Current Trend in Compaction Engineering For Highway Works and Relevance to Highway Construction in Nigeria

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ABSTRACT

Compaction of soil and other aggregates used in the construction of civil Engineering facilities is a very important and necessary operation. A well compacted highway subgrade or subbase ofa highway pavement usually will result in good pavement service and its being serviceable till the end of its life span. A soil that is well compacted meets a required or specified maximum density and an optimum moisture content. To ensure that this specified density is achieved, some tools are employed during the construction operation for measurement of these properties. These tools can be classified into two groups; namely quality control, which are used during the construction and quality assurance tools that are employed after construction. The principle of operations and use of the differenttools available for each of these stages, intelligent and deep compaction methodsand their use in the Nigerian construction Industry are examined in this article.

1.0 Introduction

Compaction, a process whereby some form of energy (static and dynamic) is impacted to loosely bound materials of construction to increase its density and ultimately strength is an integral part of construction operations. The commonest and obvious of the construction activity in which compaction is carried out is in the construction of a highway. Although compaction operation is carried out in other construction works like construction of the foundation and embankment of earth dams, foundations of large and heavy structure like stadium, railway yards/terminals, foundations of high rise buildings, power stations, airfields, refineries, quay of sea ports, sanitary landfills and other specialized structures. Materials that are compacted during construction operations of some of these structures include; soil aggregates, stone aggregates, concrete, bituminous/asphalt pavings. This write up deals mainly with compaction of soil aggregates in highway/pavement works.

2.0 Soil aggregate compaction specification

The parameters that influence ultimate compacted state of the soil include other than soil type (cohesive or cohesionless), moisture content and density. Specification for compaction is therefore stated in terms of moisture content and desired density. The values that will serve as reference for field operation are usually obtained from the laboratory compaction tests carried out on representative soil samples. The result is a value of moisture content called "optimum" at which the density is a maximum. The laboratory tests gives information onchanges in soil structure, strength, and permeability of the soil at the different moisture contents the soil is taken through during the test. The result isoptimum moisture content and maximum dry density values for the soil. Two approaches are identified from the laboratory test; these are the dry and wet side of the optimum moisture content. Depending on the design objectives and project at hand, laboratory tests will indicate the appropriate path to achieving the optimum content and maximum dry density for a given suitable soil. For example when clay soils are compacted at moisture content above the optimum; the dispersed structure results. This dispersed structure is known to sustain very large deformation without failure, even though the shear strength is smaller than that of the flocculated structure that results in compactingthe same clay soil on the dry side of optimum. This flocculated structure can sustain small strain or deformation. This suggests that for highway work clay should be compacted on the dry side of the optimum to optimum, since smaller strain are associated with highway pavement subgrade in general (Bowles...

3.0 Field control of compaction operations

Civil engineers have overtime developed methods to check the density and moisture content of compacted soil in the field. These methods can be classified into two;

- Quality control or in-construction methods, and
- Quality assurance or post construction methods.

3.1 Quality control or in-construction devices

A brief description of the devices, principle of operation, and their uses follows.

3.1.1 Sand cone and core cutter devices

Two of the oldest methods of compaction quality control devices are the sand cone or replacement method (ASTM D1556 - 07) or sometimes called balloon density method when balloon filled water is used to determine the size of hole.And core cutter method (ASTM D2937 - 10). The former is used for both fine andcoarse grained soil while the latter is used for fine grained soil(essentially clay) materials. The two methods constitute quality control methods. In close association with the two methods is the speedy moisture tester. This is a device for rapid and accurate determination of moisture in soil samples in the field. When used in association with the sand cone replacement and core cutter method a rapid determination of the field density and moisture content of compacted field is achieved in the field.

A list of other compaction quality control devices follows with brief description of each;

- The Soil Compaction Supervisor (SCS)
- The Humboldt Geogauge -ASTM D6758
- The Clegg Hammers (10-Kg and 20-kg devices)
- The Utility Dynamic Cone Penetrometer (Utility DCP)
- The Nuclear Density Gauge(NDG)

3.1.2 The Soil Compactor Supervisor

This equipment was originally developed for used by gas utility companies to check compaction of the right of way gas pipes/utilities after laying in what is called "bellhole" street excavations, (Miller and Mallick, 2003).It consists of hand- held meter and a disk shaped disposable sensor, which is connected to the meter by a wire. A polymer- based piezoelectric element is bonded inside of the top surface of the sensor. The general theory of operation is based on the mathematical procedure referred to as the "Peak Detect Algorithm" (Torbin and Heirtzler, 1995). The sensor is initially placed at the bottom of a un- compacted lift of fill. The meter is turned on as the compactor passes over the sensor and a green "processing" light appears on the meter. The enclosed piezoelectric element within the disk produces a voltage in response to compression waves transmitted through the soil from the compactor. The voltage level is proportional to the amplitude of the pressure wave reaching the sensor and is dependent on several factors (moisture, soil type, compactor characteristics, etc.). The most important factor for the peak detect algorithm is soil density. Initially, the un-compacted soil is at a relatively low density and so the efficiency of transmission of pressure waves through the soil is low. Thus, the corresponding voltage response generated by the sensor is also small. As the soil becomes more compact, the transmission efficiency increases and the voltage produced by the sensor similarlyincrease. During this process, the visual signal on the meter advances from the green processing signal to a first and then a second level green light signal. Theoretically, when compaction is optimized (i.e., when the soil reaches the maximum achievable density under a given set of conditions), the voltage increases level off. A mathematical algorithm programmed into the hand-held meter filters and manipulates successive voltage readings to determine when that asymptotic value has been achieved. The operator is then notified by a visual "red light" signal from the meter that the lift has been sufficiently compacted.

3.1.3 **The Geogauge (Soil stiffness gauge)**

The GeoGauge (formerly known as the Soil Stiffness Gauge), is a hand-held portable instrument produced by Humboldt Manufacturing Co.() The GeoGauge weighs about 11.4 kg, is 28 cm in diameter, 25.4 cm tall, and rests on the soil surface via a ring—shaped foot. Vibration of the foot produces a deflection which is proportional to the foot geometry, Young's modulus and Poisson ratio of the soil. It indicates soil stiffness as a measurement of the ratio of force to displacement;

$$K = \frac{P}{\delta} \qquad (1)$$

where K= Stifness

P= Force

δ= displacement.

Procedure for the use of the Geogauge is described in the manufacturer's manual, (Humboldt, 2007). The equipment complies with ASTM D6758.

When placed onthe surface of the ground it evaluates the stiffness of the top 225 mm to 300 mm of material.The GeoGauge imparts very smalldisplacements to the ground ($< 1.27 \times 10^{-6}$ m or < 0.00005") at 25steady state frequencies between 100 and 196 Hz. Stiffness isdetermined at each frequency and the average from 25frequencies is displayed. The entire process takes about oneminute.For quality control compaction operation in the field, a test strip section is required. Stiffness values are obtained for this tests section and these are used to set the target for the eventual compaction operation. The Geogaue performs better in Silty- Clayey soil and stone base materials than in sandy soil.

3.1.4 The Clegg Hammers (10-Kg and 20-kg devices)

The Clegg hammer is a device originally invented by Dr. Baden Clegg of Australia. It was originally designed to check the hardness of Tennis lawn, cricket field, football, and golf course field. The reading of the Clegg hammer is in Impact Values,(IV). The use of the Clegg Hammer to estimate dry density values requiredvery carefully-determined calibrations for each material under consideration.The ASTM standard D-5874 covers the determination of the Impact Value(IV) of soil.

The Clegg impact value IV, has been correlated with both CBR (Clegg Impact Soil Tester News Letter, 1986); and Strength of cement stabilized soil(Nussbaum, and Okamoto, 1985). The respective relationships are as follows;

$$CBR = [\,0.24\,(IV) + 1\,]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (2)$$

and

$$\mathrm{Log} f_c'' = 0.0005583 + 0.0090\ \mathrm{Log}\,(IV) \ \ldots\ldots\ldots\ldots\ldots\ldots \qquad (3)$$

Where f_c'' = cement stabilized soil compressive strength, N/mm^2

IV = Clegg Hammer Impact Value.

The only difference between the 10 kg and 20 kg device is just the weight and portability. The Clegg hammer does not have a moisture reading device; this forms part of the calibration.

The Clegg hammer has been modified to

- be easily used on the site,
- acquire and store data in real time,
- be more portable with wheels that can be used to move around site,
- be fitted with GPS for positioning of measured location
- Direct moisture read out facility

A study by Farrag et al (2005), indicated that the correlations between impactvalues and relative compaction for both the 10 kg and 20 kg is poor in sand and stone-base soil andbetterinsilty-clay soil.

3.1.5 The Utility Dynamic Cone Penetrometer (Utility DCP)

This was developed for use by the utility companies for evaluating the compaction of backfill in trenches and bellholes. The Utility-DCP has a drop weight of 2.27 kg, which is used to drivea small cone 8.255 cm into the soil.The number of blows that drives this distance in a given relatively compacted soil givesas an indication of the degree of compaction.The utility cone is a pass/fail gauge. The evaluation criterion is a pre-determinednumber of blows. The number of blow isusually calibrated for the various soil types.

A number of calibration testshave beenperformed (Todres, 1987, 1989a, 1989b, 1990, 1999) in order to correlate cone results withmeasurements of field densities from the sand-cone and Nuclear Density Gauge devices. Theseprevious works resulted in variouscorrelations for various soil types.

Farraget. al.(2005) indicated that the Utility DCP correlates well with respect to the no of blows and degree of relative compaction in sandy, silty-clay, stone. That is for the given penetration of 8.2 cm; the no blows required goes higher with increasing degree of relative compaction.A similar trend is observed for increase in water content up to maximum.

3.1.6 The Nuclear Density Gauge (NDG)

The Nuclear Density Gauge (NDG) represents the most advanced and precisioncompaction quality control device available today. It operates by producing small doses ofbackscattered gamma waves. The radiation reflected from the soil is detected at the base of the gauge and converted to soil density when the gauge is calibrated tothe specific soil. It is simple in operation once it is calibrated to the soils in the field. Itsoperation and use is covered in both ASTM Standard D-2922 ,(2002) and D-3017, (2002).

Some points to note that is common to the compaction measuring devices

- All the devices readings must be calibrated in each situation of use; where the measurement parameter is correlated to relative densities and moisture content
- Except the NGD none of the devices can give density and moisture values directly.
- The NDG needs a licensed personnel to operate it and the possibility of improper use of the radioactive element makes the process of purchasing it very involving,

3.2 Compaction Quality Assurance Evaluation Methods (Post Construction Evaluation)

These include

- The Standard Dynamic Cone Penetrometer (Standard DCP).
- - The Panda.
- Seismic refraction using elastic P-wave.

3.2.1 The Standard Dynamic Cone Penetrometer (Standard DCP)

The DCP consists of 6.8 kg steel mass falling through a height of 50.8 cm that strikes the anvil to cause penetration of a 3.8 cm diameter, 45° vertex angle cone that has been seated in the bottom of a hand augered hole.The penetration of the cone into the soil is read ona vertical scale and recorded in the field, while the associated numbers of blows is also recorded.

DCP is relatively inexpensive, easy to transport and to operate, and isuseful as apost compaction evaluation tool since the weight of the hammer issufficient to drive the cone to a distance of about 0.914 m into the soil. It requires two people to operate, one to drop the hammer and the other to read the depth of penetration.

In using the DCP, the main parameter is the Penetration Index which is cm/blow. The penetration index is plotted with depth. There is no direct reading from the plots with regard to the quality of soil compaction. The plots, however, can be usedto identify the boundaries of soil layers (when significant changes in DPI valuesoccur) and as an indication of the relative density of the layers. The penetration index values have been correlated with some other parameters like the CBR, dry densities by different workers.

Specification for compaction control usually comes in acceptable values of DPI; for example;Minnesota Department of Transportation specified DPIlimit values of DPI < 1.91 cm/blow for each 7.5 cm lift. If the inverse of the DPI on the horizontal axis is plotted against depth on the vertical axis, a graphic picture of the strength relationship with depth of the soil is obtained.

The DPI cannot be used independently; its results must be compared with relative compaction results from other devices.Farrag et al. (2005) gives the following results For Standard-DCP results corresponding to 90% Relative Compaction for the following soils; Sand(2.8 blow/cm),Silty-clay(5.5 blow/cm),Stone-base (5.08 blow/cm).

ASTM Standard D6951/D6951M – 09 covers the specification and operation of the standard DCP.

3.2.2 The Panda

The PANDA was designed by Dr. Roland Gourves, a lecturer in soil mechanics at CUST, Blaise PascalUniversity, Clermont-Ferrand, FranceSince 1991. It has become widely used and accepted across France, Its parts consists ofis a light-weight (total weight of equipment 20kg) dynamic conepenetrometer, which uses variable energy and can be operated by one man to testsoils in almost any location to a depth of 6 meters. Asthe cone rod is driven into the soil, an accelerometer measures the impact velocity and a retractable tape measures the penetration depth. Blow from a hammer to the head of the tool provides the energy input. A unique microprocessor records two parametersfor each blow of the hammer, the speed of impact and the depth of conepenetration, by measuring the output from two sensors The dynamic coneresistance (q_d),and current depth are then calculated and displayed in real time.The accompaniedsoftware reduces the data and compares it with established pre-calibrated curvesfor various standard soils. The calibration is based on simple classification systemusing plasticity and grain size distribution.It has 18 different natural soils to choose from, three different levels of compaction (95%of optimum Proctor, 98.5% of optimum Proctor and 97% of modified Proctor), and achoice of moisture contents (either wet or dry of the optimum moisture content), over130 different choices of materials are available in the software. After the appropriatematerial has been chosen the software then plots two 'lines of tolerance' on to thegraph which relate to a chosen density for that material. Resistance value beyond the line to the right or between the tolerances meets compaction specification, while beyond it to the left means rejection.The software is flexibleenough to allow different layers and thickness of soil compacted and hence the whole thickness to be evaluated.

3.2.3 Shallow seismic refraction survey elastic P-wave

Ilori et al.(2013), proposes this method of post construction evaluation of compaction using elastic seismic P-Wave. The method is based on the two equations namely:

$$V_p = \sqrt{\frac{E}{\rho}} \quad \dots\dots\dots\dots\dots\dots \quad (4)$$

And

$$\gamma = 3.2V_p^{\ 0.25} \quad \dots\dots\dots\dots\dots\dots \quad (5)$$

Where Vp = longitudinal wave velocity in the material

E = Young's modulus of the material, and

ρ = Density of the material

γ = Unit weight of the material

Equation 4 is a well-established relationship, while equation 5is one of two equations proposed by Tezcan et al (2009), to determine unit weight (in-situ density) of a soil from seismic P-wave velocity. In a series of seismic surveys, carried out to determine P-wave velocity of compacted subgrade of some highway pavement, the expression in equation 5 was found to predict accurately unit weights of the subgrade soil.

It is known that since P-wave is highly susceptible to moisture changes, the P-wave velocity of a soil at its optimum moisture content is both discrete and unique that it can be used to assess the quality of compaction.

Above or below the optimum moisture content, the P-wave velocity of the soil is different. Although P-wave velocity is known to increase with moisture content; however, for compaction process; moisture content that is above the optimum moisture content is accompanied with lower density. This implies lower velocity than at the optimum. Although, it has been observed that field values obtained for Young's modulus are usually larger than laboratory values obtained from tests on remolded soil (Daleiden et al, 1994; Nazarian, 1995; and Seed et al, 2000), there is no such controversy over density values with respect to compaction. The authors therefore propose the use of laboratory density values from which modulus values computed are taken as field values. The authors proposed the following procedure;

1. From the laboratory values of maximum density obtained from compaction tests to serve as control to field values: the corresponding P-wave velocity is determined using equation 5
2. From equation 4 the soil modulus of elasticity of the control sample is calculated.
3. Field values of P-wave velocities determined are referenced to that determined for the control, corresponding modulus and densities are now back calculated using equations 4and 5 respectively.

This method is aimed at compaction evaluation for subgrade and thesubbase.

4.0 From quality control and quality assurance to intelligent compaction(IC)

4.1 Introduction

Intelligent compaction (IC) is an emerging technology that involves simultaneous compaction and monitoring of the compacted material by compacting machine (often Mechanical Rollers). It is a technology that was developed in Europe about 40 years ago as a result of the investigative work of Dr. Heinz Thurner of the Swedish RoadAdministration in 1974; on the relationship between drum harmonics and soil compaction properties. Partnering with geodynamic, their association led to the development of the Compactometer and Compaction Meter Value (CMV).

4.2 Basic Features of Intelligent Compaction

Manufacturers of compaction equipment have developed widely differing technologies for intelligent compaction. Essentially, IC consists of

- Sensors and feedback control system that picks information from the materials that is being compacted, process it in real time and feed it back to the system and also to the machine for the operator to view and respond accordingly
- Sensors or compaction meter or accelerometers mounted on the drum monitors the applied compactive effort, frequency, and the response of the materials being compacted.
- Global Positioning System that maps precise location of the roller, speed, and number of passes over a given location.

according to FHWA document IF-12-002,(2011).Themethodology to calculate material response to compaction is often proprietary, resulting invarious types of intelligentcompaction measurement values (ICMV)".Like any other compaction monitoringdevice, the ICMV is calibrated with the density or modulus of the soil which have beendetermined by other in-situ test devices.Compaction curves from ICMVs and in-situ test resultscan be established to indicate the target ICMV and optimum roller passes.

4.3 Intelligent compaction meter values (ICMV)

Different manufacturer of compacting machines have come up with different mode of measuring soil response to vibratory rollers. Thefollowing is a list ofmanufacturers and type of ICMV, proprietary name and unit of measurement

1. Ammann/Case - Stiffness or ground bearing capacity (as relate to the plate loading tests)(Kb)-Ammann Compaction Expert-Plus (ACEplus).MN/m
2. Bomag -Vibration modulus (Evib).VarioControl.MN/m2
3. Caterpillar:Compaction Meter Value (CMV). No unit
4. Dynapac: Compaction Meter Value (CMV).-Dynamic Compaction Analyzer for Soil with GPS (DCA-S (GPS)). No unit
5. Sakai -Compaction Meter Value (CMV). Sakai Compaction Information System (CIS). No unit

5. **Deep compaction machines**

Smooth wheel, sheep foot, and pneumatic tire rollers are compacting machines that are routinely used in highway construction. Since soil is usually spread and compacted in 'lifts' of 150 mm to 300 mm, the effective depth of compaction for compacted lifts cannot be more than 300 mm. Vibratory rollers with over 11 tonnes has been listed with compaction depth of between 300 to 1500 mm(Compaction, 2001).Manufacturers of earthworks equipment in exploring ways to reduce cost of earthworks operation involving compaction by reducing active machine time to achieve the same amount of work began experimenting with different roller shapes other the traditional smooth wheel and sheep foot shape rollers. "BOMAG" came up with a 26 Ton polygonal shape roller compacting machine. This polygonal drum roller is fitted withhigh dynamic force generating system and also the BOMAG VARIOCONTROL system, (Kloubert, 2009). The BOMAG VARIOCONTROLintelligent system compaction accessories indicates the degree of soil compaction simultaneously as the machine carry out compaction operations. Compared to the standard smooth and sheep foot roller the polygonal drum roller achieves

- higher degrees of compaction
- deeper compaction depths up to 2.0 m
- less permeability

- higher load bearing capacities
- substantial cost savings

In two of the cases reported by Kloubert,(2009); a 20 km highway construction and the earthworks in a port expansion project in Dubai; compaction of up to 90% and 95% modified proctor density were achieved in earthworks compaction over a thickness of 1.50 m in each case.The type of compaction carriedout bythis compacting machine is referred to as "Rolling Dynamic Compaction (RDC), by Jaskaet.al,(2012). He reports from field trial of the polygonal drum of compacting roller, that depth of influence for which there is significant and quantifiable improvement with theroller is approximately 2.1 m.

6. Compaction and Highway works in Nigeria.

It is common knowledge among non-civil engineering -professionals and laymen that roads in the Northern part of the country are "better constructed" and last longer than in the Southern part. The fact that the dry season period is longer in the North than the south partly accounts for the above fact. This is because in the southern part of the country a reasonable number road construction takes place during both the rainy and dry seasons. Highway earthworks are carried out at optimum moisture content (OMC), above or below the OMC, the resulting earthwork will not be durable since the strength at this moisture content will be less than the maximum. Therefore earthworks undertaken during rainy and longer rainy seasons are prone to water content that are difficult to control which will result in lower strength than is required. This often account for high failure rate of pavement shortly afteropening such pavement to traffic.

Compaction quality control equipment within the Nigeria environment is limited to sand replacement and core cutter method. Most construction companies utilize these two methods with speedy moisture tester to determine the water content of compacted soil. Very few of the construction companiesutilize the Nuclear density logger. The other devices are not employed at all or you may have isolated cases of one of the other devices listed above. Among the quality assurance devices few may have the Dynamic cone penetrometer or a variant of it for example the German light weight penetrometer designated LRS 10 (10 kg being the weight of the hammer) which Julius Berger Nigeria PLC have. Even in this case it is rarely used for evaluating compacted soil.

Intelligent compacting machines are virtually none existent, neither the deep compacting polygonal drum compacting machines. The situation above places compaction engineering practices in Nigeria at the very basic level of practice and also completely out of tune with good modern practices.

7.0 Conclusion.

All devices mentioned above (both quality control and quality assurance) must be calibrated on site before their use on a site;exceptions to this are the two traditional devices of sand cone and core cutter. Others are utility DCP and standard DCP. Both the 10 kg and the 20 kg clegg hammers and the Panda are factory calibrated.Intelligent compaction is a technology that has a lot of advantages and promising potential for the construction industry. The present situation in which there are differentintelligent compaction measurement values (ICMV)by manufacturer poses some challenges in learning to utilize them. These will need to be harmonized so that ICMV value from one manufacturer can easily be converted to the one of another. This is a software problem. The polygonal drum roller has been proven to be time and cost saving over the usual smooth wheel and sheep foot roller, hence its active use in compaction works will definitely increase. Nigeria construction industry should make effort to gradually integrate these new innovations in compaction engineering in their operations.

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