NBRRI

CONSTRUCTION DIGEST
No. 4

LABORATORY AND FIELD TESTS FOR QUALITY CONTROL OF ROAD WORKS

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NIGERIAN BUILDING AND ROAD RESEARCH INSTITUTE
(FEDERAL MINISTRY OF SCIENCE AND TECHNOLOGY)

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Danladi Slim MATAWAL

DIRECTOR-GENERAL: *PROFESSOR DANLADI SLIM MATAWAL*

NBRRI NIGERIAN BUILDING AND ROAD RESEARCH INSTITUTE
(FEDERAL MINISTRY OF SCIENCE AND TECHNOLOGY)
(Building Capacity and Setting the Pace in indigenous Construction Technology Development)

Administrative Headquarters: NBRRI, Plot 449, Samuel Ogedengbe Crescent, Jabi. PMB 5065, Wuse GPO Abuja
National Laboratory Complex: NBRRI,Km 10, Idiroko Road, PMB 1055, Ota, Ogun State, Nigeria
Website: www.nbrri.gov.ng

JANUARY 2014

NBRRI Investigators

Matawal Danladi S. *is a Professor of Civil Engineering and the Director-General/CEO of the Nigerian Building and Road Research Institute (NBRRI) Abuja, Nigeria*

JANUARY 2014

PUBLISHER'S NOTE: All opinions expressed are entirely that of the author.

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FOREWORD

The life-span of a Road pavement depends primarily on the quality of its surface courses and, very profoundly, on the foundation materials. While surface courses are constituted from Bitumen and Coal Tars for the asphaltic layering, the foundation is intrinsically soil or soil-based materials with stabilization. The field sourcing, laboratory testing and placement procedures of construction materials for the foundations of roads are a fundamentally critical issues that define both the quality and the durability of the road pavement.

This article discusses the basic Laboratory parameters required to define and specify good quality soils and set the standards for field application. It also elaborates on some of the field equipment employed in the preparation, placement and processing of soils in-situ to form the foundations of road pavements. The basic theorems, logics and principles guiding good field practice and optimal application of these machinery are defined while the clear correlations between the laboratory specifications defining tests and field techniques are espoused. Some of the elementary mathematical expressions are explicitly defined while the extremely important influence of moisture in soils is discussed.

The article is to be viewed as an indispensable companion to engineers and practitioners who work and supervise roadworks and earthdam construction

Danladi Slim MATAWAL, DIC,PhD, CEng, FNSE, RE(coren), FAEng
(Professor of Civil Engineering)
Director-General/CEO, NBRRI

January 2014

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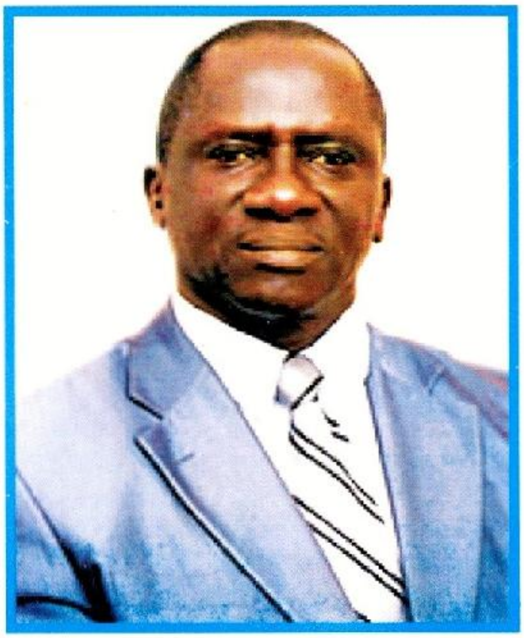

Danladi Slim MATAWAL DIC, PhD, CEng., FNSE, RE(coren), FAEng.
(Professor of Civil Engineering)
Nigerian Building and Roads Research Institute, NBRRI
(Federal Ministry of Science and Technology)

ABSTRACT

Road works comprise of many specialized operations such as land surveying, soil engineering, pavement design, reinforced concrete and numerous laboratory and field works transcending numerous branches of civil engineering. Land surveying for road works, as example, may involve aerial photogrammetric principles and mosaics, tachometric principles, Chain and/or EDM for distance measurement, Traversing for angle measurements, and Leveling for altitude/reduced level measurements. Similarly, Pavement design involves use of cutbacks, coal tar, bitumen and aggregates. Every measurement conducted is intended for direct field application to make a project successful. This paper tackles primarily laboratory and field tests that involve the use of Soil, by far the major construction material, for road works. It tackles the topics of compaction, in all ratifications: An operation so much used that it is taken for granted as to details, specifications, application and control.

1.0 INTRODUCTION

Compaction is the primary operation that processes soil, both in the laboratory and the field, for construction of roads. Compaction is the process of mechanically pressing together the particles of soil to increase its density. Compaction rearranges the soil particles into a closer state of packing, and generally results in higher shear strength, lower compressibility, increased stability and bearing capacity; and reduced susceptibility to water content changes. It has extensive applications in the construction of embankments for earthfill dams, canal embankments and other purposes, fills and for strengthening the subgrades of roads/highways and runways. It is the principal activity in the construction of sub-base and base courses for roadworks. Peculiar applications of compaction are encountered in many other common civil engineering and building operations. For example, in granular soil deposits at construction sites of buildings, bridges, highways and dams, the in-situ soil may be very loose and liable to large elastic displacements or settlement. In such a case, the soil will need to be made more dense to increase its unit weight and thus the shear strength. In other instances, the top layers of soil are undesirable and must be removed and replaced with better soil on which the structural foundation can be built, a process known as backfilling. Even in ground improvement techniques such as stabilization, compaction is always involved. Compaction can be achieved by rolling, tamping or vibratory action. Compaction is a rapid process confined to the air voids as opposed to the slow consolidation process that actually depends on the dissipation of excess pore water pressure. Consequently compaction improves characteristics of soils by increased shear strength, decreased permeability, reduced settlement of foundations and increased slope stability of embankments.

2.0 THE PRINCIPLES OF COMPACTION

Generally, the purpose of compaction is the application of mechanical energy to the soil to re-arrange the solid particles and reduce the void ratio, e, by expelling air from the voids of the soil mass. It is a general principle for improving soils so that the smallest possible void ratio is achieved economically because:

(a) The maximum shear strength occurs approximately at the minimum void ratio. The undrained shear strength of clays, as example, is known to bear a direct correlation to its density so that high strengths are achieved at higher densities and unit weights.
(b) Large air voids may lead to subsequent compaction under working loads causing undesirable settlement of the structure during service.
(c) If large air voids are allowed in the soil, they may subsequently be filled with water when there is increased precipitation. This, depending on the stability of the soil, reduces the shear strength of the soil. This increase in the water content may also be accompanied by appreciable swelling, and consequent loss of strength, in some clays.

Some natural cohesionless soils (particularly certain uniform fine sands deposited under water) have a loose structure which is very unstable. These soils must be compacted before loading and the process of vibroflotation has been used extensively in Lagos, Nigeria, on such soils.

Compaction is measured either in terms of dry density achieved, or dry unit weight. The use of density (ρ) shall be adopted in this paper, but the use of unit weight (γ) involves only a simple soil properties' translation from a scalar to a vector quantity using the acceleration due to gravity, g(=9.806m/s), so that $\gamma = g.\rho$.

If bulk density,	ρ_b = Mass (M)/volume (V)
Dry density,	ρ_b = Mass of solids (M_s)/Volume (V), and
Moisture content,	w = Mass of water (M_w)/Mass of solids (M_s)

Then $\rho_b = \frac{M}{V} = \frac{(M_s + M_w)}{V} = \frac{(M_s + w.M_s)}{V}$ Or $\rho_b = \frac{M_s}{V}(1 + w) = \rho_d(1 + w)$

Therefore $\rho_d = \frac{\rho_b}{(1+w)}$ 1

This is known as the compaction equation. The dry density is clearly a function of the soils moisture content and since it depends on the void ratio achieved from compaction, it is also much dependent on the compactive effort applied to the soil, and the nature of the soil. The unit generally used is Mg/m^3 (or g/cc) but frequently expressed in kg/m^3. The moisture content is in percent (%).

3.0 THE COMPACTION CURVE

If a plot is made of dry density, ρ_d, on the ordinate against moisture content, w, on the abscissa, a unique relationship is usually observed in the form of a curve which exhibits a clear peak, known as the maximum dry density, MDD, which occurs at a moisture content known as optimum moisture content, OMC; figure 1. The MDD of any particular soil is unique for a given compactive effort as well as the optimum moisture content, OMC, is unique. If the compactive effort is increased, the MDD will increase and the OMC will reduce. It follows that the compactive effort can be raised as high as required to achieve maximum density and consequently enhance better benefits of compaction. But the costs and energy required is not economical as the higher the compactive effort, the less the increase in MDD so that after a certain stage, it is no longer a beneficial decision. For this purpose, laboratory procedures for the determination of MDD and OMC are standardized so that the properties become intrinsic to any peculiar soil type.

3.1 AIR–VOIDS RATIO, A_r, LINE

Air voids ratio, A_r, is defined as the ratio of volume of air voids (v_a) to the total volume of soils mass (v). A line which shows the moisture content/dry density relation on the compaction curve for a constant percentage air-voids ratio (A_r) is known as an air-voids line. The soil properties relationship is:

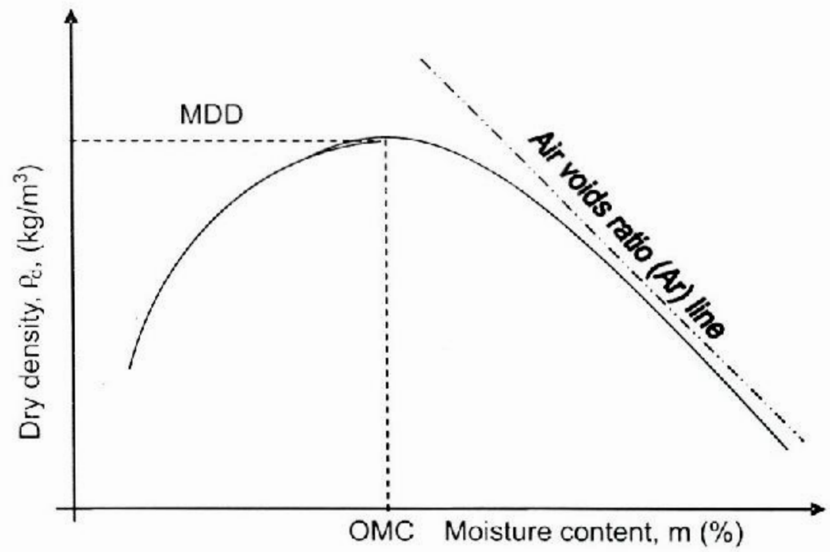

Figure 1:Typical Compaction Curve

$$\rho_d = \frac{\rho_w(1 - A_r)}{\left(m + \frac{1}{G_s}\right)}$$ 2

where G_s and ρ_w are soil specific gravity and water density, respectively; with $A_r = \frac{v_a}{v}$.

Theoretically, the maximum compaction achievable for any given moisture content corresponds to the zero air-voids ratio condition ($A_r = 0$). The line showing the dry density as a function of moisture content for soil containing no air voids is called the zero air-voids ratio line which corresponds to full saturation conditions and therefore usually referred to as the saturation line.

4.0 LABORATORY COMPACTION TESTS

Laboratory compaction tests aim at determining values of MDD and OMC for soils obtained from borrow pits and within the sites of construction in order to determine their suitability for the works. The decision as to whether any soil is competent as foundation or construction material for a given work may not depend only on compaction but also in correlation with other visual and laboratory tests. However, once the decision has been made to use the soil, the optimum moisture content, OMC, at which it must be compacted in the field to obtain a specified MDD must be determined through the compaction test in the laboratory. Three of these tests are universally used, namely:

(i) The standard proctor compaction known in UK as the British Standard Compaction or in Nigeria as the West Africa Standard Compaction, WASC. The test is governed by BS1377 and ASTM designation D-698.

(ii) The modified AASHO or British Standard (BS) Heavy Compaction and West Africa Heavy Compaction, WASC; governed by BS1377 and ASTM designation D-698.

(iii) The Vibrating Hammer test

4.1 THE STANDARD PROCTOR COMPACTION

This method is known variedly either as the standard proctor, the BS standard or the West Africa Standard Compaction (in Nigeria). Based on the BS1377 or D698-91, it was first introduced by Proctor in 1933 for Dams in California; and used a compactive effort of 600kN.m/m^3, which roughly corresponded to that available in the field at that time. The sample to be used is air-dried and passed through standard sieve size and 5kg collected. The amount of gravel retained may be noted; if quantity is large, a correction must be applied to the results. The soil passing the sieve is thoroughly mixed with water to give fairly low moisture content (some 5 percent less than the natural moisture content of the soil, if this is known, otherwise a value of about 6 percent will generally prove suitable). The soil is placed in an airtight container for 2-3 hours so that the moisture can migrate through it and then compacted in a mould by means of a 2.5kg (5.5lb) rammer with a 50mm diameter head falling freely from 304.8mm (1 foot) height above the top of the soil. Compaction is effected in 3 layers each being given a specified number of blows, N, of the rammer.

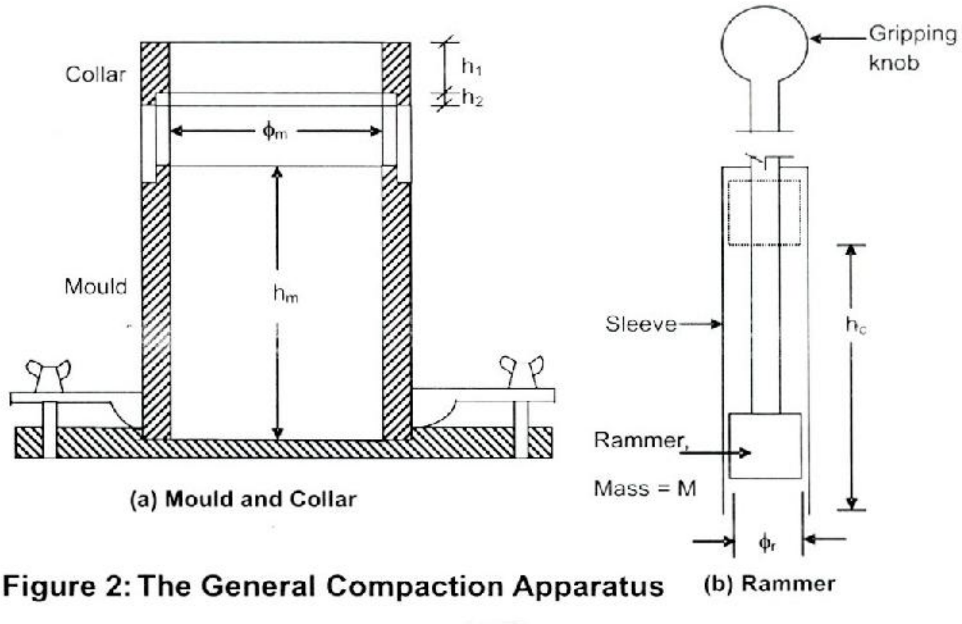

Figure 2: The General Compaction Apparatus

The compaction can be considered satisfactory when the soil in the mould is not more than about 6mm above the top into the collar, otherwise the test results should be discarded. The top of the soil is now trimmed level with the mould, on removal of the collar, the base is removed and the mould and soil are weighed. Moisture content samples are taken from the top and base of the soil. The remaining soil is broken down and mixed with the remainder of the original soil. A suitable increment of water (about 2%) is added and the test repeated. The procedure is continued until the weight of wet soil in the mould passes a maximum value and begins to decrease. Once the moisture contents have been determined, the graph of dry density, ρ_d variation with moisture content, w(%), can be plotted. Table 1 below shows that many features and specifics of this standard test actually depend on the nature of soil being tested; as a result of which there are three variations of the test.

Table 1: Specifications For Standard Proctor Test

Method	ϕ_m (mm)	Mould volume (cc OR ml)	M_r (kg)	Hc (mm)	N (No.)	Layers	Energy (kN.m/m^3)	Soil Type
I	101.6	944 (ml)	2.5	304.8	25	3	600 (kJ/m^3)	Used when ≤20%, by weight, is retained on No.4 (4.57mm) sieve
II	101.6	944	2.5	304.8	25	3	600	Used when >20%, by weight, is retained on No. 4 sieve, and sieve ≤20% is retained on 3/8" (9.5mm) sieve.
III	152.4	2124	2.5	304.8	25	3	600	Used when ≥20% is retained on 3/8" (9.5mm) and ≤30% retained on ¾" (19mm) sieve

4.2 MODIFIED PROCTOR COMPACTION

The need for higher compaction for heavier transport, airport tarmac and military aircraft gave rise to the modified proctor test designed to give a higher standard of compaction and simulate the field condition where heavy rollers are used. It was standardized by the American Association of State Highway Officials and known as modified AASHO test. In UK, it is the BS Heavy compaction while in Nigeria, it is the West Africa Heavy Compaction. The moulds used for the different soil types remain the same as for the standard proctor test but the weight of rammer is 4.54kg (10lb) falling freely through a height of 457.2mm (18") in 5 layers. The compactive energy, E, is now 2700 kN.m/m^3 (kJ/m^3), Table 2.

Table 2: Specifications For Modified Proctor Test

Method	ϕ_m (mm)	Mould volume (cc)	M_r (kg)	Hc (mm)	N (No.)	Layers	Energy (kJ/m^3)	Soil Type
I	101.6	944	4.54	457.2	25	5	2700	≤20%, by weight, is retained on No. 4 (4.57mm) sieve
II	101.6	944	4.54	457.2	25	5	2700	Used when >20%, by weight, is retained on No. 4 sieve, and ≤20% is retained on 3/8" (9.5mm) sieve.
III	152.4	2124	4.54	457.2	56	5	2700	Used when ≥20% is retained on 3/8" (9.5mm) and ≤30% retained on ¾" (19mm) sieve

5.0 OBSERVATIONS FROM COMPACTION TEST

Generally, certain conclusions are always obvious from the results of compaction tests which include:

(i) The MDD and OMC depend on the degree of compaction.
(ii) The higher the energy of compaction, the higher the MDD.
(iii) The higher the energy of compaction, the lower the OMC

(iv) No portion of a compaction curve can lie to the right of the saturation line.
(v) The MDD and corresponding OMC for a specified compaction type will vary with type of soil.

These conclusions have clearly been proved through many elaborate studies by authors in this area, example Matawal (1990) who studied the CBR-OMC relationships of several construction materials known as tropical lateritic soils whose name and properties were first espoused by pioneers like Ola (1978). However, it will be interesting to undertake further studies to supplement existing ones to analyze, in detail, the effects of compaction on such properties of soils like structure, permeability, shrinkage, swelling, pore pressure, compressibility, stress-strain characteristics and shear strength. The choice of method of compaction I, II or III clearly suggests these studies and that more care should be taken in industrial and research laboratories to comply with standards. For example, the choice is intended to address certain clear behaviors in soils; like clay which possess the propensity to swell back after compaction if the air within the voids is not effectively expelled from the fabric. Furthermore, the expeditious expulsion of water from such soils within the momentary impact of compaction is resisted by the low permeability of the clayey soils. Similar argument can be made for fine grained sands and silts.

6.0 VIBRATING HAMMER TESTS

The use of the vibrating hammer is very convenient and common for compaction tests in many laboratories, but is surprisingly omitted in most soil literature. It uses the CBR mould 127mm high (h_m) and diameter, ϕ_m, of 152.4mm with a 50.8mm collar and attached to a base plate. Soil passing the 37.5mm (1½") sieve is compacted in 3 layers using a 3kg heavy electric vibrating hammer fitted with a special diameter (ϕ_r) rammer operating for 60 seconds (1min) per layer. The operation is conducted in the same manner as for other normal compaction tests and the MDD and OMC determined from the dry density/moisture content curve. It has advantage of uniformity of impact over the manual procedure.

7.0 OTHER LABORATORY COMPACTION TESTS

A number of other uncommon compaction techniques intended for laboratory determination of dry density/moisture content curve relationship are discussed in literature. The reinforced earth specimen compaction mould was intended specifically for reinforced earth specimens but the others are fashioned for similar reasons with the routine proctor molds. They include the HARVARD MINIATURE COMPACTION, DIETERT TEST, ABBOT COMPACTION TEST, JODHPUR MINI-COMPACTOR TEST, and the MATAWAL REINFORCED EARTH COMPACTOR AND CUTTER for reinforced earth specimens.

8.0 FIELD COMPACTION

The different types of soils can be compacted in the field using a variety of techniques individually or combined to produce optimal effects. These compaction techniques can broadly be either rolling, ramming (by impact) and/or vibration; the choice of method depending on soil type, the MDD required, and economic considerations. It is important to note that general field compaction does not include special ground improvement techniques like vibroflotation, pounding, ponding and others. Broadly, we may have either Tampers or Rollers.

8.1 TAMPERS: This is a hand-operated rammer consisting of a block of iron or stone of 3–5kg mass attached to a wooden rod. The rammer or tamper is lifted up about 300mm and dropped on the soil for compaction. Mechanical rammers of compressed air or gasoline power device can be much heavier, 30–150kg even though up to 1000kg exist. As expected, Tampers are for smaller jobs and compaction adjacent to existing structures of confined areas which will be damaged by the larger rollers. Examples include building foundations and floor fillings, trenches and drainages, and behind bridge abutments and culvert wingwalls, where other methods of compaction cannot be used. They may be used for all soils but owing to low output, Tampers are uneconomical where large quantities of compaction are required, like highways.

8.2 ROLLERS: These are driven and designed to apply a specific contact pressure which is directly related to the degree of compaction achievable. The more the number of passes the roller makes on the soil, the higher the compaction achievable. For economy, the number of passes is generally restricted to reasonable limit of 5 to 15 because beyond a certain limit, the increase in density with increased passes is no longer appreciable. Similarly for economy, a layer thickness should not be below 150mm even though compaction of soil increases with decrease in the thickness of the layer. Furthermore, the compaction depends upon the speed of the roller which should be so adjusted to achieve maximum effect. The general types of rollers include:

a) SMOOTH-WHEEL (Or DRUM) ROLLERS: The conventional three-wheel type has two large smooth-faced steel wheels in the rear and one smaller smooth-faced drum in the front weighing from 2,000 to 15,000kg. Tandem rollers weigh from 1,000 to 14,000kg while the three axle Tandem rollers weigh from 12,000 to 18,000kg. Smooth-wheel rollers are usually self-propelled equipped with a dutch-type reversing gear so that they can be operated forth and back without turning. Many smooth wheel rollers now produce vertical vibration during compaction and are suitable for proof-filling subgrades and finishing the construction of fills with sandy or clayey soils. They provide 100 percent coverage under the wheels with a contact pressure as high as 300 – 400kN/m^2. They do not produce uniform compaction when used on thick layers but are excellent for granular base courses of highways.

b) PNEUMATIC RUBBER-TYRED ROLLERS: These range in size from the smaller wobble wheel rollers to the very heavy types comprising of 9 to 11 wheels fixed on two axles and are thought to be better, in many respects, than smooth wheel rollers. The common form of pneumatic roller, weighing up to 2,000kN, consists of a box or platform mounted between two axles, the rear of which has one more wheel than the front, the front axle arrangement to track in-between those mounted on the rear axle producing 70-80 percent rolling coverage of the width of the roller. Tyre pressures in small rollers can be up to 250kpa but range from 400 to 1050kpa in the heavier rollers. Small rollers have tyre loads of about 7.5kN while it ranges between 100 to 500kN per tyre in the heavier types. They are usually loaded with kentledge so that the contact pressures are in the order of 600 – 700 kN/m^2. Pneumatic rollers, which are suitable for sandy and clayey soil compaction, produce a combination of direct rolling pressure and kneading action. The rollers are either available as a self-propelled unit or towed by either a track laying or a pneumatic tyred tractor.

c) SHEEPFOOT ROLLERS: This consists of a hollows drum with a large number of projections (each of area of 25 – 90cm^2), mounted on a steel frame (chassis). The projections penetrate the soil layers during the rolling operations causing compaction. The drum weight can be varied by filling partly or fully with water, sand or ballast; they are mounted singly or in pairs. They are most effective in compacting cohesive soils, the contact pressure under the projections varying from 1500 to 7500kN/m^2. Rammers for compacting the soils comprise of pneumatic and internal combustion type while there are internal combustion type jumping rammers, known as frog rammers. The vibrators consist of a vibrating unit of either the out-of-balance weight type or a pulsating hydraulic type mounted on a screed plate or roller.

d) VIBRATORY ROLLERS: In these, vibrations are induced in the soils which make it efficient in compacting granular soils, with no fines, up to 1m thick. However, the thickness must be appreciably reduced to maximum of 300mm if there are fines. As observed for sheepfoot rollers, vibrators can also be attached to smooth wheel and pneumatic tyred rollers to send vibrations into the soil being compacted. Table 3 presents a summary of general knowledge of rollers taught in the classroom.

The effort or compaction energy is measured from the relation:

$E = (N.n.w_r.h_m)/V$ 3

Where E = Compaction energy, N = number of blows per layer

n = Number of layers, w_r = mass of rammer

h_m = Height of drop of rammer, V = volume of mould

Generally, compactive effort is raised by vibration for both heavy clays and granular soils. Rammers and vibrators are used for all soil types and are useful when rolling is impracticable due to restricted site conditions. Vibrators will produce high dry densities at low moisture contents in sands and gravels and are particularly useful when other plants cannot be used.

Table 3: Roller Types and Output

Type of plant	Average output of plant						Remarks (suitability)
	Compacted width, mm	Rolling speed, m/min	No. of passes	Compacted area/hr(m^2)	Layer depth, mm	Output per hr (m^3)	
8,000kg smooth wheel roller	1800	70	4	1220	150	185	All soil types except clay and uniformly graded sand
8,000kg vibrator tyre roller	2000	37	4	870	300	265	All soils types
45,000kg pneumatic tyred roller	2400	66	3	4000	250	612	All soil types but particularly good on wet cohesive soils
Sheepfoot roller (towed and non vibratory, clubfoot)	3700	270	6 14 32	8200 3500 1530	225	1875 804 350	Different No. of passes required on clay, sandy clay, and gravel/sand
13500kg grid roller (with 80HP track layer)	1600	135	7	1500	200	300	All soil types over wide moisture content range
13500kg grid roller (with 150 HP and wheeled)	1600	270	8	2640	200	536	Not especially suited for uniformly graded sand or in wet conditions
Stothert and Pitt 72000kg towed vibratory roller (4000kg)	1700	40	7	485	225	111	Granular soils

9.0 FIELD COMPACTION CONTROL

9.1 PLACEMENT MOISTURE CONTENT

The laboratory compaction tests provide the optimum placement moisture content for utilization of soils in the field so that maximum desired density can be achieved during rolling. However, the moisture contents are not sacrosanct because the methods of compaction in the field are different from those in the laboratory. For this purpose, it is recommended in all important works that a full-scale test is conducted for the project in the field to determine the suitable placement moisture content, based on the specified layer thickness, type, mass and speed of roller as well as the number of passes. In case of small and unimportant projects, the placement moisture content may be made equal to OMC of the standard proctor test for light compaction or equal to the modified proctor test for heavy compaction. Nonetheless, it may be deliberate to alter the field moisture content to be different from OMC to achieve or improve a specific engineering property of the soil. Therefore, the laboratory OMC value may be taken as a rough guide for the placement moisture content in the field. Ideal placement moisture content when pneumatic-tyred rollers are used should be guided by OMC from standard proctor test. When sheepfoot, smooth wheel and vibratory rollers are used, OMC from the modified proctor test is preferred as a guide for the field placement moisture content.

Cohesive soils beneath pavements and floors are usually compacted wet of optimum resulting in density less than MDD to avoid large expansions and swelling pressure if the voids were left open to absorb water. Similarly, to avoid swelling pressure in the clayey cut-off soil in the impervious core of an earth dam, they are compacted wet of optimum. Highway embankments of cohesive soils, on the other hand, are generally compacted slightly dry of optimum to achieve high shear strength and low compressibility. Soil in the outer zones (upstream and downstream shells) of earth dams are compacted dry of optimum to obtain high shear strength, high permeability and build up little or no pore water pressures.

It is logical when treating borrow pits to determine whether their soil natural moisture content is dry or wet of optimum requiring sprinkling of water or spreading and drying out, respectively. However, in periods of high precipitation, drying out is not feasible and all compaction works must therefore be suspended in the face of inclement weather. The treatment of cohesionless soils is a special concern because they may not compact and do not exhibit well-defined OMC.

9.2 **RELATIVE COMPACTION:** Based on the results of laboratory compaction, specifications may be made for the compaction of the soil in the field. The ratio of the dry density ρ_{df} in the field to MDD, expressed as percentage is called relative compaction, RC.

$$RC = \left(\frac{\rho_{df}}{MDD}\right) \times 100\% \qquad \text{.........4}$$

Relative density, RD on the other hand compares void ratios but can also be in terms of density

as: $$RD = \left[\frac{\rho_d - \rho_d(\text{min.})}{\rho_d(\max) - \rho_d(\min)}\right] \frac{\rho_d(\max)}{\rho_d} x100\% \qquad \text{.........5}$$

where ρ_d = in-situ dry density, ρ_d(max) = dry density in the densest state, when void ratio is $e_{min;}$ ρ_d(min) = dry density in the loosest state, when void ratio is e_{max}. Relative density is relevant mostly for granular soils. Basically $\rho_d = \rho_{df}$ while ρ_d(max.) and ρ_d(min) are the maximum and minimum densities of laboratory compaction, respectively.

If $A = \dfrac{\rho_d(\min)}{\rho_d(\max)}$, then $$RC = \frac{A}{1 + RD(1 - A)} \qquad \text{.........6}$$

For cohesive soils, RC of 95 percent, based on standard proctor test, can be achieved using sheepfoot or pneumatic-tyred rollers. Only sheepfoot rollers are however effective in very heavy clays. In moderate cohesive soils, pneumatic-tyred rollers can be used, with tyre inflation over 600kpa, to achieve 95 percent RC based on modified proctor test. RC of 100-110 percent based on modified proctor test can be achieved on cohesionless soils using pneumatic-tyred and vibratory rollers.

9.3 FIELD QUALITY CONTROL

It is essential to check the field compaction, via physical measurements, to compare with the OMC and MDD obtained from the relevant laboratory compaction test. Basically, the desired specified dry densities dictated from laboratory tests must be achieved in the field. The dry densities and water contents must therefore be measured in the field.

Density can be very accurately measured in the field using either the core-cutter method or the sand replacement method, which are very common and simple. Nuclear methods; which are non-destructive, can also be used occasionally and they are very convenient. The oven-drying method of determination of moisture content is very accurate but takes 24 hours and cannot be used for controlling construction. The soil layer from which the sample was taken would have been buried by the time the water content is computed. Therefore the method used must give rapid, almost instant results. The Rapid Moisture Meter using calcium carbide is common and accurate but other general methods are the sand-bath technique and Alcohol method. Moisture content may also be indirectly determined using the Proctor Needle (also known as Plasticity Needle).

10.0 OTHER FIELD COMPACTION TECHNIQUES

Compaction for purposes of ground improvement is usually achieved using different techniques, with no use of Rollers. These include VIBROFLOTATION, TERRA PROBE, DYNAMIC COMPACTION, COMPACTION BY EXPLOSIVES, PRECOMPRESSION, and COMPACTION PILES.

10.1 CORRECTION FOR OVER-SIZED PARTICLES

Oversized particles, example those retained on No. 4 (¾") sieve and others specified in Table 4.1, may usually need to be removed from the soil during conduct of laboratory tests. ASTM test D4718-87 provides a correction for MDD and OMC in the presence of oversized particles. The corrected values to be used for field application are calculated as:

$$MDD(corrected) = \frac{100\rho_w}{\frac{P_o}{G_{50}} + \frac{\rho_w(100 - P_o)}{MDD}} \quad \text{.........7}$$

and OMC (corrected) = OMC $(100 - P_O) + w_O . P_O$ 8

where

ρ = density of water,

P_o = percentage of over-sized particles, by weight

G_{50} = specific gravity of the oversized particles;

w_o = saturated surface dry moisture content of the over-sized particles (fraction)

OMC and MDD are the actual laboratory compaction results and the corrections are valid for over-sized fractions of 30 percent or less of the total soil sample, by weight.

11.0 CALIFORNIA BARING RATIO, CBR

California bearing ratio, CBR, is a measurement of the strength of compacted soil, like subgrades, sub-base and base courses developed by the California Division of Highways in 1992 for evaluating the suitability of the material. It is also correlated with the thickness of the various materials required for flexible pavements. CBR is simply the resistance to a penetration of a standard cylindrical plunger of diameter 49.6mm, expressed as a percentage of the known resistances of the plunger to various penetrations in crushed aggregate, notably 13.44kN at 2.54mm and 20.16kN at 5.08mm penetrations (generally 2.50mm and 5.00mm are now used). The original test used a cross-sectional area of 3.0 'square-inches' which translates to 2395mm^2 giving the odd diameter of 49.6mm of plunger.

The CBR mould, also used for the vibrating hammer test, has internal diameter of 152.4mm with height 127mm. A 50mm collar attached makes the complete height 177mm but the final compacted trimmed height is 127mm. Dial gauges are used for the measurement of penetration and expansion on soaking. The test may be performed on a prepared specimen in the mould according to the specified compaction standard or on the soil in-situ condition.

The plunger is first seated unto the top of the sample under a specified load: 50N for CBR values up to 30% and 250N for soil CBR values over 30%. The plunger is caused to penetrate, using a motorised base support, at the rate of 1.25mm per minute. The plunger load is recorded for each 0.25mm penetration up to a maximum of 7.5mm and the load-penetration curve is drawn. Sometimes a correction is made by drawing the tangent to the curve at its steepest slope and extending it backwards to cut the penetration axis. The new point is regarded as the origin of the penetration scale for the corrected curve.

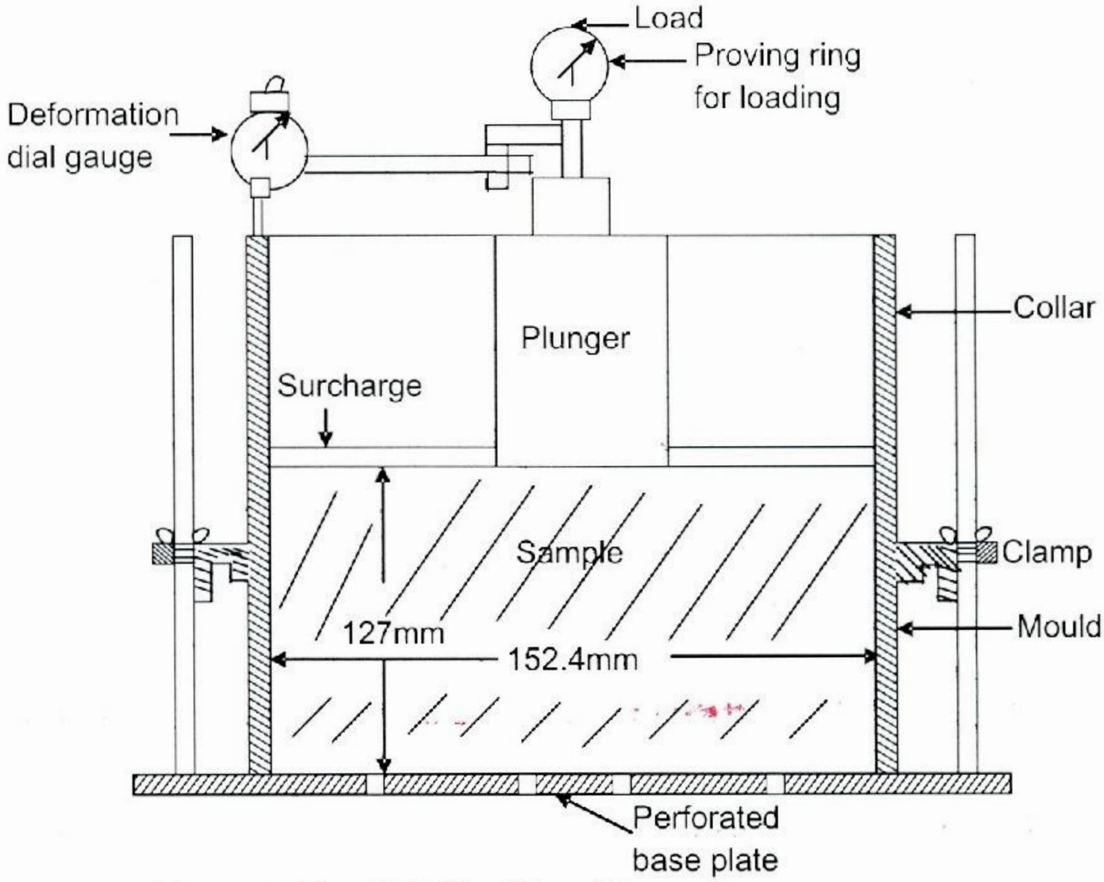

Figure 3: The CBR Mould and Test

ϕ_r = diameter of rammer; M_r = mass of rammer; h_c = height of free-fall of rammer
h_m = height of mould; ϕ_m = internal diameter of mould; h_1 = height of collar
h_2 = height of collar groove

The loads required for a penetration of 2.5mm and 5.0mm are recorded by a proving ring attached to the plunger on the loading frame. This is expressed as a percentage of the standard load at the corresponding deformation levels, for crushed rock, and is the CBR of the material.

$$CBR = \frac{Resistance\ to\ penetration\ in\ soil\ at\ 2.5m, 5.0mm}{Resistance\ to\ penetration\ in\ crushed\ rock\ at\ 2.5mm,\ 5.0mm} \times 100\% \quad ....9$$

Table 4: Resistances of Penetration in Crushed Rock

Penetration, mm	2.5	5.0	7.5	10.0	12.5
Resistance, kN	13.44	20.16	25.80	31.20	35.32

Generally, the CBR got 2.5mm penetration is higher. When CBR at 5.0m penetration is higher, the test should be repeated and if it remains so, then the 5.0mm penetration CBR is taken as the defining value. Upward concavity of curves requiring correction could be because the plunger did not come in full contact with the top of the specimen at the start of experiment or that the top layer of the soil was very soft. Surcharge weights, in the form of annular discs with a mass of 2kg, placed on the top of the