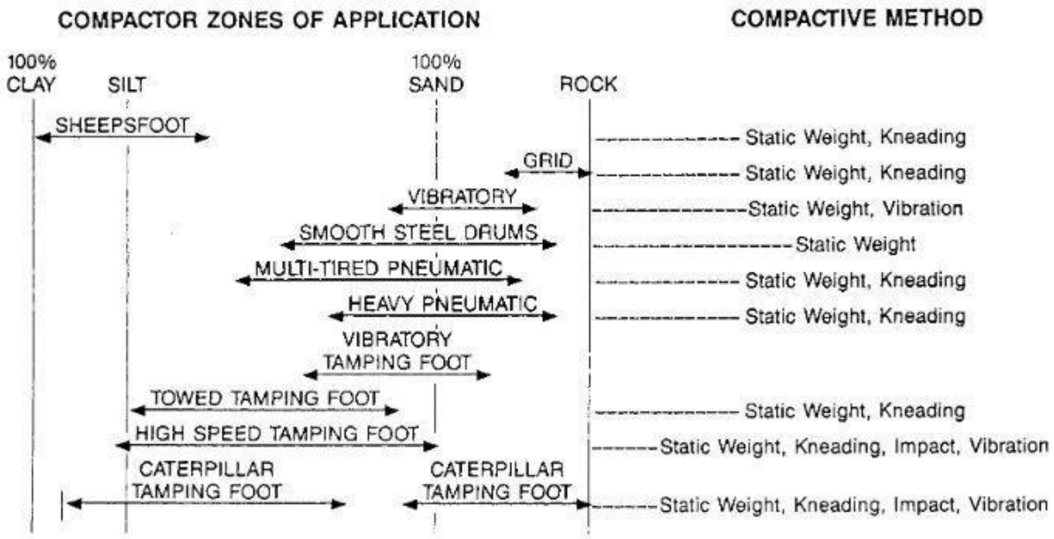


Figure 2.2: Compaction applications and methods (Parsons et al., 2001).

The selection of the type of compaction equipment depends on the soil type, degree of compaction and space available for compaction. Among the types of compaction equipment are roller compactors, vibratory plates, sheepsfoot compactors, etc, as shown in Figure 2.3. Smooth-wheel rollers are suitable for well graded sand, gravel, asphalt etc. They are of two types namely the static and vibrating smooth wheeled rollers. Pneumatic rubber-tired rollers give a better performance in many respects than the smooth-wheel rollers. They are suitable for coarse grained soils with some fines. The tyres are closely spaced four to six in a row. The tyres provide uniform pressure throughout the width of the roller giving 70 to 80% coverage. Sheepsfoot rollers are most effective in compacting fined grained soils such as clays and silty clays. They are of the static and vibratory. They are generally used for compaction of layers in projects such roads and rails but can also be use also for dams and embankments works. The compaction effort is maximum when the foot is vertical. Vibratory rollers are used in small areas (confined) and for compacting granular base coarse. They are sometimes used for asphaltic concrete work.

Smooth-wheel roller

Pneumatic rubber tired roller

Sheepsfoot roller

Vibratory plate

Figure 2.3: Different types of compaction equipment.

2.2.1.1 Factors affecting field compaction

Various other factors such as number of roller passes, thickness of lift, compaction energy level (CEL) etc., must be considered to achieve the desired level of compaction in the field. Field compaction control tests are specified, and the results of these become the standard for controlling the project. Tatsuoka (2015) reported on the effect of CEL on the compaction characteristics. From his study, an increase in the compaction energy level (CEL) associated with an increase in the number of passes (N=2, 4, 8, 16) of a compaction machine in the full-scale compaction tests resulted in an increase in the maximum dry density (ρ_{dmax}) with its corresponding optimum water content (w_{opt}) decreasing. He also reported that with an increase in the dry density (ρ_d) associated with an increase in CEL during compaction at a fixed w, the

CBR value increases until it becomes maximum at a point.

2.2.2 Laboratory Compaction Test

Laboratory compaction test provide the basis for determining the percent compaction and molding water content needed to achieve the required engineering properties, and for controlling construction to assure that the required compaction and water contents are achieved. The two commonest laboratory tests are standard Proctor compaction test (ASTM D 698-91) and modified Proctor compaction test (ASTM D 1557-91). In the Standard Proctor Test, the soil is compacted by a 2.5kg hammer falling freely through a distance of 305mm into a soil filled mould. The mould is filled with three equal layers of soil, and each layer is subjected to 25 drops of the hammer.

In the Modified Proctor Test, a 4.5kg hammer falling freely through a distance of 457mm, and uses five equal layers of soil instead of three. Each layer is compacted by 56 blows. The ratio of specific energy of Modified Proctor to Standard Proctor is 4.5.

2.2.2.1 Factors affecting the compaction test

The degree of compaction that can be achieved is affected by a number of factors namely soil type, water content and compactive effort. Different soil types have different specific gravities, grain-size distributions, shape of the soil grains, percentage and the type of fine content contained in them. These characteristics of the soil greatly influence the maximum dry unit weight and optimum moisture content expected.

Figure 2.4 shows the typical compaction curves obtained from four different soils.

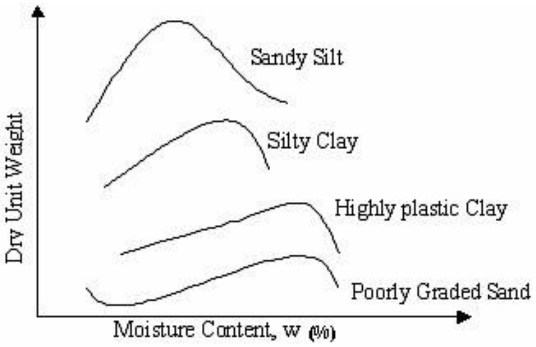


Figure 2.4: Typical compaction curves for four different soils (Guerrero, 2001).

Soils containing fines produce bell-shaped compaction curves as shown in Figure 2.4. An increment in the plasticity and percentage of fines gives a flatter compaction curve of relatively low maximum dry density and, therefore, less sensitivity to moisture content. For sands, the dry unit weight has a general tendency first to decrease as moisture content increases, and then to increase to a maximum value with further increase of moisture. Clays of high plasticity may have water contents over 30% and achieve similar densities (and therefore strengths) to those of lower plasticity with water contents below 20%.

Soil compaction has an applied energy which is measured by its specific energy value (E), which is the applied energy per unit volume. The ratio of specific energy of modified proctor to standard proctor is 4.5. When the energy per unit is increased, the maximum dry unit weight is also increased and the optimum water content is reduced. This is as shown in the Figure 2.5.

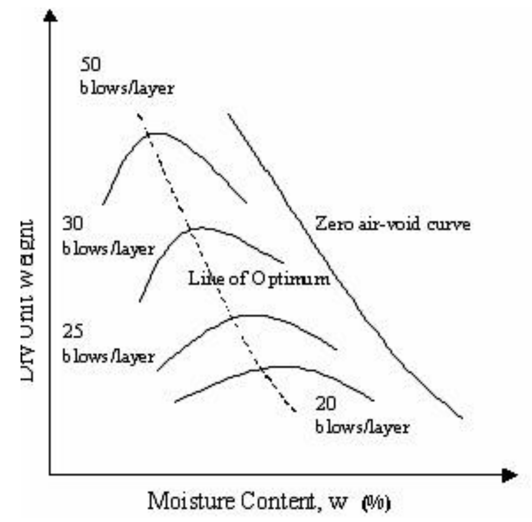


Figure 2.5: Effect of compaction energy on the compaction of sandy clay (Guerrero, 2001).

Addition of water to the soil increases it density and allows further compaction as a result of the lubrication effect the water has on the soil particles. This effect allows the particles to be compacted tightly together. At a certain moisture content further increase in moisture content will not result in further densification of the soil but would result in a reduction in density. Therefore, too much water in the soil will lead to low densification on compaction.

2.2.3 Effect of compaction on geotechnical characteristics of lateritic soils

Compaction is a very common soil improvement technique used in earthworks and in highway pavement construction. It is a design tool used in quality control during earthworks and pavement construction. Compaction parameters (ρ_{dmax} & w_{opt}) are determined in the laboratory. Sample preparation procedures for compaction test in the laboratory are known to affect ρ_{dmax} and the corresponding w_{opt} values. However depending on the climatic condition, different lateritic soils have different sensitivity to drying and to manipulation. Sample preparation of laterites for compaction were studied by several authors (Gidigasu, 1970; Lyon, 1971; Ababew, 2005; Ackah, 2014). Oven dried (OD) samples were found to give the highest ρ_{dmax} and lowest w_{opt} as compared to natural moisture content (NMC) and air-dried (AD) samples. Also reusing the sample for each compaction point gave slightly higher dry densities with corresponding low w_{opt} . However, the sample preparation by AD (simulate field condition) and fresh material for each point for establishing the moisture-density curve is recommended. This was attributed to coarse laterite particle becoming brittle when OD hence gravel disaggregate upon rolling and repeated traffic with resultant increase in fines leading to a change in the compaction characteristics used in the design. In term of CBR, the moisture content at the time of compaction is reported to have a critical influence on CBR results. The CBR values drastically reduces when the compaction is at a slightly higher than the w_{opt} (Lyon Associates Inc, 1971). For instance, (Gidigasu and Bhatia, 1971) reported that CBRs at w_{opt} are on the average about 50% higher than soaked CBRs of laterites at intermediate compaction.

2.2.4 Conventional methods of quality control

Compaction quality control assesses the level of compaction achieved as per the specification. The desired level of compaction is checked by computing the relative compaction. Relative compaction (RC) is the percentage of the maximum dry density obtained from the laboratory compaction test that is achieved in the field.

$$RC = \frac{\rho_d \text{ in the field}}{\text{maximum } \rho_d \text{ from the lab test}} \times 100\% \qquad (2.1)$$

Several different methods are used to determine the in-situ density of soil. They include Sand Cone Method (ASTM D 1556-90 or BS 1377-90), Rubber Balloon Method (ASTM D 2167-94 or BS 1377-90), Core Cutter Method (ASTM D 2937-94 or BS 1377-90) and Nuclear Density Gauge (ASTM D 2922-96 or BS 1377-90). For the kind of granular materials used in pavement layers in Ghana, the sand cone test is the most widely used to determine the in-situ density of compacted soil. The test is carried out in accordance with ASTM D 1556-90 or BS 1377-90. This method is said to be tedious and time consuming because at the start of the test, all construction activities nearby the test spot ceases (Krebs and Walker, 1971). It is also reported to measure the average compaction density for the top 150mm for the tested surface (Ampadu & Arthur, 2006).

The balloon density method is similar to the sand cone density method but less time consuming to perform. It is suitable for wide range of soils except those with large quantities of heavy gravel.

For cohesive or fine grained soils, the core cutter is used. The field density is determined by driving cylindrical cores of standard volume, diameter 100mm and diameter 130mm into the surface to be tested. The cutter is dug out and the soil trimmed to the size of cutter. The bulk density is determined knowing the weight and dimensions of the cutter.

The nuclear gauges provides a rapid, nondestructive and fairly accurate way of determining the in situ density and moisture content. It operates using two basic techniques, backscatter and direct transmission to determine the moisture content and density respectively. It works based on the source and detector at the soil surface (backscatter) or from a probe placed into the soil at a known depth up to 300mm (direct transmission). The isotope source (cesium 137) gives off photons (gamma rays) which radiate back to the detector on the bottom of the unit. Dense material absorbs the gamma radiation and acts as a radioactive shield resulting in a low reading and vice versa. The moisture content can also be read after a few minutes. Aside the test being hazardous and expensive, the direct transmission method is not a truly nondestructive method since an access hole is made in the surface to be tested and suited for cohesive and cohesionless materials. The backscatter density measurement also requires different calibration curves for all materials.

2.3 Dynamic Cone Penetration Test

2.3.1 Historical Development of DCP

The dynamic cone penetration test (DCPT) was originally developed as an alternative for assessing the properties of sub grade soils. In the conventional approach to evaluating strength and stiffness of sub grade soils, core samples are taken and subjected to laboratory testing. These tests are expensive and time consuming. To cut down on cost and time, the Dynamic Cone Penetrometer was developed in the mid1950s by Scala.

Scala developed the dynamic cone penetrometer based on an older Swiss original for evaluating the strength of subgrade soils and base and sub base of new and existing pavement structures (Scala, 1956). The penetrometer consisted of a 9kg mass dropping 508mm and driving a cone with a 30˚ point into the material being tested. A newer form of the DCP was designed in South Africa by Dr. D. J. Van Vuuren. The new version consisted of 30° cone, of mass 10kg dropping at a height of 460 mm (Van Vuuren, 1969). According to Van Vuuren (1969), the DCP is suited for use with soils having CBR values of 1 to 50. The DCP was further developed in South Africa by Kleyn (1975) of the Transvaal Roads Department. This is the present version of the DCP used in this study. The DCP device has been proven to be an effective tool in the assessment of in-situ strength of pavement layers and subgrade.

The present DCP device consists of an 8 kg sliding hammer falling a distance of 575 mm onto an anvil attached to the penetrometer rod, which drives a 60 steel cone located at the end of the long steel rod (Figure 2.6). The diameter of the cone and the rod are 20 mm and 16 mm respectively. The DCP design of the ASTM D6951-03 uses an 8-kg hammer dropping through a height of 575mm and a 60˚ cone. The characteristics of the different DCP apparatus are represented in Table 2.1. Table 2.1: Different types of the DCP equipment (modified after Nguyen & Mohajerani).

DCP design	Drop mass (kg)	Cone	Falling Height (mm)	Potential energy per drop (J)
Scala (1959)	8.0	60^0	575	45.1
Australian Standard	9.0	30^0	510	45.0
Van Vuuren (1969)	10.0	30^0	460	45.1
Kleyn (1975)	8	60^0	575	45.1
ASTM D6951-03	8.0	60^0	575	45.1

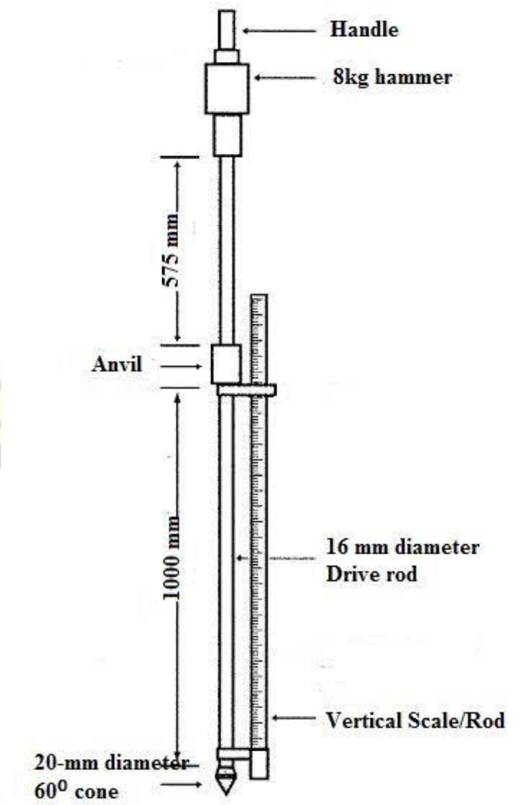


Figure 2.6: Dynamic Cone Penetrometer Equipment.

2.3.2 Definition of DPI

The DCP is positioned vertically on the surface of the material layer to be tested. The hammer is raised to the stop and dropped freely onto the anvil to drive the rod into the soil. The cumulative number of blows and penetration depth is recorded during the operation. The slope of the curve defining the relationship between the penetration depth and the cumulative number of blows is represented as the dynamic cone penetration index (DPI) in mm/blow (Figure 2.7).

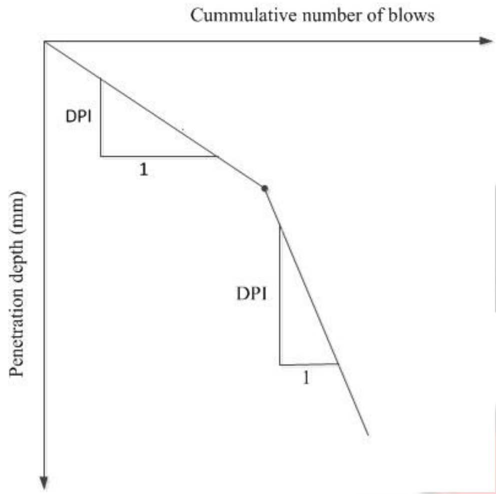


Figure 2.7: Typical DCP test results.

2.3.3 Principle & Theory

The principle of the dynamic cone penetrometer test is based on dynamic resistance offered by soil to deformation caused by dynamic penetrometer. The degree of the resistance is a measure of the soil's shear strength and hence its bearing capacity. The calculation of the dynamic resistance is based on the principle of conservation of energy (Sun et al., 2011; Minasny, 2012). The hammer (mass *M*) is lifted to height *h* and made to drop to produce an amount of kinetic energy, *W* (in J kg^{-1}), described as:

$$W = Mgh \qquad (2.2)$$

Where, g is the gravity acceleration constant (=9.81ms^{-2}).

The penetration resistance R_d (in kN/m^2) is then calculated as:

$$R_d = \frac{Mgh}{A\Delta z} \qquad (2.3)$$

A = cross-sectional area of the cone (m^2)

Δz = depth of penetration (m)

However, not all of this energy produced is transmitted to the soil at the impact (when the hammer hits the anvil) because both the hammer and the shaft move downward together into the soil. The energy equation was modified using the so-called “Dutch formula” (Sanglerat, 1972; Cassan, 1988). The soil resistance was calculated as follows:

$$R_d = \frac{Mgh}{A\Delta z}\,\frac{M}{M+m_s} \qquad (2.4)$$

m_s= mass of the shaft (kg)

2.3.4 Capabilities and Limitations of DCP

The advantages of the DCP are:

1. It is not expensive to acquire and can be manufactured locally from available materials.
2. It is portable and suitable and it is not restricted by space like the traditional boring equipment.
3. It is a simple, easy to operate device requiring at most three persons and does not take extensive experience to interpret results.
4. It provides continuous vertical record and repeatable results for subgrade characterization.
5. Because it is a rapid test, large amount of data can be gathered over wider area.
6. Many correlations have been established between the DCP and other expensive or time consuming parameters such as CBR, unconfined compressive strength, shear strength and SPT N-values.

Limitations of the DCP are:

1. Samples of subsurface material cannot be retrieved for either visual inspection or laboratory analysis.

2. It is not suitable for use in collapsible granular soils and highly plastic soils due to the lack of adhesion between the rod and soil.
3. The DCP has the problem of penetrating into gravel soils and hard formations such as highly weathering and fresh rock formations and may give erroneous results.
4. Information on the groundwater conditions at the test area becomes difficult.
5. The depth of penetration is limited as beyond a certain depth would require the use of lubrication between the hole and rod throughout the test.

2.3.5 Applications of dynamic cone penetrometer

Some applications of the DCP include correlations to CBR, shear strength, resilient modulus and performance evaluation of pavement layers and quality control of compaction of fill.

2.3.5.1 DCP-CBR

Different empirical relationships have been suggested between the DPI and CBR values. Two types of equation have been suggested for this correlation; log-log and Inverse. Thus the general form between the CBR and DPI is expressed below:

Log CBR: $\propto -\beta(logDPI)^{n}$ (2.5)

Inverse equation: $CBR = A(DPI)B + C$ (2.6)

Where CBR = California Bearing Ratio

DPI = Dynamic cone Penetration Index (mm/blow)

n = 1.00

∝, β, A, B, C = Regression constants for the relationships

The log – log equation was adopted after many statistical analysis as compared to the Inverse equation. Harison (1987) developed a theoretical explanation for the log-log equation using different soil. From his regression analysis, he concluded that the loglog model relates the DCP and CBR by giving a more reliable results than the inverse equation. Several authors including Kleyn (1975), Harison (1987), Livneh et al., (1992), Coonse (1999) and Gabr et al., (2000) based on the log-log equation have proposed different values for use for ∝ and β. Table 2.2 presents a summary of these correlations.

Table 2.2: DCP-CBR Correlations

Authors	Material tested	Correlation Equation	Testing Conditions
Kleyn (1975)	Different soil type	$Log(CBR) = 2.62 - 1.27 \log (DPI)$	Laboratory
Harison (1987)	Claylike Well-graded sand and Well-graded gravel	$Log(CBR) = 2.81 - 1.32 \log (DPI)$	Laboratory
Livneh et al (1992)	Granular and cohesive	$Log(CBR) = 2.45 - 1.12 \log (DPI)$	Field and Laboratory
Coonse (1999)	Piedmont residual soil	$Log(CBR) = 2.53 - 1.14 \log (DPI)$	Laboratory
Gabr et al (2000)	ABC	$Log(CBR) = 1.4 - 0.55 \log (DPI)$	Field and Laboratory

2.3.5.2 DCP-Shear Strength

Based on laboratory shear strength studies on granular soils, Ayers et al (1989) proposed the following relationship between DPI and deviator stress at failure:

$$\mathrm{DS} = \mathrm{A} - \mathrm{B(DPI)}$$

Where DS = Deviator stress at failure

A, B = regression coefficients

Mohammadi et al. (2008) proposed classification for estimating ϕ′from DPI. Based on direct shear test results, they proposed the following correlation between average DPI and effective angle $\emptyset'$.

$$\emptyset'(\mathrm{Deg}) = 52.16/(\mathrm{DPI})^{0.13} \quad (2.7)$$

2.3.5.3 DCP-Moduli

Several studies have been conducted to formulate correlation between DPI and different moduli such as the elastic modulus and resilient modulus. Chen et al (2001) proposed the following relationship between the DPI and back calculated FWD resilient modulus for values ranging from 10 and 60 mm/blow through regression analysis:

$$M_{FWD} = 338(DPI)^{-0.39} \quad (2.8)$$

Where M_{FWD} = FWD back calculated resilient modulus (MPa)

Another relationship was determined by Abu-Farsakh et al. (2005) between the DPI and back calculated FWD resilient modulus. The equation is of the form

$$\mathrm{In}\ (M_{FWD}) = 2.35 + \mathrm{In}\_\_\_\_\_\_ 5(.\mathrm{DPI}21\ ) \quad (2.9)$$

Ampadu & Okang (2011) developed models to predict the resilient modulus of subgrade and unbound material. The correlation coefficient was found to be poor for the relationship. The results gave the following:

$\mathrm{Log}\ M_R = 2.56776 - 0.82232 \log\ (\mathrm{DPI})$ (2.10) for subgrade soil

$\mathrm{Log}\ M_R = 3.12991 - 0.66116 \log(\ \mathrm{DPI})$ (2.11) for unbound materials

De Beer (1991) proposed a correlation between the DPI and Elastic modulus (Es) as it

$$\mathrm{Log}(E_s) = 3.05 - 1.07\mathrm{Log}(\mathrm{DPI}) \quad (2.12)$$

2.3.5.4 DCP-Compaction Properties

The qualities of the DCP as a rapid, nondestructive device has led to its wide acceptance as an effective tool to estimate strength characteristics of soils. The density and moisture content which define compaction and the application of DCP for compaction purposes have been studied by several authors. Harison (1987) conducted a study on the correlation of CBR and DCP strength measurement of soils and concluded that the lower the density, the higher the penetration rate (i.e. DPI increases). Patel & Patel (2012) also concluded from their study that increase in the dry density of soil results in decrease of the penetration resistance.

Application of DCP as a compaction verification tool has been proposed by many authors including Abu-Farsakh et al. (2005), Chaigneau et al., (2000), Gabr et al., (2000), Ampadu and Arthur, (2006) and Chen et al., (2001). According to Chen and Wang (2001), the DCP can be used to verify both the level and uniformity of compaction for layers tested, which makes it an ideal device for quality control in pavement construction. Salgado and Yoon (2003) established that a correlative equation for dry density and DPI can be used in DCP field tests to predict the in-situ dry density of clayey sand. The general form of the correlation between the level of compaction (LC) and the penetration rate denoted by the parameter DPI is given by

$$\text{Log (LC)} = \kappa - \lambda(Log(DPI)) \qquad (2.13)$$

Where, LC = level of compaction

DPI= dynamic cone penetration index

λ, κ = constants

2.3.6 Factors Affecting the DCP Results

Several investigations have been conducted on the factors that affect the DPI. Various factors namely soil type, density, gradation and moisture content are attributed to material factors and soil. Kleyn and Savage (1982) indicated that the moisture content, gradation, density and plasticity were important soil parameters influencing the DPI. Hassan (1996) reported that for fine grained soils factors such as moisture contents, soil classification, dry density and confining pressures significantly affect the DPI. For coarse-grained soils, coefficient of uniformity and confining pressures are important variables.

Ampadu & Fiadjoe (2015) performed a study on the influence of water content on the DPI stabilised with quarry dust and observed that the change in DPI with change in water content was non-linear and depended on the magnitude of the water content change relative to the optimum. They concluded that small changes in water content could lead to significant effects on DPI and that the fines content do not seriously affect the correlation equation for compaction verification. This means that small changes in material properties as is inevitable in the field may not seriously affect the correlation equation for compaction verification. This strengthens the case of the use of DCP for compaction verification.

In the case where the DCP device is not upright during its operation, the penetration resistance would be apparently higher due to side friction. The apparent higher resistance may also be caused when penetrating in a collapsible granular material. The effect has been found to be small in cohesive soils. Livneh (2000) suggested the use of a correction factor to correct the DCP/CBR values for the side friction effect.

2.3.7 Confinement Effect

Kleyn has been reported to be the first author to study the effects of confining effect of the mould on DPI. In 1975, he compared the results using a wide range of soil types among mould diameters 150mm, 200mm and 250mm. From his study, he observed confinement effect on the DPI using the 150 mm mould diameter against the 200mm and 250mm mould diameters. However, when results between the mould diameters 200mm and 250mm were compared, confinement effect on the DPI was negligible.

Livneh et al. (1995) conducted an engineering analysis and experimental testing in the laboratory and ·in the field to investigate the vertical confinement effect on dynamic cone penetrometer strength values in pavement and subgrade evaluations. The results have shown that there is no vertical confinement effect by rigid pavement structure of the upper granular layers, or the upper cohesive layers on the DCP strength values of lower cohesive subgrade layers. However, vertical confinement effects by the upper asphaltic layers in the DCP values of the granular pavement layers was observed. These confinement effects usually result in a decrease in the DCP values. In this case, the friction developed in the asphalt and granular layers resulted in decreased DCP value and therefore with indication of increased strength. Gabr et al., (2000) noted in their study that as the distance between the cone tip and the side of the mould increases from 75mm to 100mm, the DPI increase by up to 20%.

Abu-Farsakh et al., (2005) and Mohammadi et al., (2008) suggested negligible confining effect when the distance between the cone tip to the edge of the mould exceeds 250mm, implying a chamber to cone diameter ratio of 25. According to Mohammadi et al., (2008), the DPI increased with increasing mould size but there was no significant effect between the 500mm and 700mm moulds.

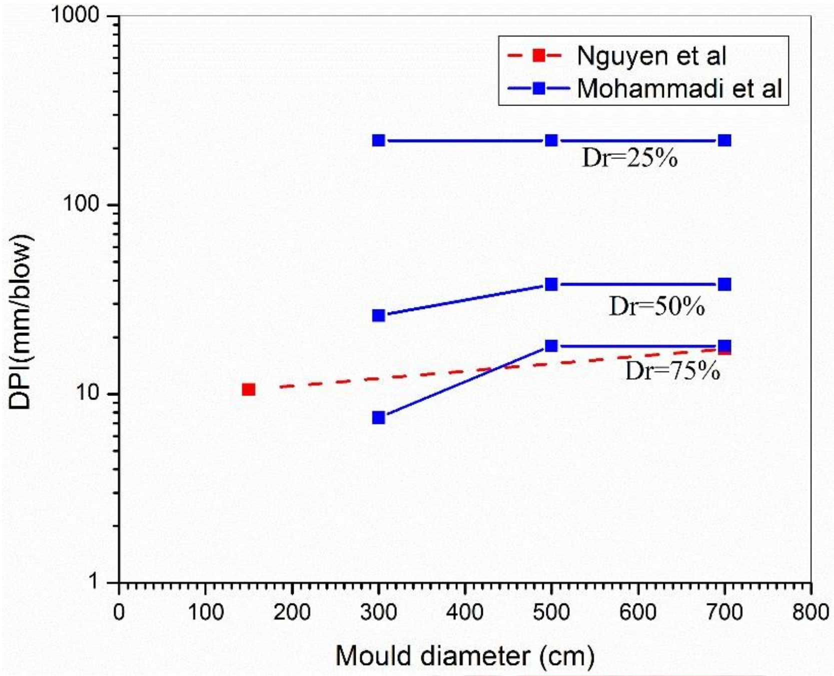
A study on the confining effect of the CBR mould on the DPI was investigated by Nguyen & Mohajerani (2012). DCP tests were performed on a fine grained compacted soil at the same moisture content and density in two different moulds of diameters 150mm and 700mm. The DPI value obtained was different for the two moulds and this was attributed to the difference in the mould diameter (i.e. confining effect of the mould). Ampadu & Fiadjoe (2015) in their investigations which builds upon previous work of using the DCP for compaction verification found out that when the in mould test results are compared to field data there is significant difference in the correlation equation. The discrepancies were attributed to the boundary conditions and the chamber to cone diameter ratios (i.e. confinement effect). In their study, the chamber to cone diameter ratio was 7.5. This therefore calls for the effect of confinement to be clearly defined if the in-mould test results are to be used directly in the field.

Conclusions from George et al. (2009) stated that a plot of DPI values against the penetration depth did not reveal evidence of the existence of any significant baseboundary effect in the experiments when a cylindrical test-box of diameter 450mm was used. Some values obtained from the references in Table 2.3 have been plotted on the relationship between the mould diameter and DPI. (see Figure 2.8).

Table 2.3: List of studies conducted on confinement and DPI.

Authors	Testing conditions	Material tested	Results
Kleyn (1975)	Laboratory and Field	Different soil types	Horizontal confinement
Livneh et al. (1995)	Laboratory and Field	Granular and Cohesive	Vertical confinement
Gabr et al. (2000)	Laboratory and Field	ABC*	Vertical confinement
Abu-Farshakh et al. (2005)	Laboratory and Field	Different soil types	Horizontal confinement
Mohammadi et al. (2008)	Laboratory	Sandy soil	Horizontal confinement
George et al. (2009)	Laboratory	Laterite soil	Horizontal confinement
Nguyen and Mohajerani (2012)	Laboratory	Fine grained soil	Horizontal confinement
Ampadu and Arthur (2006) Ampadu and Fiadjoe (2015)	Field Laboratory	Lateritic soil	Horizontal confinement

*Aggregate base course



Dr refers to relative density

Figure 2.8: A plot of confinement on DPI values.

CHAPTER 3: METHODOLOGY

3.1 Sample Collection and Preparation

The lateritic soil for the study was collected on the upper slope from two (2) trial pits of depth ranging from 0.5m-1.5m at the Faculty of Arts, KNUST. The site terrain slopes down towards a stream and rises gradually until becoming flat around the College of Engineering (COE). Major parts of the site area are covered with secondary vegetation. Plate 3.1 is a Google earth map of the location of the trial pits. The lateritic soil was air dried for about 5 days at room temperature, bagged and stored for use.

Plate 3.1: Layout of test location.

3.2 Sample Characterisation

3.2.1 Atterberg limits

Atterberg limit tests were carried out on (LL and PL), a representative portion of the bagged soil. The procedure given in BS 1377: Part 2 Clause 4.3 was the methodology employed. The sample was sieved through 0.425mm sieve. Cone penetration method was employed to determine the liquid limit as the method gives more reproducible results (BS 1377: part 2 clause 4.3.1).

3.2.2 Grain Size Distribution

A representative sample from the bagged soil was pulverized and screened through a nest of sieves. During the preparation stage, the sample was divided into three portions using sieve No.10 (2mm) and □□□m. Portions retained on 2mm and

□□□m were soaked in water separately and left overnight. The portion retained on the 2mm sieve was washed on the 2mm sieve and that on the 75µm was washed on the 75µm sieve. The washed samples were then oven dried and later sieved through a nest of sieves. Portions from the samples passing the 75µm was fetched for the Hydrometer test with sodium hexametaphosphate as the dispersing agent. The test was done in accordance with BS 1377-2 1990 Clause 9.

3.2.3 Specific Gravity

The specific gravity of the lateritic soil was determined as per BS 1377-2 1990 Clause 8.2, using the glass jar method. The soil sample was oven dried prior to the test and passed through riffling box. A representative sample was placed into two glass jars covered with their lids and weighed. Water was added to the soil and agitated to remove entrapped air. The glass vessels were placed on a level surface and left overnight. Afterwards, the water was topped to the brim and carefully slid with their lids and weighed. The soil sample was discarded and glass vessel washed clean.
Finally, the bottles were completely filled with water only and weighed plus their lids.

3.2.4 Compaction

Compaction was performed on the soil sample to determine its Maximum Dry Density (ρ_{dmax}) and Optimum Water Content (w_{opt}). The test procedure was done in accordance with BS 1377: Part 1990 specification. Compaction test was performed on the lateritic sample portion sieved through 19mm. Soil was mixed with water at water content increments of 3% on a tray. The mixture was compacted in a CBR mould of diameter 150 mm in five equal layers, applying 55 blows to each layer using the Modified Proctor rammer of mass 4.5 kg, falling freely over a height of 457mm. The moisture content before and after each cycle of compaction was determined.

3.3 Equipment

3.3.1 Fabrication of Moulds

Seven moulds were used for this study as shown in Plate 3.2. Five of the seven moulds were manufactured using 7mm thick mild steel plate as the moulding material prior to testing. The mould, base plate and collar were constructed for the individual mould diameters.

Plate 3.2: Equipment used for the study.

The newly-fabricated mould had nominal diameters of 200mm, 300mm, 400mm, 500mm, and 600mm. The 100mm and 150mm mould diameters used for this study were those referred to as the Standard Proctor and the CBR moulds, respectively. Table 3.1 presents the dimensions of the different moulds used during the investigation.

Table 3.1: Dimensions of moulds used in this study.

Mould diameter (mm)	Height (cm)	Volume (cm^3)
100	11.70	938

150	17.70	3170
200	21.10	6630
300	20.30	14833
400	30.20	36639
500	21.00	40745
600	32.00	90490

3.3.2 DCP Equipment

The characteristics of the DCP equipment used for the study are shown in Table 3.2. The DCP equipment used for this study is as shown in Figure 2.6. The DCP equipment met the specification of ASTM D6951-03.

Table 3.2: Basic data of DCP equipment used.

Total mass of equipment	14kg
Drop Hammer mass (M)	8kg
Height of fall (H)	575mm
Cone angle	60^0
Cone diameter	20mm
Cone base area (A)	$3.1416 \times 10^{-4} m^2$
Energy per blow per cone area ($kN\text{-}m/m^2$)	144

3.4 In-Mould Test

3.4.1 Sample Preparation by Compaction

Compaction test was performed in moulds of diameters 100mm, 150mm, 200mm, 300mm, 400mm, 500mm and 600mm to achieve three different densities corresponding to the ρ_{dmax}, 90% ρ_{dmax} & 80% ρ_{dmax} at w_{opt} . The procedure is as enumerated below. The equations used for obtaining the mass of soil and water were:

$$\gamma_d = \frac{\gamma_{bulk}}{1 + w_{opt}} \qquad (3.1)$$

$$W_{opt} = (w_R + E_m) \qquad (3.2)$$

Where, γ_d = dry density

γ_{bulk} = bulk density

w_{opt} = optimum water content

E_m = existing moisture content

1. Samples were taken from the bags and the existing moisture content (E_m) determined. Then the mass of water required to bring it to w_{opt} was determined as $w_R = (W_{opt} - E_m)$
2. The bulk densities (ρ_{bulk}) corresponding to the three target densities were calculated using the respective volume of mould and optimum water content. The mass of soil required to fill the mould was then computed. Typical computation for compaction in the 100mm diameter is shown in Table 3.3. The details of the other moulds are presented in Table E & F in Appendix II.

Table 3.3: Typical results for 100mm mould diameter based on the procedure adopted.

Mould ϕ (mm)	Height (cm)	Volume (cm^3)	Target $\frac{\rho d}{(\rho d)max}$ (%)	Actual ρ_d (Mg/m^3)	w_R (%)	ρ_{bulk} (Mg/m^3)	Mass of water	Mass of soil
100	11.70 11.70 11.70	938 938 938	100 90 80	1.836 1.656 1.468	14.17 14.17 14.17	2.119 1.907 1.696	268.53 241.68 214.83	1712.58 1541.32 1370.06

For $\rho_{d\,(max)}$ =1.85Mg/m^3, w_{opt} =15.68%, E_m=1.14%

3. The mass of soil sample calculated to fill each mould was then mixed thoroughly in a bowl (Plate 3.3) with the required water content (w_R) and stored in polythene bags to prevent loss of moisture (Plate 3.4).

Plate 3.3: Mixing of the lateritic sample.

Plate 3.4: Mixed sample store in polythene bags.

4. The bagged samples were left overnight to attain moisture equilibration throughout the sample.
5. Each mould height was measured and divided into five equal divisions and marked along its height.
6. The mass of sample was divided into five equal portions. The first portion was spread evenly into the mould (Plate 3.5) with the remaining portions covered to preserve moisture (Plate 3.6). Each layer was given blows from the 4.5 kg rammer falling over a height of 457mm until the layer height fills up to onefifth of the mould height (Plate 3.7). The number of blows required were recorded.

Plate 3.5: Pouring of determined mass of soil in mould to fill a layer of the marked mould height.

Plate 3.6: Covering of remaining portions of soil to preserve moisture.

Plate 3.7: Compaction of sample in the mould using the 4.5kg rammer.

Plate 3.8: Compacted sample in the mould.

7. The second and subsequent layers were equally placed and given the same number of blows.
8. The completed specimen was then levelled off to flush with the mould (Plate 3.8).

3.4.2 In-mould DCP test

1. At the end of compaction, the mould containing the compacted sample was turned upside down and clamped onto a wooden platform to absorb vibrations.

2. The DCP equipment was then assembled for testing in the mould with the tip of the cone placed centrally (Plate 3.9).

Plate 3.9: Position of the DCP cone centrally on the compacted sample.

Plate 3.10: Performing of in-mould DCP test.

3. The rod was held vertical and the 8kg hammer raised over the full height of 575mm and allowed to fall freely onto the anvil to drive the 20mm diameter cone through the compacted sample (Plate 3.10).
4. The penetration was recorded for each blow until the cone penetrated the approximate depth of the sample in the mould.
5. Samples were taken at the top, middle and bottom for water content determination.
6. The penetration was plotted against the cumulative number of blows to obtain the gradient called DPI.
7. This procedure was carried out in mould diameters 100mm, 150mm, 200mm, 300mm, 400mm, 500mm and 600mm.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Sample Characterisation

4.1.1 Index Properties

Results of the index properties tests have been summarized and presented in Table 4.1. Wet sieving of coarse fractions and sedimentation test by hydrometer method produced the grading curve shown in Figure 4.1. According to the Unified Soil Classification System, the material is a clayey sand. With the AASHTO classification system, the sample is a silt-clay material belonging to A-7-6(10). Soil belonging to this group is rated as a fair to poor subgrade. The soil was observed to be reddish to brown in colour and located on the upper slopes which suggests that the predominant mineral is goethite (Ampadu, 2015).

Table 4.1: Summary of index properties

Grading (%)				Atterberg Limits (%)			Specific Gravity	Classification
Gravel	Sand	Silt	Clay	LL	PL	PI	G_s	A-7-6(10)
13.67	42.14	18.88	25.31	51.64	17.97	33.68	2.66	

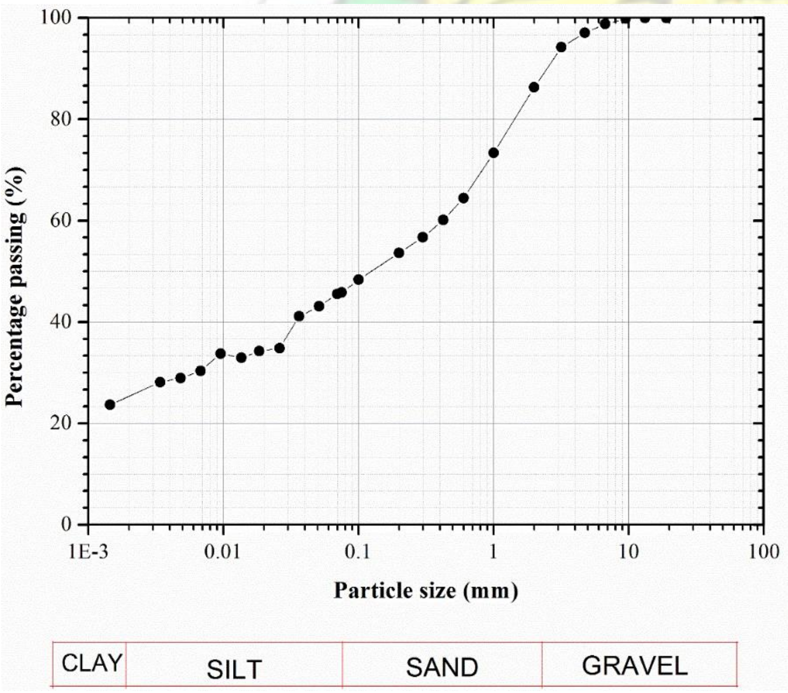


Figure 4.1: Grading characteristics of lateritic soil.

4.1.2 Compaction Characteristics

The compaction curve for the lateritic sample is shown in Fig 4.2. The compaction characteristics of the soil gave ρ_{dmax} of 1.85 Mg/m^3 and w_{opt} of 15.68%.

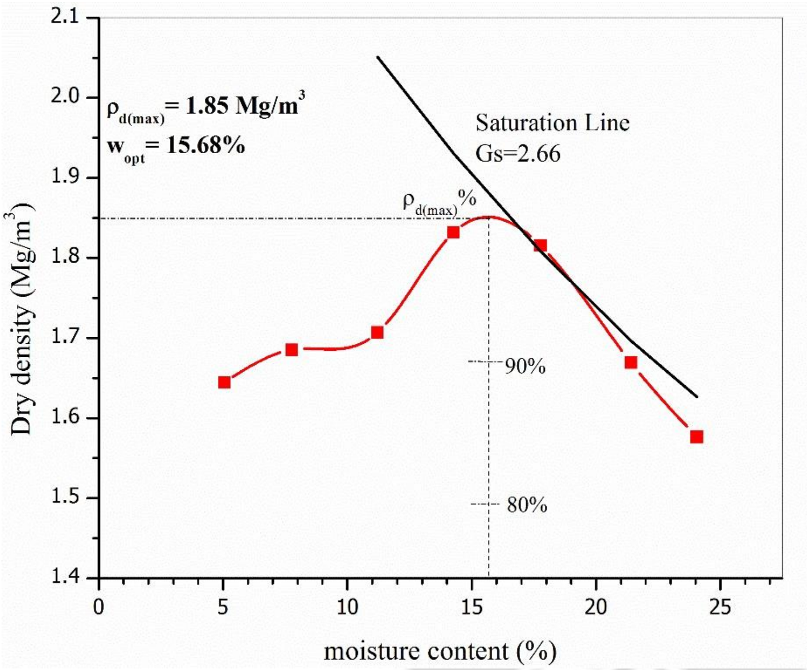


Figure 4.2: Moisture density relationship of the lateritic soil.

Compaction levels of 80%, 90% and 100% of the modified proctor maximum dry density at the optimum water content (w_{opt}) were used for the study. The dry densities corresponding to the levels of compaction are given in Table 4.2.

Table 4.2: Density range for the study at constant water content.

w_{opt} (%)	100% ρ_{dmax} (Mg/m^3)	90% ρ_{dmax} (Mg/m^3)	80% ρ_{dmax} (Mg/m^3)
15.68	1.850	1.665	1.480

4.2 Uniformity of Test Samples

4.2.1 Variation of the water content

The test preparation objective was to prepare the samples at w_{opt}. The values of the moisture content at the top, middle and bottom are shown in Table 4.3-4.5. A statistical analysis of the water content was done within the sample for the different moulds as shown in the tables. The analysis was examined using the relative standard deviation (RSD), defined as the standard deviation divided by the mean expressed as a percentage.

Table 4.3: Water content variations within test sample for LC 100%.

Test location	Mould diameters (mm)						
	100	150	200	300	400	500	600
Top	15.25	15.66	14.87	15.34	14.58	15.27	15.52
Middle	15.65	15.34	15.68	15.46	15.31	15.77	15.66
Bottom	15.48	16.02	15.13	14.90	15.14	15.43	15.49
Mean	15.46	15.67	15.23	15.23	15.01	15.49	15.56
Standard deviation	0.20	0.34	0.41	0.29	0.38	0.26	0.09
Relative standard deviation	1.30	2.17	2.72	1.94	2.54	1.65	0.58

Table 4.4: Water content variations within test sample for LC 90%.

Test location	Mould diameters (mm)						
	100	150	200	300	400	500	600
Top	16.82	15.62	15.23	14.09	14.24	17.19	15.50
Middle	14.50	15.80	15.20	15.08	15.08	15.59	15.85
Bottom	14.14	15.10	16.09	14.13	15.84	15.11	15.87
Mean	15.15	15.51	15.51	14.43	15.05	15.96	15.74
Standard deviation	1.45	0.36	0.51	0.56	0.80	1.09	0.21
Relative standard deviation	9.60	2.34	3.26	3.88	5.32	6.82	1.32

Table 4.5: Water content variations within test sample for LC 80%.

Test location	Mould diameters (mm)						
	100	150	200	300	400	500	600
Top	15.89	15.89	14.93	15.55	13.72	15.46	15.98
Middle	15.20	15.71	15.50	15.50	15.57	15.89	15.53
Bottom	15.71	15.20	15.38	15.43	14.93	15.65	15.42
Mean	15.60	15.60	15.27	15.50	14.74	15.67	15.64
Standard deviation	0.36	0.36	0.30	0.06	0.94	0.22	0.30
Relative standard deviation	2.29	2.29	1.97	0.39	6.37	1.38	1.90

The results show that the RSD values were less than 10%. Infact, apart from three samples, the values were all less than 4%. Hence the variation in water content of the individual samples for the different mould diameters may be considered low. The objective of the test preparation was also to prepare the test samples at the optimum water content. Tables 4.6-4.8 presents the average water contents in each of the test samples. These tables also compare the deviation of the average water content from the w_{opt} (i.e. water content change (w-w_{opt})) for the different samples in the different mould sizes. The values of the w-w_{opt} may be negative or positive. A negative value means the current sample is on the dry side of optimum and positive value when it is on the wet side.

Table 4.6: Comparison of water content across the different test samples for LC 100%.

Test location	Mould diameters (mm)						
	100	150	200	300	400	500	600
Mean	15.46	15.67	15.23	15.23	15.01	15.49	15.56
w_{opt} (%)	15.68	15.68	15.68	15.68	15.68	15.68	15.68
w-w_{opt} (%)	-0.22	-0.01	-0.45	-0.45	-0.67	-0.19	-0.12

Table 4.7: Comparison of water content across the different test samples for LC 90%.

Test location	Mould diameters (mm)						
	100	150	200	300	400	500	600
Mean	15.15	15.51	15.51	14.43	15.05	15.96	15.74
w_{opt} (%)	15.68	15.68	15.68	15.68	15.68	15.68	15.68
w-w_{opt} (%)	-0.53	-0.17	-0.17	-1.25	-0.63	0.28	0.06

Table 4.8: Comparison of water content across the different test samples for LC 80%.

Test location	Mould diameters (mm)						
	100 mm	150 mm	200 mm	300 mm	400 mm	500 mm	600 mm
Mean	15.60	15.60	15.27	15.49	14.74	15.67	15.64
w_{opt} (%)	15.68	15.68	15.68	15.68	15.68	15.68	15.68
w-w_{opt} (%)	-0.08	-0.08	-0.41	-0.19	-0.94	-0.01	-0.04

Even though the sample was conditioned at the w_{opt}, most of the samples returned a small negative (w-w_{opt}) value suggesting some inevitable drying during the test preparation procedures. Conversely, the largest negative value, smaller than 1.25% dry of the optimum was observed for test T-300-90 i.e. test in 300mm mould at 90% level of compaction. The water content for test series T-400 i.e. test in the 400mm mould consistently decreased from 0.63% to 0.94% below the optimum. Apart from these two cases, the deviations from the w_{opt} may be considered small.

4.2.2 Specific Energy (Es)

4.2.2.1 Effect of mould diameter on compaction energy

The specific energy, Es, is defined as the applied energy per unit volume of the soil in the mould. For a mould of diameter D, and length, L, filled in n layers, with each layer receiving N blows of a 4.54kg rammer falling from a height of 0.457m height, the specific energy is given by Equation (4.1). The detailed computation for all moulds and at each of the three levels of compaction is shown in Table C in Appendix II. Typical results of the computation of Es at LC of 100% is shown in Table 4.9. The

Es thus computed is plotted against the nominal diameter of the mould in Figure 4.3.

$$Es = \frac{N \times n \times W \times H}{V} \qquad (4.1)$$

N= Number of Blows per layer n=

Number of Layers

W= Weight of Hammer

H= Height of Drop of Hammer

V= Volume of Mould

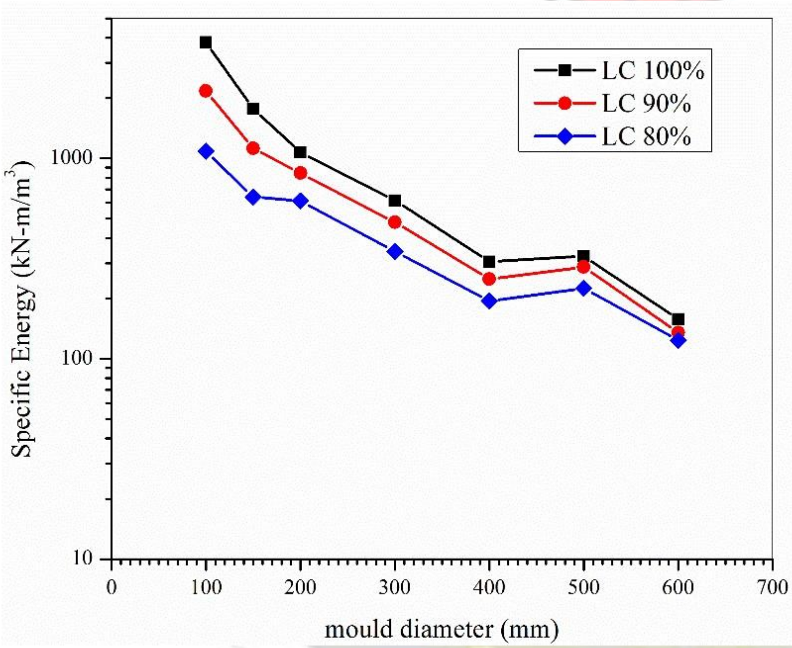


Figure 4.3: Effect of mould diameter on specific energy.

Table 4.9: Typical results of specific energy for LC of 100%.

Nominal Mould Diameter (mm)	No of Blows	Volume of Mould (m^3)	Specific Energy ($kN\text{-}m/m^3$)
	N	V	E
100	35	0.0009375	3799.31
150	55	0.0031701	1765.63
200	70	0.0066296	1074.53
300	90	0.0148334	617.464
400	110	0.0366385	305.538
500	130	0.0407454	324.695
600	140	0.0904896	157.449

The results in the table shows that in order to achieve the same dry density, the number of blows per layer increases as the mould diameter increases. It is observed that the specific energy required decreases as the mould diameter increases for all levels of compaction. This is because the larger the diameter of the mould, the less energy required per unit volume of the mould to force the soil into the mould.

4.2.2.2 Effect of energy on density

Figure 4.4 presents the relationship between the level of compaction and specific energy on logarithmic scale (i.e.ρ_d/ρ_{dmax})-log (Es) for the different mould diameters. The relationship is linear with a strong correlation coefficient of 0.91-1.00.

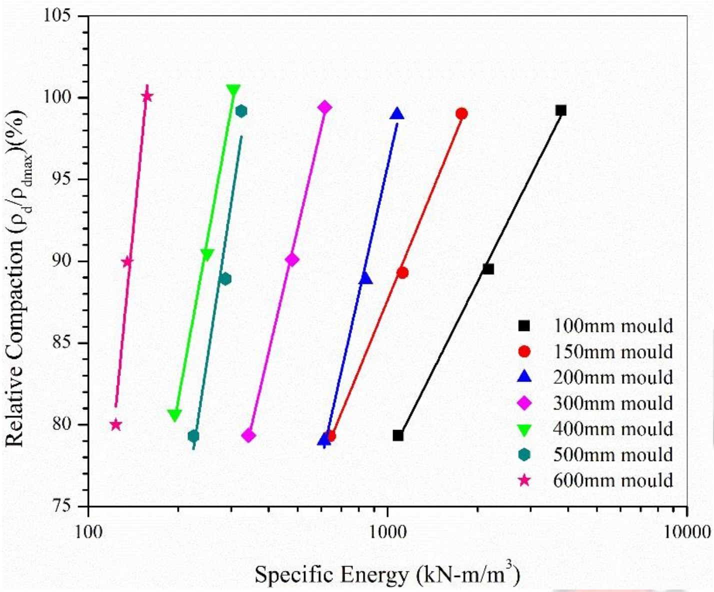


Figure 4.4: Effect of specific energy on density.

For each mould diameter, the plot indicates the effect of specific energy on the density. The rate of increase in the level of compaction with increase in specific energy (i.e. the gradient) was found to increase with increasing mould diameter. This suggest that the influence of specific energy on the density diminishes as the diameter increases.

4.3 In-Mould DCP Test

4.3.1 Blows-Penetration Plots

The results of the penetration were plotted against the cumulative number of blows. The plots are shown in Appendix II. The blows-penetration plots were also used as a check for the uniformity of sample in each mould since in the DCP test, uniform sample produces linear cumulative blows-penetration plot. Typical cumulative blowspenetration plots are shown in Figure 4.5-4.6 for 100mm and 600mm diameters. The DPI values, defined as the gradient of the cumulative number of blows-penetration curve are indicated in the plots. Examining the plots, small deviations were found at the top and bottom of the sample which suggested that the largest non-uniformity was at the top and bottom. The coefficient of regression which is an indicator of the fit quality obtained for the plots also produced values ranging from 0.98-1.00. This indicates very good uniformity of density for the compaction at the sample preparatory stage and hence very high degrees of uniformity achieved.

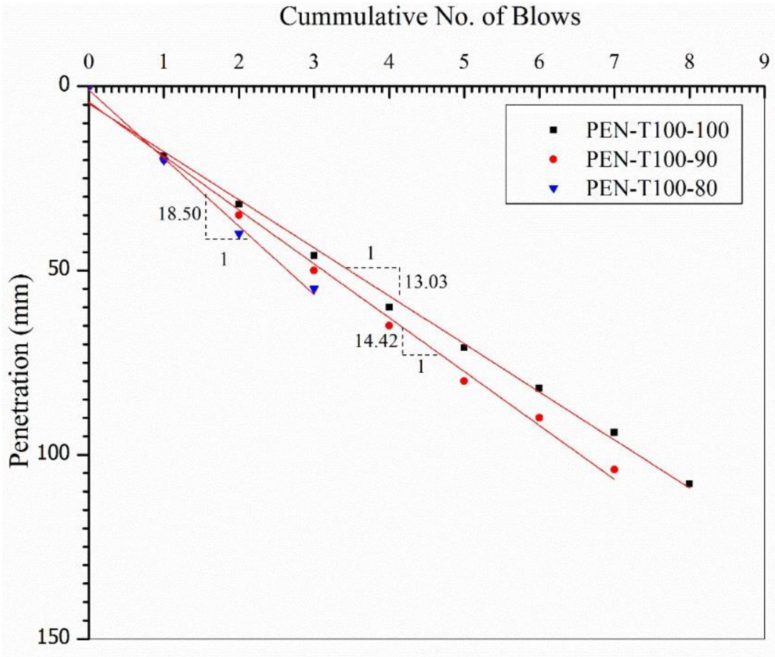


Figure 4.5: Cumulative blows-penetration plots for 100mm mould diameter.

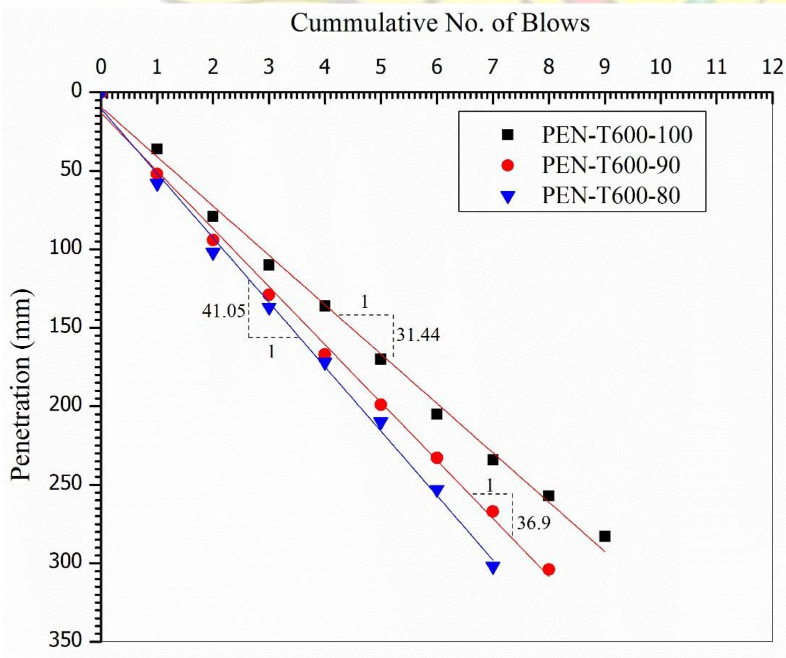


Figure 4.6: Cumulative blows-penetration for 600mm mould diameter.

The effect of density on the DPI at relatively constant water content can be appreciated in the plots. It is observed that as the density decreases, the plots get steeper and the

DPI value increases. Steeper plots are characteristics of materials with fewer number of blows hence easy penetration.

The relative compaction(ρ_d/ρ_{dmax}) was also obtained by dividing the dry densities obtained for each test by the maximum dry density ρ_{dmax} determined from standard laboratory compaction test. These values were measured against the three targets(ρ_d/ρ_{dmax}) values of 100%, 90% and 80%. The actual(ρ_d/ρ_{dmax}) values varied between 79% and 101%. Many factors could account for the variations. The values (ρ_d/ρ_{dmax}) deviate from the target values because of the water content variations from the w_{opt} value. The influence of the path of the water content for lateritic soil may make a difference for instance if the water content is added incrementally to the same soil during compaction or, the water is added to a fresh sample. This is explained by Ackah et al., (2015) and Ampadu & Fiadjoe (2015) that using fresh samples as was done in this study gives a lower ρ_{dmax} with corresponding w_{opt} compared with sample reuse.

Table 4.10: In-mould DCP test results.

Mould Diameters (mm)	Test No.	ρ_d (Mg/m^3)	Average Water Content (%)	Relative Compaction (%) (ρ_d/ρ_{dmax})	DPI (mm/blow)
100	T100-100/1	1.836	15.46	99.24	13.03
	T100-90/1	1.656	15.15	89.51	14.62
	T100-80/1	1.468	15.55	79.35	18.50
150	T150-100/1	1.832	15.67	99.03	14.35
	T150-90/1	1.652	15.51	89.30	16.33
	T150-80/1	1.467	15.60	79.30	20.00
200	T200-100/1	1.831	15.23	98.97	15.4
	T200-90/1	1.644	15.51	88.86	18.06
	T200-80/1	1.462	15.44	79.03	21.43
300	T300-100/1	1.839	15.23	99.41	19.89
	T300-90/1	1.667	14.43	90.11	21.73
	T300-80/1	1.468	15.50	79.35	25.4
400	T400-100/1	1.86	15.01	100.54	22.93
	T400-90/1	1.674	15.05	90.49	26.53
	T400-80/1	1.492	14.74	80.65	30.2
500	T500-100/1	1.835	15.49	99.19	31.57
	T500-90/1	1.645	15.96	88.92	36.63
	T500-80/1	1.467	15.56	79.30	40.8
600	T600-100/1	1.852	15.56	100.11	31.44
	T600-90/1	1.664	15.74	89.95	36.9
	T600-80/1	1.480	15.64	80.00	41.05

4.3.2 Relationship between the mould diameter and DPI

As a calibration chamber test, the in-mould DCP results were affected by the boundary conditions and the chamber to cone diameter ratios. Figure 4.7 shows a plot of DPI against the ratio of mould diameter (Dm) to cone diameter (Dc) for all the test results.

DCP tests conducted by researchers such as Kleyn (1975) and Gabr et al. (2001) reported that as the mould-to-cone ratio increases from 7.5 to 10, the DPI increases by up to 20%. Again, from the study by Nguyen & Mohajerani (2012) focusing on a DCP equipment of 8kg, the DPI was found to increase from 10.55 to 17.31 mm/blow as the mould-to-cone ratio increased from 7.5 to 35. For this study, moving from a CBR mould with a mould to cone ratio of 7.5 to a mould with mouldto-cone diameter ratio of 25, (i.e. for the same water content and levels of compaction) the DPI increased by about two fold. This suggests very large effect of confinement. This means, as the chamber-to-cone ratio increases, the restriction provided by the sides of the mould reduces hence the soil particles moves further apart. This movement of the particles tends to reduce the ability of the soil to resist penetration thereby allowing the cone to penetrate deeper accounting for the larger DPI values.

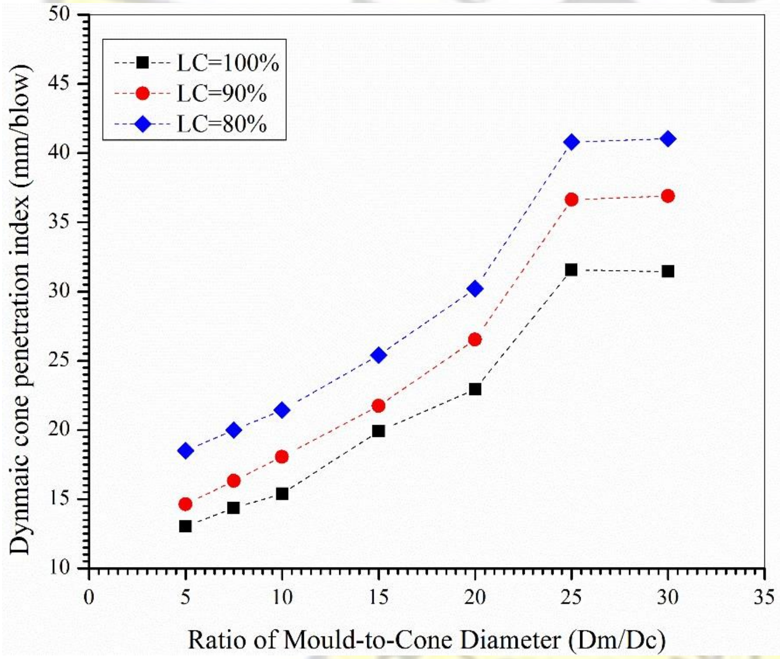


Figure 4.7: Relationship between DPI and Mould diameter.

From mould-to-cone diameter ratio of 25, the DPI was observed to be almost constant for all the levels of compaction. This suggests that beyond this point, the influence of confinement is insignificant. Researchers such as Abu-Farsakh et al. (2005) and Mohammadi et al., (2008) have suggested negligible confining effect when the distance between the cone tip and the side of the mould exceeds 250mm, implying a mould-to-cone ratio of 25.

4.3.3 Effect of density on DPI

Figure 4.8 shows plots of DPI values against densities. The relationships were linear with different values of gradients increasing from 14.91 to 25.84 mm/blow Mg/m^3 as the mould diameter increases from 100 to 600 mm. High coefficient of regression values lying between 0.90-1.00 were obtained indicating very good linear fit for each set of data points. The statistical data is presented at Table B in Appendix II. The results show that for a given mould diameter, the DPI reduces with increasing dry density. Also for a given dry density, the DPI increases as the mould diameter increases.

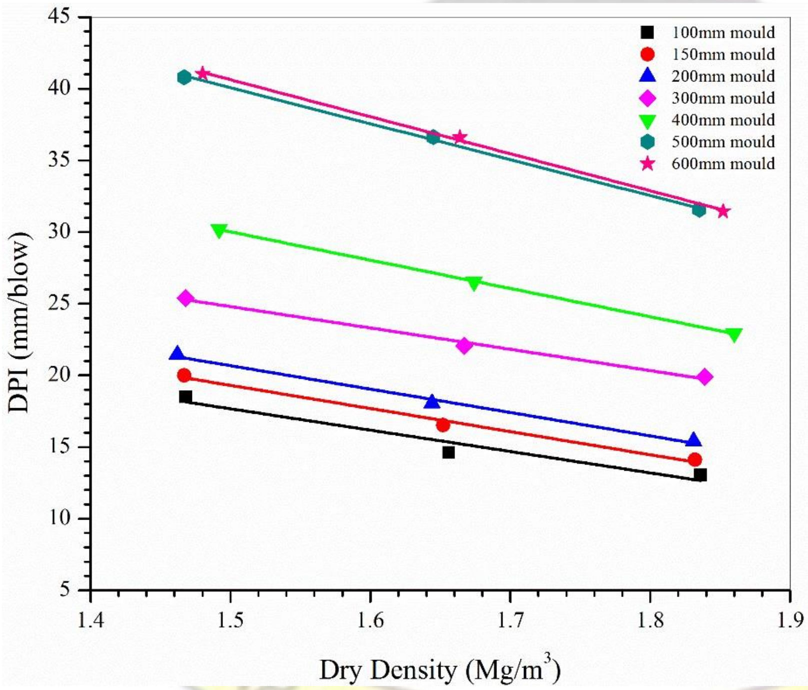


Figure 4.8: Effect of density on DPI.

The observation that an increase in density of the soil, results in decreasing DPI was also reported by Harison (1987), Hassan (1996) and Patel & Patel (2012).

4.3.4 Relationship between the relative compaction and DPI

The relation in terms of relative compaction and DPI is examined in detail. Ampadu and Arthur (2006) proposed Equation (4.2) as the relationship between the level of compaction $\frac{\rho d}{(\rho d)max}$ and DPI for levels of compaction varying between 79% and 101%.

$$\log \frac{\rho_d}{(\rho_d)_{max}} = \kappa - \lambda \, Log(DPI) \qquad (4.2)$$

In equation (4.2), λ is a measure of the rate of change of the level of compaction with DPI (i.e. the gradient) and □ is the intercept on the $\log(\rho_d/\rho_{dmax})$ when DPI =1.

The results of this study have also been plotted in Figure 4.9.

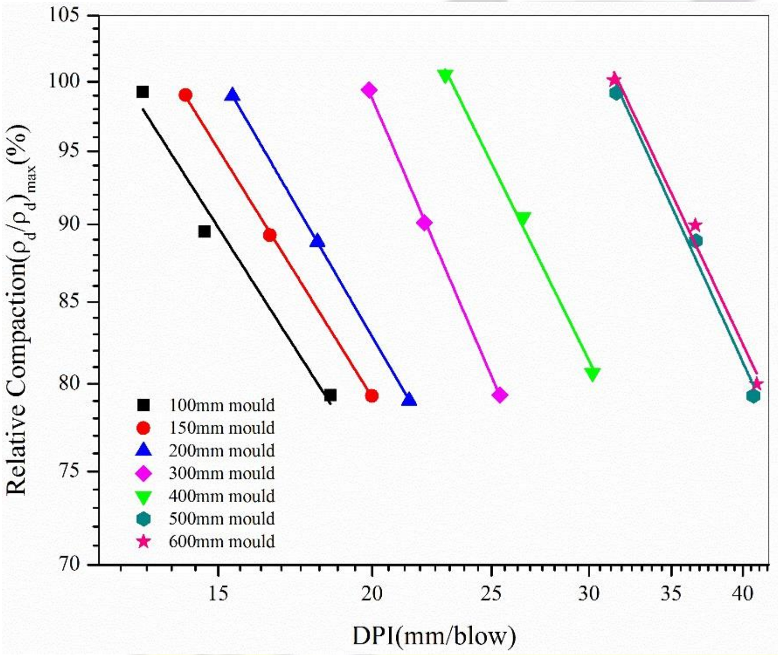


Figure 4.9: Relation of the relative compaction with DPI for different mould diameters.

The coefficient of regression for the lines of best fit for each mould ranged from 0.95 to 1.00 indicating very good linear fit for each set of data points. This shows that for the in-mould DCP test as well, there exists a correlation in the form of the field calibration equation of Equation (4.2).

The □□and□□□values are known to be constants for a given material at a constant water content. Typical values of □□and□□□values from various sources are shown in Table 4.11.

Table 4.11: Typical values of □ and □ values

Reference	Equivalent mould diameter (mm)	soil type	LL (%)	PI (%)	fines content (%)	$Wopt$ (%)	□□	□□	Testing conditions
Ampadu & Arthur (2006)	600	Lateritic	45	19	13.0	10.80	2.184	0.337	Field
Ampadu & Fiadjoe (2015)	150	Lateritic (sandy clay)	63	34	45.2	14.56	2.091	0.161	Lab
This study	150	Lateritic (clayey sand)	52	34	44.2	15.68	2.727	0.636	Lab
This study	600	Lateritic	52	34	44.2	15.68	3.251	0.834	Lab

A comparison of the results of Ampadu and Fiadjoe (2015) and those of the 150mm diameter mould from this study shows that, even though the soil parameters are similar (lateritic sandy clay and lateritic clayey sand), the □□and□□ values are different. This suggests that there are other soil factors than those listed that affect

□□and□□□

Figure 4.10 presents the variations of □□and□□□with the various mould sizes. The □□and□□□values increase sharply till 300mm diameter but become relatively constant at the 500mm mould. This is because, from this point the confinement provided by the mould as established previously is insignificant. The anomalous behavior at 400 mm diameter may be due to the larger deviation of this series of tests from the optimum water content, which varied from 0.63% to 0.94%.

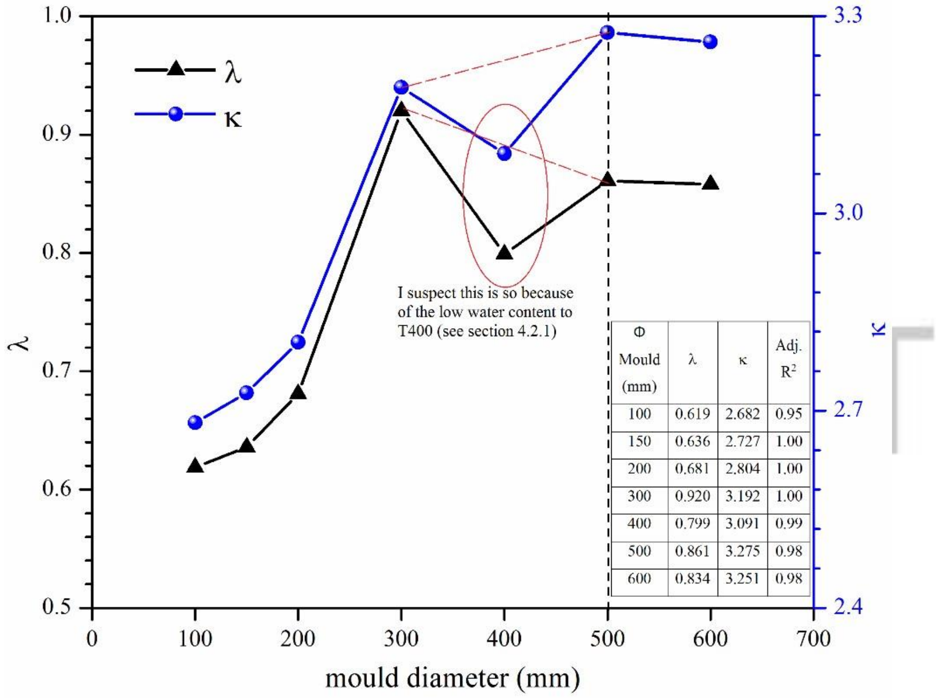


Figure 4.10: Plot of □ and □□ values for each mould diameter.

By this deduction, ratio of the □□and□□□values for 150mm (commonest compaction mould) and 600mm (likened to field conditions due to negligible confinement) were determined. This is summarised in Table 4.12.

Table 4.12: λ and □□values for use in calibration equation.

Mould diameter (mm)	□□	□□	$\frac{\kappa field}{\kappa lab}$	$\frac{\lambda field}{\lambda lab}$
150	2.727	0.636	1.192	1.311
600	3.251	0.844		

Substituting these parameters into Equation (4.2) yields equation (4.3).

$$log \frac{\rho d_{field}}{\rho_{dmax}} = \kappa_f - \lambda_f \text{Log}\,(DPI) \qquad (4.3)$$

Where

ρ_{dfield} = field dry density

ρ_{dmax}= laboratory dry density

$\kappa_f = 1.192\kappa_{lab}$ and λ_f=1.311λ_{lab}

4.3.5 Influence of the level of compaction on DPI-Dm/Dc relationship

The shape and magnitude of the curves for the three levels of compaction are different. This means there exists a relationship for every compaction level. However, when the DPI values plotted in Fig 4.7 are normalised with the DPI value obtained in the CBR mould, Figure 4.11 is obtained. The figure shows that the three plots are almost the same and may conveniently be represented by a single curve.

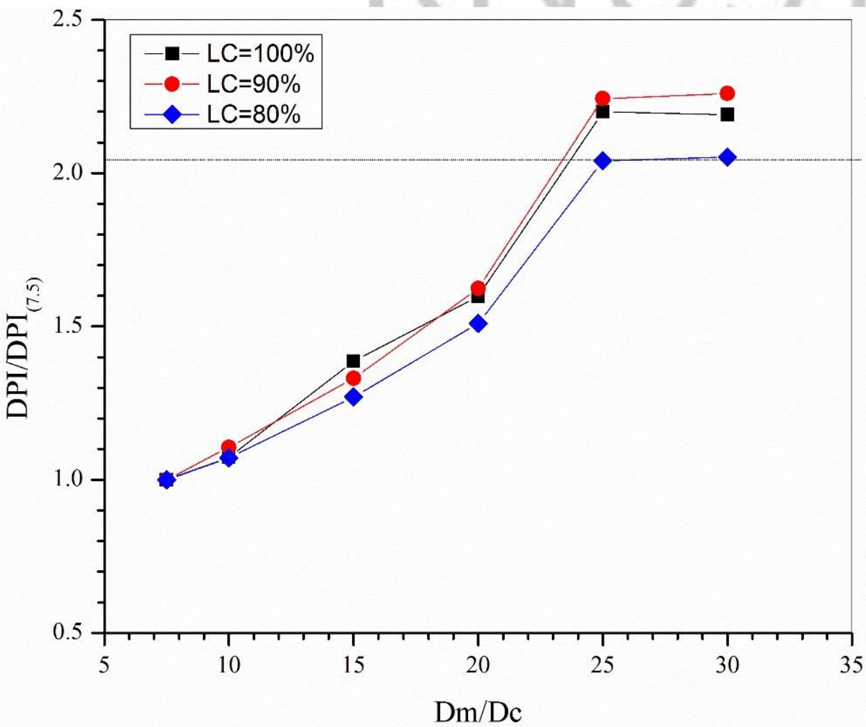


Figure 4.11: Plot normalizing the confinement in lab for field application. This appears to suggest that for LC between 80 and 100%, the relationship between $\frac{DPI}{DPI_{7.5}}$ and $\frac{Dm}{Dc}$ is independent of level of compaction.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In mould DCP tests were conducted in the laboratory on a lateritic clayey sand of maximum dry density of 1.85Mg/m^3 and an optimum water content of 15.68% on mould of diameters ranging from 100mm to 600mm to investigate the influence of horizontal confinement provided by the walls of the mould on the DPI values. Based on the results of the study it was concluded that:

1. For levels of compaction between 80% and 100%, the DPI values increase with increasing mould diameter until mould diameter of about 500mm, beyond which the increase in DPI was insignificant. At mould diameters of 500mm and more, the confinement provided by the moulds increased the magnitude of the DPI by about 2.2 times the DPI value in the CBR mould.
2. The relationship between the DPI values and the mould size appears to be largely independent of the level of compaction
3. For a given mould diameter, the DPI reduces as the dry density increases and a linear relationship of the form Log(ρ_d/ρ_{dmax}) =□-□Log (DPI) exists between the levels of compaction(ρ_d/ρ_{dmax}) attained and the equivalent DPI values.
4. The mould diameter influences both the gradient, □, and the intercept, □, of the linear relationship such that the influence of horizontal confinement is to increase the intercept and the gradient obtained in the CBR mould by factors of 1.192 and 1.311 respectively. This suggests that for levels of compaction between 80% and 100%, the field □ and □ are 1.192 and 1.311 times the equivalent values obtained by in-mould DCP test in the CBR mould.

5.2 Recommendations

1. The effect of index properties on the DPI values of lateritic soils needs to be established.
2. The calibration equation from this study be subjected to field validation and then extended to a large range of soil types.
3. Repeat of test for same material to confirm the “anomaly” around diameter of 400mm.

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APPENDIX I

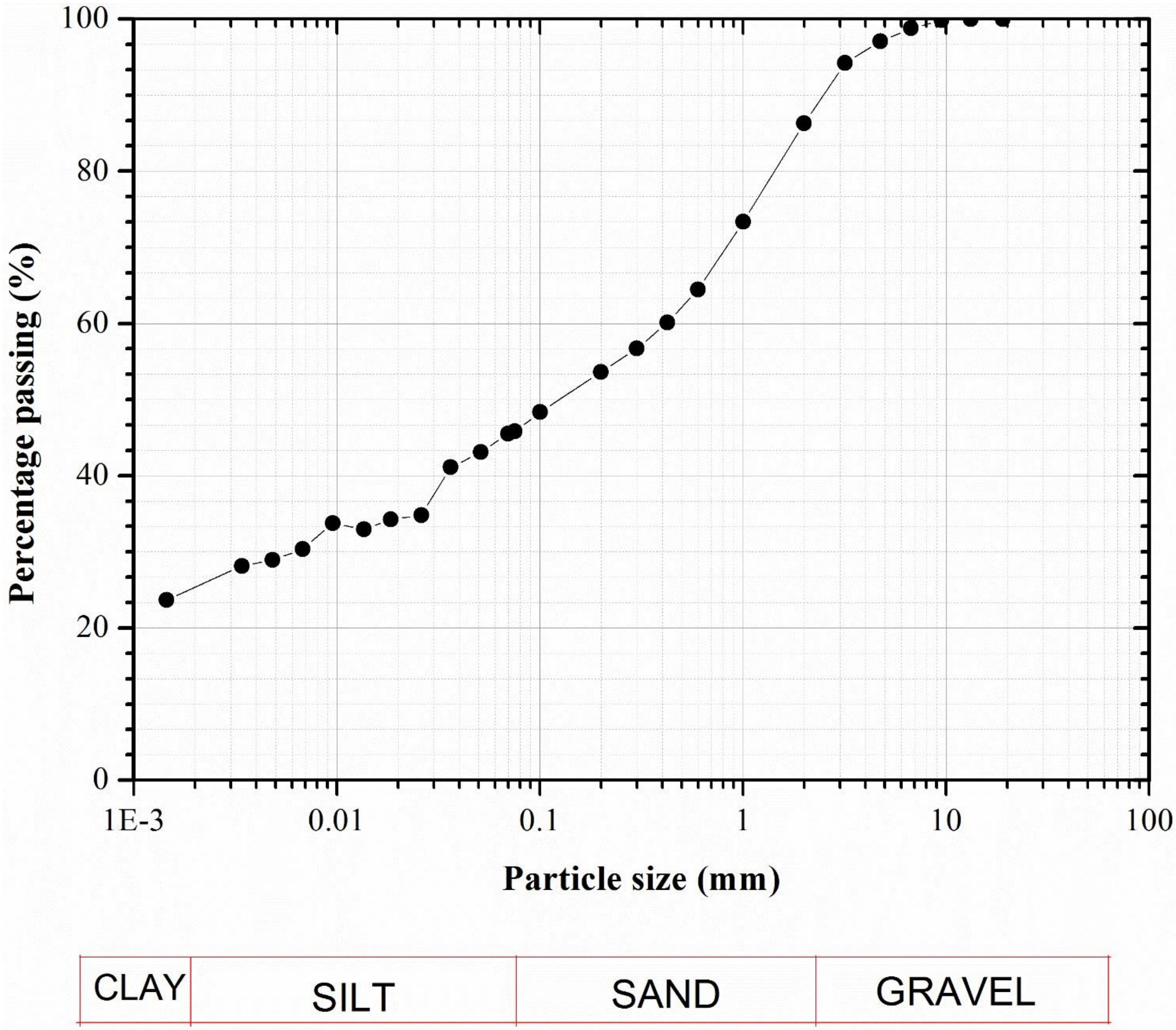
Sample Characterization: Grading, Atterberg limits test, Specific Gravity, Laboratory Compaction test

sample ID:- Lateritic soil			
Weight (g)		955	
	Weight	Percentage	Percentage
Metric	retained	retained	passing
(mm)	(g)	(%)	(%)
75.00		0.0	100.0
63.00		0.0	100.00
53.00		0.0	100.00
37.10		0.0	100.00
26.50		0.0	100.00
19.00		0.0	100.00
13.20		0.0	100.00
9.50	1.69	0.2	99.82
6.70	9.93	1.0	98.78
4.75	16.43	1.7	97.06
3.18	27.35	2.9	94.20
2.00	75.33	7.9	86.31

Weight (g)		287			
Sieve size		Weight	Percentage	Percentage	Percentage
BS designation	Metric	retained	retained	passing	passing corr
	(mm)	(g)	(%)	(%)	(%)
No. 14	1.00	43.02	14.99	85.01	73.37
No. 25	0.600	34.33	10.32	74.69	64.46
No. 36	0.425	16.67	5.01	69.67	60.14
No. 52	0.300	13.25	3.98	65.69	56.70
NO. 72	0.200	11.82	3.55	62.13	53.63
No. 100	0.100	20.37	6.13	56.01	48.34
No. 200	0.075	9.67	2.91	53.10	45.83

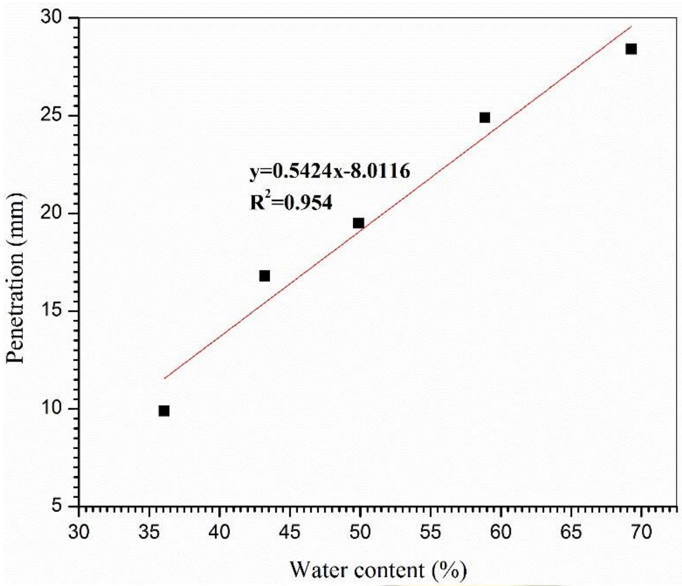
Hydrometer readings weight: 15.38g

Elapsed tme,(min)	Time (mins)	Temp (º c)	Direct hydrometer readings Rh'	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'Ro'+Mt	K (%)	Kcorr (%)
0.50	11:29	28.70	1.0110	11.00	11.5000	155.1750	0.8148	0.0698	1.9753	9.3753	99.2957	45.51
1.00	11:29	28.70	1.0105	10.50	11.0000	157.1500	0.8148	0.0511	1.9753	8.8753	94.0001	43.08
2.00	11:30	28.70	1.0101	10.10	10.6000	158.7300	0.8148	0.0363	1.9753	8.4753	89.7636	41.14
4.00	11:32	28.70	1.0088	8.80	9.3000	163.8650	0.8148	0.0261	1.9753	7.1753	75.9950	34.83
8.00	11:36	29.00	1.0086	8.60	9.1000	164.6550	0.8093	0.0184	2.0580	7.0580	74.7526	34.26
15.00	11:43	28.00	1.0086	8.60	9.1000	164.6550	0.8279	0.0136	1.7861	6.7861	71.8729	32.94
30.00	11:58	29.00	1.0085	8.50	9.0000	165.0500	0.8093	0.0095	2.0580	6.9580	73.6934	33.77
60.00	12:28	29.00	1.0078	7.80	8.3000	167.8150	0.8093	0.0068	2.0580	6.2580	66.2796	30.38
120.00	1:28	29.00	1.0075	7.50	8.0000	169.0000	0.8093	0.0048	2.0580	5.9580	63.1022	28.92
240.00	3:28	29.50	1.007264	7.20	7.7000	170.1850	0.8002	0.0034	2.1979	5.7979	61.4073	28.14
1440.00	11:29	26.00	1.0072	7.20	7.7000	170.1850	0.8672	0.0014	1.2745	4.8745	51.6272	23.66



LIQUID LIMIT(LL)

Container number	C11	X14	Z0	172	A2
Mass of container(gm)	3.59	3.6	3.74	3.67	3.59
Penetration(mm)	9.9	16.8	19.5	24.9	28.4
Mass of container + wet sample(gm)	25.32	17.95	16.42	16.57	20.5
Mass of container + dry sample(gm)	19.56	13.62	12.2	11.79	13.58
Mass of water(gm)	5.76	4.33	4.22	4.78	6.92
Mass of dry sample(gm)	15.97	10.02	8.46	8.12	9.99
Water content(%)	36.07	43.21	49.88	58.87	69.27
	PLASTIC LIMIT(PL)				
Container number	C3	B30			
Mass of container(gm)	3.56	3.65			
Mass of container + wet sample(gm)	15.39	15.85		LL	52
Mass of container + dry sample(gm)	13.59	13.99		PL	18
Mass of water(gm)	1.8	1.86		PI	34
Mass of dry sample(gm)	10.03	10.34			
Water content(%)	17.95	17.99			
Average water content(%)	18.0				

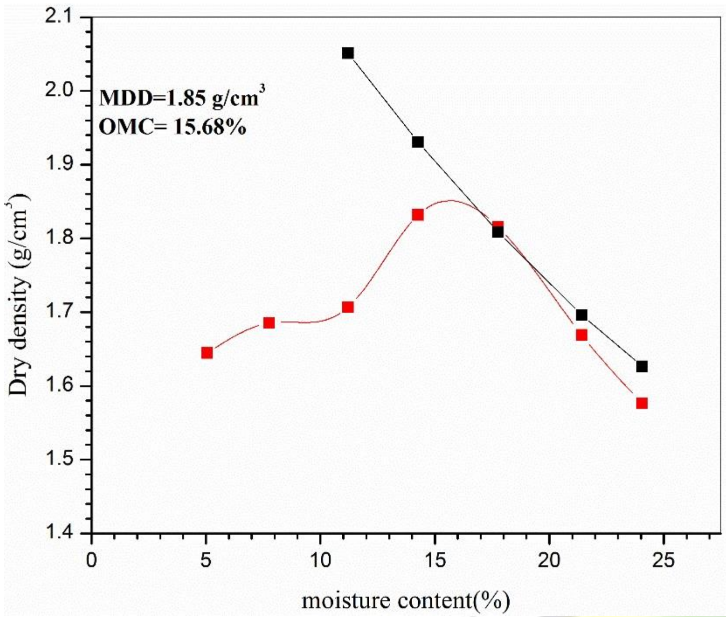


SPECIFIC GRAVITY TEST		
Sample : Lateritic soil		
Bottle No.	A	B
Mass of bottle empty(g) + lid M1	823	806
Mass of bottle and dry soil (g) + lid + soil M2	1044	1035
Mass of bottle + sample + water + lid (g) M3	2250	2200
Mass of bottle + water (g) + lid M4	2111	2058
M2 - M1	221	229

M3 - M4	139	142
(M2 - M1)- (M3 - M4)	82	87
Specific Gravity	2.70	2.63
Average Specific Gravity	2.6637	

SAMPLE ID:-Lateritic soil														
TRIAL NO:	1		2		3		4		5		6		7	
mass of cylinder+ wet sample(gm)	10881		11067		11241		11650		11745		11510		11361	
mass of cylinder(gm)	7244		7244		7244		7244		7244		7244		7244	
mass of wet sample(gm)	3637		3823		3997		4406		4501		4266		4117	
Bulk density(g/cm³)	1.73		1.82		1.90		2.09		2.14		2.03		1.96	
container number	H12	g2	GET	U50	H17	H14	B1	U51	MK2	U52	M4	BK5	R3	A13
mass of container+ wet sample(gm)	174.63	176	189.42	202.13	174.88	190.88	162.71	155.71	184.4	168.33	149.33	170.67	136.97	165.73
mass of container+ dry sample(gm)	166.92	169.26	178.52	189.7	159.47	174.43	146.49	140.23	161.77	148.11	127.25	145.5	115.36	139.54
mass of container	25.3	25.03	33.22	34.59	24.38	25.27	31.67	32.67	34.05	34.6	26.04	25.65	25.63	30.59
mass of wet soil(gm)	149.33	150.97	156.2	167.54	150.5	165.61	131.04	123.04	150.35	133.73	123.29	145.02	111.34	135.14
mass of dry soil(gm)	141.62	144.23	145.3	155.11	135.09	149.16	114.82	107.56	127.72	113.51	101.21	119.85	89.73	108.95
mass of water	7.71	6.74	10.9	12.43	15.41	16.45	16.22	15.48	22.63	20.22	22.08	25.17	21.61	26.19
water content(%)	5.44	4.67	7.50	8.01	11.41	11.03	14.13	14.39	17.72	17.81	21.82	21.00	24.08	24.04
average water content	5.06		7.76		11.22		14.26		17.77		21.41		24.06	

dry density(kg/m³)	1.64	1.69	1.71	1.83	1.82	1.67	1.58
height of mould(cm)	11.6						
diameter of mould(cm)	15.2						
volume of mould(cm³)	2105.19						



APPENDIX II

IN MOULD DCP TESTS

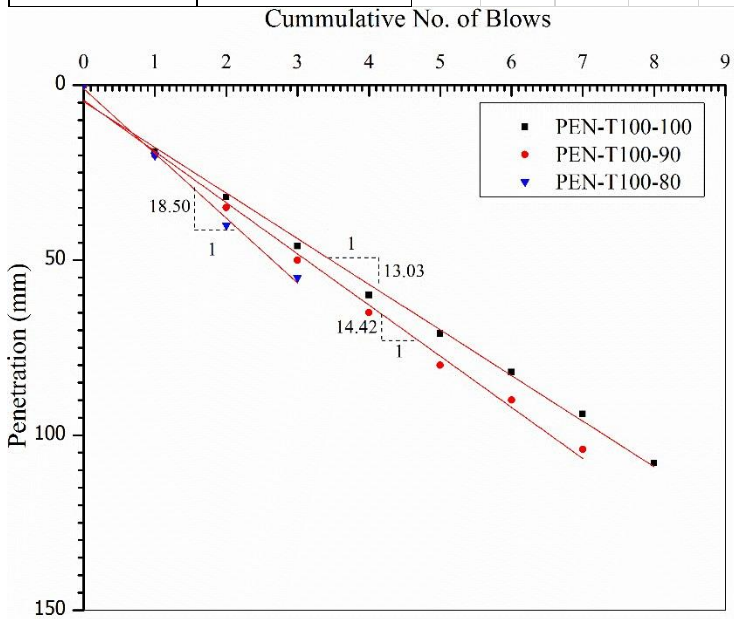
SAMPLE ID:-TEST SERIES 100

BEFORE TEST									
Test No.:	T100-100			T100-90			T100-80		
Mould No.	100%			90%			80%		
Mass of wet sample	1,987			1,788			1,590		
Volume of mould	938			938			938		
Bulk density (g/cc)	2.119			1.907			1.696		
MOISTURE CONTENT									
Test.	Top	Mid	Bottom	Top	Mid	Bottom	Top	Mid	Bottom
Container No.	F1	H16	SD	FT	K20	A2	H1	BK4	8Z
Wet sample + cont. (g)	116.49	133.91	138.79	144.05	158.35	153.91	149.46	162.18	155.55
Dry sample + cont. (g)	104.46	119.21	123.58	126.63	141.51	138.51	132.45	144.15	137.90
Mass of container	25.59	25.29	25.34	23.09	25.34	29.59	25.43	25.57	25.55
Mass of water	12.03	14.70	15.21	17.42	16.84	15.40	17.01	18.03	17.65
Mass of dry sample	78.87	93.92	98.24	103.54	116.17	108.92	107.02	118.58	112.35
Water content	15.25	15.65	15.48	16.82	14.50	14.14	15.89	15.20	15.71
Ave. Water Content	15.462			15.153			15.603		
Dry density	1.836			1.656			1.467		
MDD	1.850			1.665			1.499		

In-Mould DCP Test 1			In-Mould DCP Test 2			In-Mould DCP Test 3		
Cum. No. Blows	Pen. (mm)	Actual Pen (mm)	Cum. No. Blows	Pen. (mm)	Actual Pen (mm)	Cum. No. Blows	Pen. (mm)	Actual Pen (mm)
0	70	0	0	70	0	0	70	0
1	89	19	1	90	20	1	90	20
2	102	32	2	105	35	2	110	40
3	116	46	3	120	50	3	125	55
4	130	60	4	135	65	4		
5	141	71	5	150	80	5		
6	152	82	6	160	90	6		
7	164	94	7	174	104	7		
8	178	108	8	186	116	8		
9			9			9		
10			10			10		
11			11			11		
12			12			12		
13			13			13		
14			14			14		

Relative density (%)	99.223	89.525	79.302
Mould Dimensions	100mm		
Height (cm)	11.70		
Diameter (cm)	**10.1**		

15			15			15		
16			16			16		
17			17			17		
18			18			18		
19			19			19		

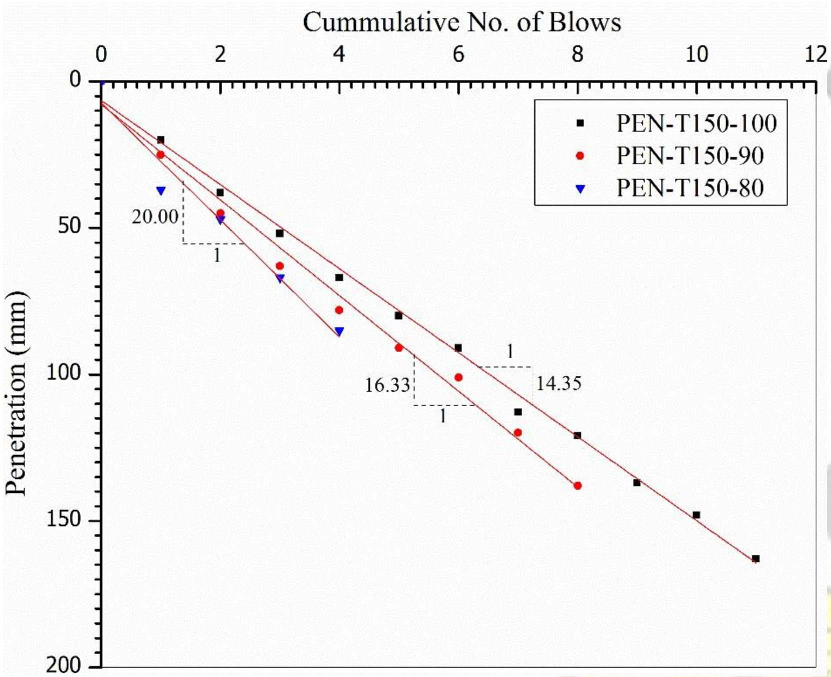


SAMPLE ID:-TEST SERIES 150

BEFORE TEST				In-Mould DCP Test 1			In-Mould DCP Test 2			In-Mould DCP Test 3		
Test No.:	T150-100	T150-90	T150-80	Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)
Mould No.	100%	90%	80									
Mass of wet sample	6,719	6,047	5,376	0	73.5	0	0	70	0	0	73	0

Volume of mould	3170			3170			3171		
Bulk density (g/cc)	2.119			1.908			1.695		
MOISTURE CONTENT									
Test.	Top	Mid	Bottom	Top	Mid	Bottom	Top	Mid	Bottom
Container No.	YF	H19	AB1	GF	AYX	10Z	9Z	Q3	B2
Wet sample + cont. (g)	171.59	170.42	161.43	137.10	135.17	148.12	149.46	155.55	162.18
Dry sample + cont. (g)	151.79	151.13	142.56	121.98	120.27	132.00	132.45	137.90	144.15
Mass of container	25.34	25.37	24.79	25.17	25.96	25.28	25.43	25.55	25.57
Mass of water	19.80	19.29	18.87	15.12	14.90	16.12	17.01	17.65	18.03
Mass of dry sample	126.45	125.76	117.77	96.81	94.31	106.72	107.02	112.35	118.58
Water content	15.66	15.34	16.02	15.62	15.80	15.10	15.89	15.71	15.20
Ave. Water Content	15.673			15.507			15.603		
Dry density	1.832			1.651			1.467		
MDD	1.850			1.665			1.456		
Relative density (%)	99.044			89.269			79.272		
Mould Dimensions	150mm								
Height (cm)	17.70								
Diameter (cm)	**15.1**								

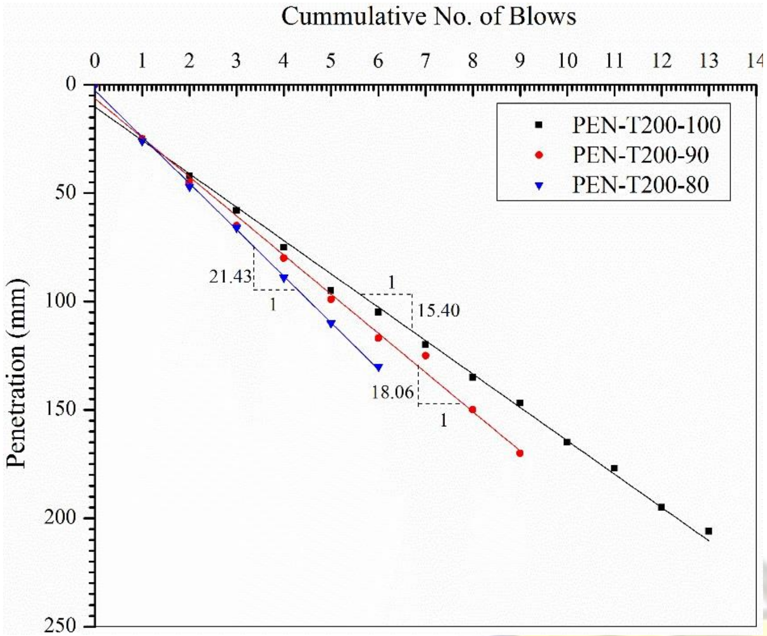
1	93	20	1	95	25	1	110	37
2	111	38	2	115	45	2	120	47
3	125.5	52	3	133	63	3	140	67
4	140	67	4	148	78	4	158	85
5	153.5	80	5	161	91	5		
6	164.5	91	6	171	101	6		
7	186	113	7	190	120	7		
8	194	121	8	208	138	8		
9	210	137	9			9		
10	221	148	10			10		
11	236	163	11			11		
12			12			12		
13			13			13		
14			14			14		
15			15			15		
16			16			16		
17			17			17		
18			18			18		
19			19			19		



SAMPLE ID:-TEST SERIES 200																		
BEFORE TEST										**In-Mould DCP Test 1**			**In-Mould DCP Test 2**			**In-Mould DCP Test 3**		
Test No.:	T200-100			T200-90			T200-80			Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)
Mould No.	100%			90%			80%											
Mass of wet sample	13,985			12,586			11,188			0	75	0	0	75	0	0	75	0
Volume of mould	6630			6630			6630			1	100	25	1	100	25	1	101	26
Bulk density (g/cc)	2.109			1.898			1.688			2	117	42	2	120	45	2	122	47
MOISTURE CONTENT										3	133	58	3	140	65	3	141	66
Test.	Top	Mid	Bottom	Top	Mid	Bottom	Top	Mid	Bottom	4	150	75	4	155	80	4	164	89

Container No.	Q3	2Z	MY	H13	K20	GF	FJ	AD	4Z
Wet sample + cont. (g)	166.13	160.73	131.25	172.25	154.63	135.35	149.68	137.45	144.40
Dry sample + cont. (g)	147.92	142.42	117.44	152.80	137.57	120.08	133.49	122.43	128.54
Mass of container	25.43	25.68	26.16	25.13	25.36	25.18	25.05	25.54	25.42
Mass of water	18.21	18.31	13.81	19.45	17.06	15.27	16.19	15.02	15.86
Mass of dry sample	122.49	116.74	91.28	127.67	112.21	94.90	108.44	96.89	103.12
Water content	14.87	15.68	15.13	15.23	15.20	16.09	14.93	15.50	15.38
Ave. Water Content		15.227			15.510			15.271	
Dry density		1.831			1.644			1.464	
MDD		1.850			1.665			1.480	
Relative density (%)		98.958			88.840			79.136	
Mould Dimensions	200mm								
Height (cm)		21.10							
Diameter (cm)		**20**							

5	170	95	5	174	99	5	185	110
6	180	105	6	192	117	6	205	130
7	195	120	7	200	125	7		
8	210	135	8	225	150	8		
9	222	147	9	245	170	9		
10	240	165	10			10		
11	252	177	11			11		
12	270	195	12			12		
13	281	206	13			13		
14			14			14		
15			15			15		
16			16			16		
17			17			17		
18			18			18		
19			19			19		



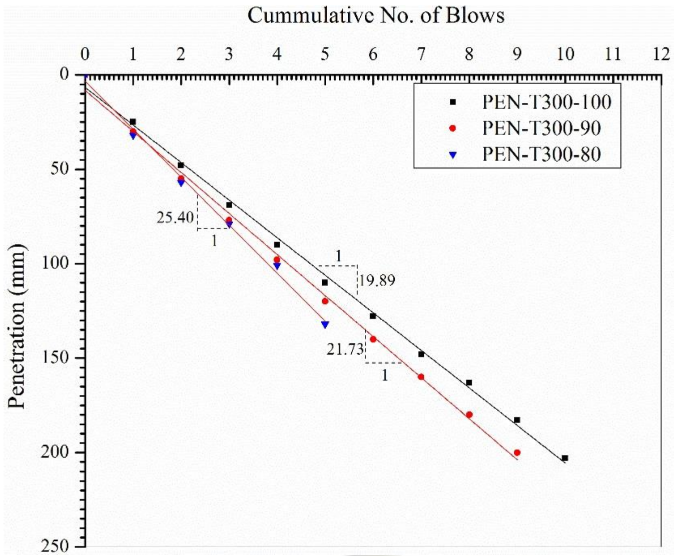
SAMPLE ID:-TEST SERIES 300

BEFORE TEST									
Test No.:	T300-100			T300-90			T300-80		
Mould No.	100%			90%			80%		
Mass of wet sample	31,439			28,295			25,151		
Volume of mould	14833			14833			14833		
Bulk density (g/cc)	2.119			1.908			1.696		
MOISTURE CONTENT									
Test.	Top	Mid	Bottom	Top	Mid	Bottom	Top	Mid	Bottom

In-Mould DCP Test 1			**In-Mould DCP Test 2**			**In-Mould DCP Test 3**		
Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)
0	77	0	0	80	0	0	70	0
1	102	25	1	110	30	1	102	32
2	125	48	2	135	55	2	127	57
3	146	69	3	157	77	3	149	79
4	167	90	4	178	98	4	171	101

Container No.	BK1	R5	AB	H13	GF	LK	BC	G8	SA
Wet sample + cont. (g)	144.04	156.92	154.13	163.01	152.53	149.53	162.70	159.22	154.14
Dry sample + cont. (g)	128.27	139.35	137.46	145.98	135.85	134.18	144.24	141.26	136.93
Mass of container	25.47	25.70	25.58	25.15	25.21	25.51	25.54	25.37	25.43
Mass of water	15.77	17.57	16.67	17.03	16.68	15.35	18.46	17.96	17.21
Mass of dry sample	102.80	113.65	111.88	120.83	110.64	108.67	118.70	115.89	111.50
Water content	15.34	15.46	14.90	14.09	15.08	14.13	15.55	15.50	15.43
Ave. Water Content		15.233			14.432			15.495	
Dry density		1.839			1.667			1.468	
MDD		1.850			1.665			1.480	
Relative density (%)		99.421			90.105			79.356	
Mould Dimensions	300mm								
Height (cm)		20.30							
Diameter (cm)		**30.5**							

5	187	110	5	200	120	5	202	132
6	205	128	6	220	140	6		
7	225	148	7	240	160	7		
8	240	163	8	260	180	8		
9	260	183	9	280	200	9		
10	280	203	10			10		
11			11			11		
12			12			12		
13			13			13		
14			14			14		
15			15			15		
16			16			16		
17			17			17		
18			18			18		
19			19			19		

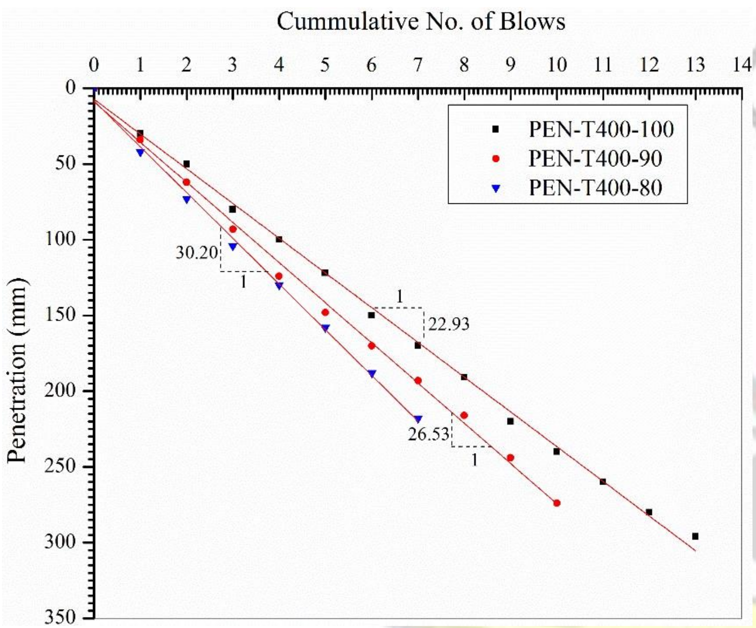


SAMPLE ID:-TEST SERIES 400

BEFORE TEST										In-Mould DCP Test 1			In-Mould DCP Test 2			In-Mould DCP Test 3		
Test No.:	T400-100			T400-90			T400-80			Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)
dry density	100%			90%			80%											
Mass of wet sample	78,385			70,546			62,708			0	80	0	0	74	0	0	74	0
Volume of mould	36639			36639			36639			1	110	30	1	108	34	1	116	42
Bulk density (g/cc)	2.139			1.925			1.712			2	130	50	2	136	62	2	147	73
MOISTURE CONTENT										3	160	80	3	167	93	3	178	104
Test.	Top	Mid	Bottom	Top	Mid	Bottom	Top	Mid	Bottom	4	180	100	4	198	124	4	204	130
Container No.	H8	TX	RS	F9	EA	TX1	GET	B16	MK3	5	202	122	5	222	148	5	232	158

Wet sample + cont. (g)	175.43	184.19	141.05	135.36	135.91	133.49	192.16	151.18	177.41
Dry sample + cont. (g)	156.41	163.11	125.88	121.67	121.40	118.72	172.98	134.28	158.55
Mass of container	25.94	25.40	25.67	25.52	25.17	25.46	33.17	25.71	32.23
Mass of water	19.02	21.08	15.17	13.69	14.51	14.77	19.18	16.90	18.86
Mass of dry sample	130.47	137.71	100.21	96.15	96.23	93.26	139.81	108.57	126.32
Water content	14.58	15.31	15.14	14.24	15.08	15.84	13.72	15.57	14.93
Ave. Water Content	15.008			15.051			14.738		
Dry density	1.860			1.674			1.492		
MDD	1.850			1.665			1.480		
Relative density (%)	100.553			90.463			80.631		
Mould Dimensions	400mm								
Height (cm)	30.20								
Diameter (cm)	**39.3**								

6	230	150	6	244	170	6	262	188
7	250	170	7	267	193	7	292	218
8	271	191	8	290	216	8	297	223
9	300	220	9	318	244	9		
10	320	240	10	348	274	10		
11	340	260	11	370	296	11		
12	360	280	12			12		
13	376	296	13			13		
14			14			14		
15			15			15		
16			16			16		
17			17			17		
18			18			18		
19			19			19		



SAMPLE ID:-TEST SERIES 500																		
BEFORE TEST										**In-Mould DCP Test 1**			**In-Mould DCP Test 2**			**In-Mould DCP Test 3**		
Test No.:	T500-100			T500-90			T500-80			Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)
Mould No.	100%			90%			80%											
Mass of wet sample	86,358			77,722			69,086			0	80	0	0	80	0	0	80	0
Volume of mould	40745			40745			40745			1	117	37	1	120	40	1	122	42
Bulk density (g/cc)	2.119			1.908			1.696			2	155	75	2	151	71	2	156	76
MOISTURE CONTENT										3	185	105	3	187	107	3	194	114
Test.	Top	Mid	Bottom	Top	Mid	Bottom	Top	Mid	Bottom	4	215	135	4	227	147	4	248	168

Container No.	GET	H15	H9	H2	H4	X5	DC	BK1	U51
Wet sample + cont. (g)	156.83	184.50	146.25	166.38	183.87	191.32	152.82	187.02	200.47
Dry sample + cont. (g)	140.45	162.81	130.08	145.71	162.52	169.53	135.94	164.86	177.77
Mass of container	33.20	25.24	25.30	25.48	25.57	25.33	26.79	25.44	32.70
Mass of water	16.38	21.69	16.17	20.67	21.35	21.79	16.88	22.16	22.70
Mass of dry sample	107.25	137.57	104.78	120.23	136.95	144.20	109.15	139.42	145.07
Water content	15.27	15.77	15.43	17.19	15.59	15.11	15.46	15.89	15.65
Ave. Water Content	15.491			15.964			15.556		
Dry density	1.835			1.645			1.467		
MDD	1.850			1.665			1.480		
Relative density (%)	99.199			88.914			79.313		
Mould Dimensions	500mm								
Height (cm)	21.00								
Diameter (cm)	**49.7**								

5	244	164	5	265	185	5		
6	270	190	6	290	210	6		
7	290	210	7			7		
8			8			8		
9			9			9		
10			10			10		
11			11			11		
12			12			12		
13			13			13		
14			14			14		
15			15			15		
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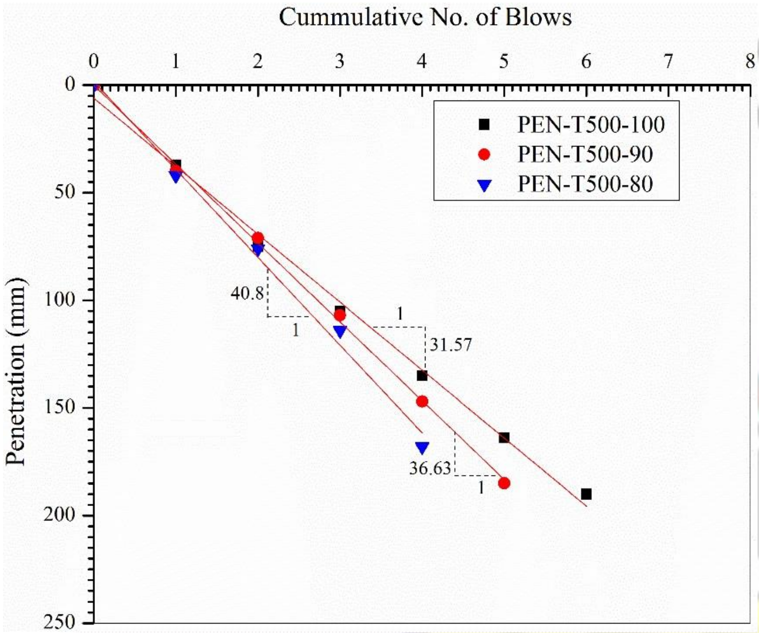
17			17			17		
18			18			18		
19			19			19		



SAMPLE ID:-TEST SERIES 600

BEFORE TEST										In-Mould DCP Test 1			In-Mould DCP Test 2			In-Mould DCP Test 3		
Test No.:	T600-100			T600-90			T600-80			Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)	Cum. No.	Pen. (mm)	Actual Pen (mm)
Mould No.	100%			90%			80%											
Mass of wet sample	193,623			174,222			154,864			0	74	0	0	86	0	0	77	0
Volume of mould	90490			90490			90490			1	110	36	1	135	49	1	135	58
Bulk density (g/cc)	2.140			1.925			1.711			2	153	79	2	180	94	2	179	102
MOISTURE CONTENT										3	184	110	3	219	133	3	214	137
Test.	Top	Mid	Bottom	Top	Mid	Bottom	Top	Mid	Bottom	4	210	136	4	253	167	4	249	172

Container No.	G10	AS	A6	KY	SD	SAB	B16	MK3	GET
Wet sample + cont. (g)	105.75	141.31	157.77	136.69	147.93	149.29	153.02	164.08	195.12
Dry sample + cont. (g)	94.88	126.32	140.15	121.82	131.17	132.42	135.48	146.36	173.49
Mass of container	24.86	30.59	26.42	25.86	25.42	26.14	25.73	32.26	33.21
Mass of water	10.87	14.99	17.62	14.87	16.76	16.87	17.54	17.72	21.63
Mass of dry sample	70.02	95.73	113.73	95.96	105.75	106.28	109.75	114.10	140.28
Water content	15.52	15.66	15.49	15.50	15.85	15.87	15.98	15.53	15.42
Ave. Water Content	15.559			15.739			15.644		
Dry density	1.852			1.664			1.480		
MDD	1.850			1.665			1.480		
Relative density (%)	100.089			89.919			79.994		
Mould Dimensions	600mm								
Height (cm)	32.00								
Diameter (cm)	**60**								

5	244	170	5	285	199	5	287	210
6	279	205	6	319	233	6	330	253
7	308	234	7	353	267	7	379	302
8	331	257	8	390	304	8		
9	357	283	9			9		
10	388	314	10			10		
11			11			11		
12			12			12		
13			13			13		
14			14			14		
15			15			15		
16			16			16		
17			17			17		
18			18			18		
19			19			19		

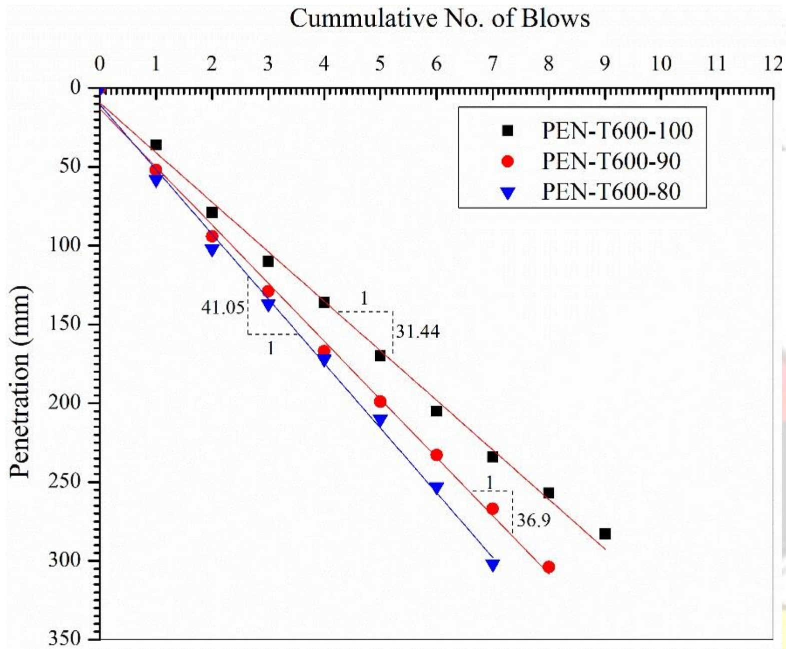


Table A: showing the □□and□□□value

Table B: Statistical data of density-DPI plot

Φ Mould	□□	□□
100	0.619	2.682
150	0.636	2.727
200	0.681	2.804
300	0.920	3.192
400	0.799	3.091
500	0.864	3.295
600	0.834	3.251

Φ Mould	gradient	Intercept	Adj. R^2
100	14.91	40.03	0.90
150	16.15	43.53	0.98
200	16.33	45.17	0.99
300	14.90	47.16	0.99
400	19.75	59.64	1.00
500	25.10	77.72	1.00
600	25.84	79.39	1.00

Table C: Computation of the specific energy for the three levels of compaction

LC=100%

Mould Diameter (mm)	No of blow per layer	No of layer	Diameter	Length of mould (m)	Height (m)	Volume of mould (m^3)	Mass of rammer (kg)	Weight of rammer (kg m/s^2)	Specific energy using weight (kN-m/m^3)
	N	n	D(m)	L(m)	H	V	M	W	E
100	35	5	0.101	0.117	0.457	0.0009375	4.54	0.0445374	3799.30632
150	55	5	0.151	0.177	0.457	0.0031701	4.54	0.0445374	1765.63286
200	70	5	0.2	0.211	0.457	0.0066296	4.54	0.0445374	1074.53476
300	90	5	0.305	0.203	0.457	0.0148334	4.54	0.0445374	617.464037
400	110	5	0.393	0.302	0.457	0.0366385	4.54	0.0445374	305.538201
500	130	5	0.497	0.21	0.457	0.0407454	4.54	0.0445374	324.695415
600	140	5	0.6	0.32	0.457	0.0904896	4.54	0.0445374	157.44919

LC=90%

Mould Diameter (mm)	No of blow per layer	No of layer	Diameter	Length of mould (m)	Height (m)	Volume of mould (m^3)	Mass of rammer (kg)	weight of rammer (kg m/s^2)	Specific energy using weight (kN-m/m^3)
	N	n	D(m)	L(m)	H	V	M	W	E
100	20	5	0.101	0.117	0.457	0.0009375	4.54	0.0445374	2171.03218
150	35	5	0.151	0.177	0.457	0.0031701	4.54	0.0445374	1123.58455
200	55	5	0.2	0.211	0.457	0.0066296	4.54	0.0445374	844.277311
300	70	5	0.305	0.203	0.457	0.0148334	4.54	0.0445374	480.249807
400	90	5	0.393	0.302	0.457	0.0366385	4.54	0.0445374	249.985801
500	115	5	0.497	0.21	0.457	0.0407454	4.54	0.0445374	287.230559
600	120	5	0.6	0.32	0.457	0.0904896	4.54	0.0445374	134.956449

LC=80%

Mould Diameter (mm)	No of blow per layer	No of layer	Diameter	Length of mould (m)	Height (m)	Volume of mould (m^3)	Mass of rammer (kg)	weight of rammer (kg m/s^2)	Specific energy using weight (kN-m/m^3)
	N	n	D	L	H	V	M	W	E

100	10	5	0.101	0.117	0.457	0.0009375	4.54	0.0445374	1085.51609
150	20	5	0.151	0.177	0.457	0.0031701	4.54	0.0445374	642.048314
200	40	5	0.2	0.211	0.457	0.0066296	4.54	0.0445374	614.019862
300	50	5	0.305	0.203	0.457	0.0148334	4.54	0.0445374	343.035576
400	70	5	0.393	0.302	0.457	0.0366385	4.54	0.0445374	194.4334
500	90	5	0.497	0.21	0.457	0.0407454	4.54	0.0445374	224.789133
600	110	5	0.6	0.32	0.457	0.0904896	4.54	0.0445374	123.710078

Table D: Analysis from density vrs energy plot

Φ Mould	gradient	Intercept	Adj. R^2
100	36.45	31.54	1.00
150	44.76	46.64	0.99
200	81.47	148.57	0.98
300	78.31	119.40	1.00
400	100.87	150.57	0.99
500	119.67	202.91	0.91
600	187.35	310.90	0.95

Table E: Summary of In-mould test

Mould Diameters (mm)	Test No.	Height (cm)	Volume (cm3)	□d/ (□dmax) (Mg/m3)	Actual □dmax (Mg/m3)	Average Water Content (%)
100	T100-100/1	11.70	938	100	1.836	15.462
	T100-90/1	11.70	938	90	1.656	15.153
	T100-80/1	11.70	938	80	1.468	15.55
150	T150-100/1	17.70	3170	100	1.832	15.673
	T150-90/1	17.70	3170	90	1.652	15.507
	T150-80/1	17.70	3170	80	1.467	15.603
200	T200-100/1	21.10	6630	100	1.831	15.227
	T200-90/1	21.10	6630	90	1.644	15.51
	T200-80/1	21.10	6630	80	1.462	15.441
300	T300-100/1	20.30	14833	100	1.839	15.233
	T300-90/1	20.30	14833	90	1.667	14.432
	T300-80/1	20.30	14833	80	1.468	15.495
400	T400-100/1	30.20	36639	100	1.86	15.008
	T400-90/1	30.20	36639	90	1.674	15.051
	T400-80/1	30.20	36639	80	1.492	14.738
500	T500-100/1	21.00	40745	100	1.835	15.491
	T500-90/1	21.00	40745	90	1.645	15.964
	T500-80/1	21.00	40745	80	1.467	15.556

600	T600-100/1	32.00	90490	100	1.852	15.559
	T600-90/1	32.00	90490	90	1.664	15.739
	T600-80/1	32.00	90490	80	1.48	15.644

Table F: cont'd of summary of in-mould test

Target □dmax (Mg/m3)	omc (%)	wr (%)	□bulk (Mg/m3)	Ms	Mw	Mt= (Ms+Mw)
1.85	15.68	14.1653	2.112	1712.58	268.53	1981.11
1.665	15.68	14.1653	1.901	1541.32	241.68	1782.999
1.48	15.68	14.1653	1.690	1370.06	214.83	1584.888
1.85	15.68	14.1653	2.112	5787.71	907.51	6695.224
1.665	15.68	14.1653	1.901	5208.94	816.76	6025.702
1.48	15.68	14.1653	1.690	4630.17	726.01	5356.179
1.85	15.68	14.1653	2.112	12104.90	1898.05	14002.94
1.665	15.68	14.1653	1.901	10894.41	1708.24	12602.65
1.48	15.68	14.1653	1.690	9683.92	1518.44	11202.36
1.85	15.68	14.1653	2.112	27081.74	4246.42	31328.16
1.665	15.68	14.1653	1.901	24373.57	3821.78	28195.34
1.48	15.68	14.1653	1.690	21665.39	3397.13	25062.53
1.85	15.68	14.1653	2.112	66894.62	10489.08	77383.69
1.665	15.68	14.1653	1.901	60205.16	9440.17	69645.33
1.48	15.68	14.1653	1.690	53515.69	8391.26	61906.96
1.85	15.68	14.1653	2.112	74391.26	11664.55	86055.81
1.665	15.68	14.1653	1.901	66952.13	10498.09	77450.22
1.48	15.68	14.1653	1.690	59513.01	9331.64	68844.64
1.85	15.68	14.1653	2.112	165214.50	25905.63	191120.1
1.665	15.68	14.1653	1.901	148693.05	23315.07	172008.1
1.48	15.68	14.1653	1.690	132171.60	20724.51	152896.1