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Investigation of the Suitability of Light Falling Weight Deflectometer for calculating Resilient Modulus

Nduka Ijeh
Nile University of Nigeria

Abstract - Engineering practice looks for ways to diffuse the intensity of traffic loads through a layered system of materials in such a way that the sub grade can bear them without excessive deformation. Reliable measurements for proper characterization of materials are of essence. Measuring instruments such as the lightweight deflectometer must be continuously appraised to identify aspects that require improvement. In this research a lightweight deflectometer is assessed using three important criteria namely, the depth to which the it can be used to infer the Resilient Modulus, repeatability of results and similarity of results with values obtained by laboratory-based methods under a variety of conditions.

Being a nondestructive and portable instrument, its use in pavement condition survey may increase if data integrity is proven to be acceptable. Its suitability for calculating resilient modulus was investigated and discussed in this research with emphasis on the three stated criteria. A Dynatest 3031 model of deflectometer was used in a text box with subject materials in compacted layers. The effects of moisture content, compacted density and the flooding of subgrade on resilient modulus are also examined and discussed. Results showed a depth of influence of 300 to 450mm and Resilient Modulus values comparable to ones obtained from Dynamic Cone Penetrometer DCP and Cyclic triaxial tests but operator's expertise is of great consequence.

1.0 INTRODUCTION

Traffic loads on pavements and rails are ultimately born by sub grades. Efficient operation of roads and rails and its resultant benefits are contingent on the performance of sub grades. Although sub grades are important, their load carrying capacities are often limited and vary with the different types of soil. Sub grades can be characterized by their resilient modulus which is an important parameter in mechanistic design of pavements.

Empirical design methodology for roads and railways relying on static properties of soil are gradually giving way with the emergence of mechanistic design which considers the dynamic response of sub grades to loads. This has brought the concept of resilient modulus to the fore front. Arguably, the most critical aspect of mechanistic design is that it uses material properties that relate better to actual pavement performance.

A typical pavement element is subjected to three principal stresses namely vertical stress, shear stress and horizontal stress. The magnitudes of these stresses vary with time under the influence of a moving load. The stress levels change as the moving load approaches and are reversed as the load leaves a spot. The resilient modulus is the measure of the ratio of the deviator tress to the recoverable strain.

Resilient modulus can be obtained directly in the laboratory by performing the repeated load triaxial test on sample. It can also be obtained indirectly using a number of geophysical methods including the use of the lightweight deflectometer.

Quick and reliable in situ test results are required for speedy quality assurance of construction works. Laboratory test results take time and often create disruption of work with huge consequences. The potentials for the use of the lightweight deflectometer being a portable in situ nondestructive measuring device for resilient modulus appear great. In theory, it utilizes the response of a material to a predetermined load in estimating its surface modulus but the level of accuracy and repeatability to be expected from this device need to be determined

The portable or lightweight deflectometer LWO was developed to rapidly assess the in situ elastic modulus of surface soils. The LWO is portable and testing is quick. A typical LWO has a mass of approximately 20 kg, can be operated by one person [1]. It measures deflections and surface modulus as a result of the impulse load delivered to the pavement. The data generated are then used in back calculating resilient modulus.

Accurate measurement and testing of engineering properties of materials is vital to the road engineer's job as good engineering

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decisions are often based on them. Using a series of laboratory tests, this research sort to determine how suitable the lightweight deflectometer can be in some specific and general terms. Results of tests are analyzed and discussed.

This research work aims to investigate the suitability of lightweight deflectometer in estimating the resilient modulus of granular materials for pavements and railway embankment construction. To this end specific objectives are outlined as follows.

- Perform tests to obtain deflection and surface modulus values with a lightweight deflectometer on sand samples which are to be compacted in layers.
- Perform dynamic cone penetration test on same layered system of sand and ballast.
- Perform repeated load triaxial test on soil sample.
- comparative analysis on data obtained from tests.

2.0 LITERATURE REVIEW

2.1.1 Mechanical behavior of soil

The engineering approach to the study of soil focuses on the characteristics of soils as construction materials and the suitability of soils to withstand the load applied by structures of various types.
Earth materials are three-phase systems. In most applications, the phases include solid particles, water, and air. Water and air occupy voids between the solid particles. For soils in particular, the physical relationship between these phases must be examined. The relationship between weight and volume can be expressed as:

Wm=VmGmyw

Where:

Wm is the weight of the material (solid, liquid or gas),

Vm is the volume of the material,

Gm is the specific gravity of the material (weight of a material relative to the weight of an equal volume of water - dimensionless) and
yw is the unit weight of water (mass x gravity 1.0 g/cm3 and 9800 N/m3).

Relationships between volumes of soil and voids are described by the void ratio (e) and porosity (n).
The void ratio is the ratio of the volume of voids to the volume of solids:

e=Vv/Vs

Whereas the porosity is the ratio of void volume to total volume: (expressed as a percent)

n = Vv / VT x 100%

These terms are related and it is possible to show that

e= n/1-n

Poisson's Ratio

u = E1/ IE

Where E1= lateral and strain E = is axial strain

2.1.2 Index Properties and Classification

An important division of soils for engineering purposes is the separation of coarse-grained or cohesionless soils, from fine-grained or cohesive soils. Cohesive soils, which contain silt and clay, behave much differently from cohesionless materials. The term cohesion refers to the attractive forces between individual clay particles in soils. The index properties that apply to cohesionless soils refer to the size and distribution of particles in the soil. These characteristics are evaluated by mechanical analysis, a

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laboratory procedure that consists of passing the soil through a set of sieves with successively smaller openings. The size of the sieve openings determines the size of the particles that can pass through them. After the test, the particles retained on each sieve are converted to a weight percentage of the total and then plotted against particle diameter as determined by the known sieve opening size. The result is a grain-size distribution curve

2.1.3 Shear strength

The strength of a soil determines its ability to support the load of a structure or remain stable upon a hillside. Engineers must therefore incorporate soil strength into the design of embankments, road cuts, buildings, and other projects. The strength of a soil is often determined by its ability to withstand shearing stresses. The Mohr-Columb equation relates normal stress, cohesion, pore pressure, and friction angle to the shear strength of rock or soil:

$$\tau = C + (\sigma - \mu)tan\varphi$$

Where:

τ is shear stress,

c is cohesion,

σ is normal stress,

μ is hydrostatic stress (pore pressure),

φ is the angle of internal friction

In the Mohr-Coulomb theory of failure, shear strength has two components:

One for inherent strength due to bonds or attractive forces between particles, and the other produced by frictional resistance to shearing movement

The shear strength of cohesionless soils is limited to the frictional component. When the direct shear test is used to investigate a cohesionless soil, successive tests with increasing normal stress will establish a straight line that passes through the origin. The angle of inclination of the line with respect to the horizontal axis is the angle of internal friction.

The shear strength of a cohesive soil is more complicated than a cohesion less material. The differences are due to the role of pore water in a cohesive soil. Most cohesive soils in field conditions are at or near saturation because of their tendency to hold moisture and their low permeability. When load is applied to a soil of this type, the load is supported by an increase in the pore-water pressure until pore-water can drain into regions of lower pressure. At that point, soil particles are forced closer together and the strength increases, just like a cohesionless soil. Time is an important factor however, because it takes longer for water to move out of a low permeability material.

As cited by [2], the schema of mechanical soil behavior can be summarized following the ideas proposed by [3]. The essential features of this representation are as illustrated in the normalized stress plane in Figure 2.1, where for axisymmetric conditions like triaxial tests:

$$p' = (\sigma'1 + 2\sigma'3)/3 \qquad (2.1)$$

$$q = \sigma'1 - \sigma'3 \qquad (2.2)$$

Where p' is the effective mean normal stress, $\sigma'1$ and $\sigma'3$ are the axial and radial effective stresses respectively. The normalized stress plane p' /p'e versus q/p'e where (p'e is the equivalent pressure on the isotropic virgin compression line) can be divided in three distinct zones as in figure I:

Zone A, where the material exhibits a linear elastic stress-strain response. The Young's modulus Eo and shear modulus Go within this zone can be regarded as the initial stiffness of the relevant stress-strain curves of a given material. This corresponds to the plateau portion on the modulus decay curve of soils. In most non cohesive materials this behavior is observed in a very small range of strains generally until around 0.00I% [3]. [4] suggested that in some cases a large elastic limit strains results from rate effects in the dynamic tests, being significantly increased with plasticity index and for cemented materials.

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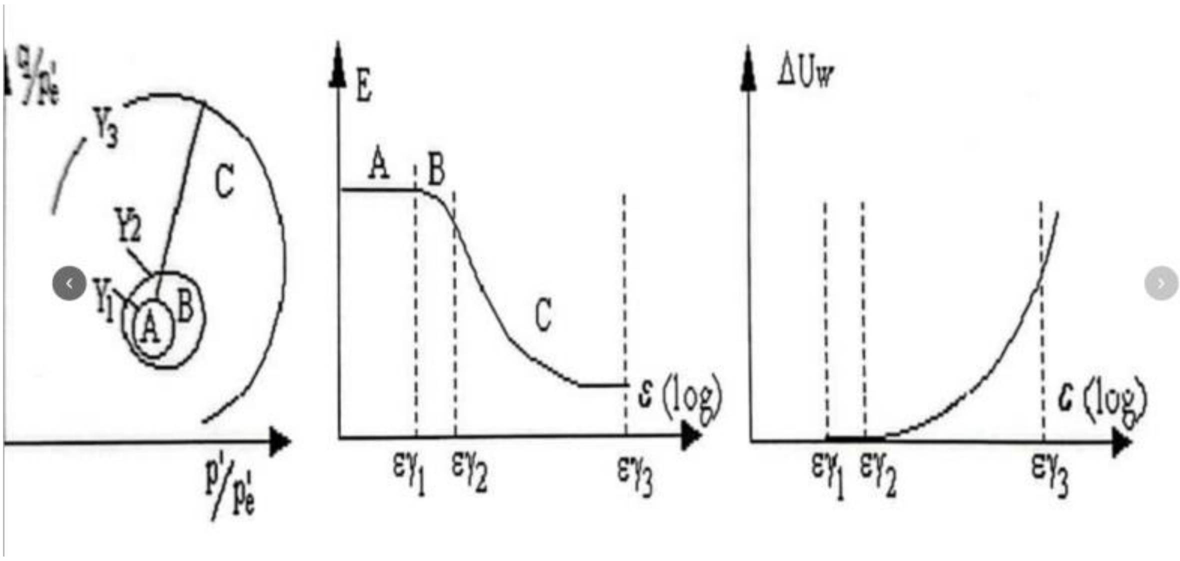

Fig 2.1 Simplified framework of soil behaviour (Jardine et.al,1991)

In this range of elastic behavior the Young's modulus Eo or the shear modulus (Go=Eo/2(1 +v)) are key parameters for both dynamic and static geotechnical problems, and particularly for track modeling. [2]. They are also very used to normalize experimental curves from different types of tests in order to obtain simple mathematical stress-strain curves [2, 5]. For practical applications, the behavior of soils in zone A can be considered only dependent on the current material state assessed by the void ratio, effective consolidation stresses and
the material fabric.

Zone B. where the material is hysteretic and non-linear and the plastic strains are delayed until the stress path engages the surroundings of boundary Y2. This zone shows for soils a reduction in the secant modulus with increasing strain, which generally does not exceed 20-30% of their initial value.
Zone C, where the material becomes increasing plastic strains. The stress-strain response to cyclic loading is no more stable and a degradation of the mechanical properties of material is observed [6]. This conducts in undrained conditions to the built up of pore pressures. When boundary Y3 is reached the total strains are almost plastic strains.

2. 1.3 Modulus
As a consequence of the non linear behavior of soils and unbound granular materials there are different moduli that can be defined as illustrated in Figure 2.2. Therefore, it is necessary to be aware of which is used, being obligatory to specify it precisely.

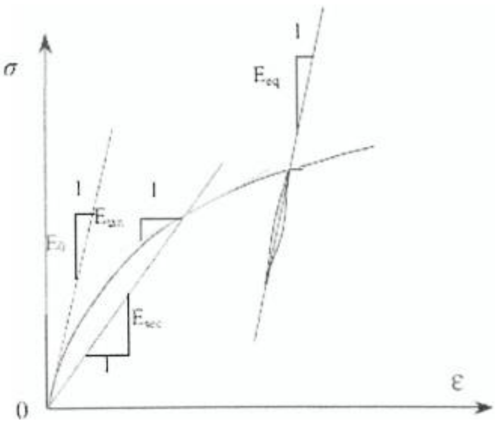

Figure 2.2 Definitions of different moduli. [2]

Young's Modulus' applies to the linear part of the stress-strain curve or when no straight portion exists, to the tangent to the

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curve at the origin. This is the initial 'Tangent Modulus' and is of little practical significance. It is also possible to define a 'Tangent Modulus' at any point on the stress-strain curve. The 'Secant Modulus' is defined as the slope of the line from the origin to any specified point on the curve. It represents an average modulus between zero load and the load at which the modulus is determined. Figure 2.3 is an example of a comprehensible representation of modulus associated with a strain level and stress dependent [2].

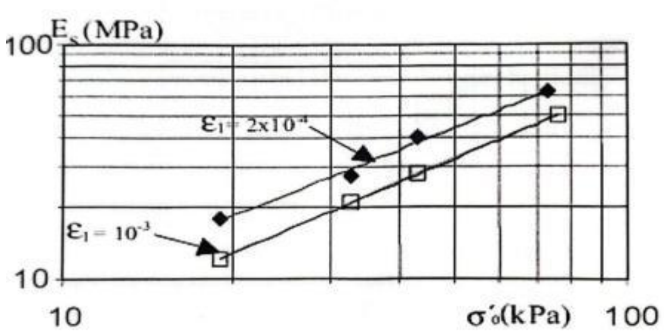

Fig 2.3 Modulus in function of stress and strain levels for Loach clay [2]

If the modulus is expressed in the elastic domain (small strains), then it is enough to represent its stress dependency as illustrated in Figure 2.4 for an unbound granular material [2].

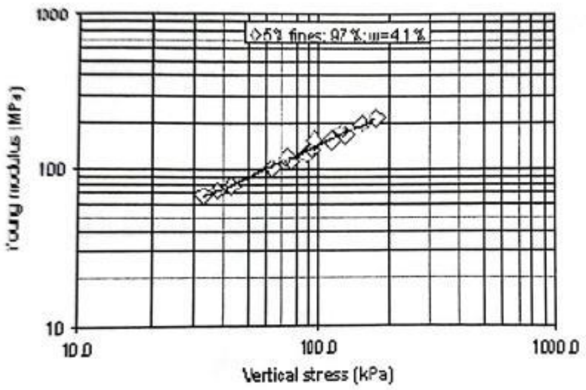

Fig 2,4 Small strain modulus in function of stress level obtained in a granite aggregate mixture[2]

2.1.4 Selection of Appropriate Modulus

The rational assessment of the properties of the pavement constituent layers is a key factor for the formulation of the models used for the description of both the short and long-term pavement performance. [7]. Furthermore, the analysis system should enable a proper behavioral representation of the materials subjected to an applied load. Because of the complexity associated with modeling pavement materials, researchers use considerable simplifications and employ their engineering judgment to develop reasonably accurate models. The values of the material stiffness properties (essentially only the moduli) input to these models are usually derived from a variety of laboratory tests. [7]. The associated moduli types may be classified as follows:

• Young's Modulus (E).

• Resilient Modulus (Mr).

• Complex Modulus (E*).

• Dynamic Modulus ([E*]).

2.2 The Resilient Modulus

The term resilience in engineering materials refers to the capacity of a material to absorb energy when ii is deformed elastically and then, upon unloading to have this energy recovered. In other words, it is the maximum energy per unit volume of the material

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that can be elastically stored.
Resilient modulus of a material is actually an estimate of its modulus of elasticity. While the modulus of elasticity is stress divided by strain for a slowly applied load, resilient modulus is the stress divided by strain for rapidly applied loads.
It is a measurement of the soil response when subjected to repeated loading, and is one of the most important characteristics of sub grades used in pavement design.
It was introduced by [8] and later solidified in NCHRP Project 1-37A, static tests fail to capture the hysteretic behavior of soils under moving wheel loads. It was defined as dynamic deviator stress divided by recoverable strain under a transient dynamic pulse load. Numerically, it is the ratio of the deviator stress to the resilient or recoverable strain after a large number of load cycles
MR=**σ***d* /*εr* This value may be estimated directly from laboratory testing, indirectly through correlation with other laboratory/field tests, or back-calculated from deflection measurements. Figure 2.5 shows the slope of the stress/strain curve

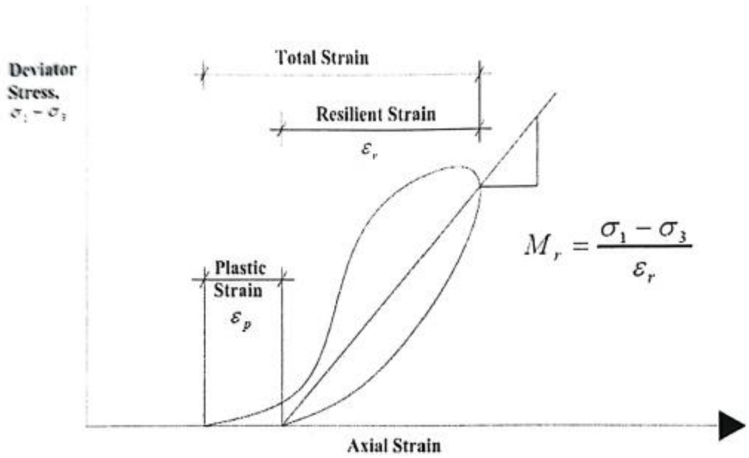

Fig. 2.5 Resilient Modulus

At initial stage of load application there will be considerable permanent (plastic) deformation. As the number of load repetitions increases, the plastic strain decreases and after I00 to 200 repetitions the strain is practically recoverable which represents the resilient behavior.
Linear relationships between California bearing ratio (CBR) and resilient modulus, have been established by early researchers where the resilient modulus was not stress-depend. Heukelom and Foster's empirical equation was expressed as CBR (MPa)= 10MR
Where MR= resilient modulus·,
Due to the difficulties in obtaining MR from laboratory tests, many correlations have been developed in order to obtain the resilient modulus values by easier means. California Bearing Ratio (CBR) is one of the most commonly used methods to predict resilient modulus as shown in table 2.1
However, the results from lab testing [9] and back-calculation of in-situ deflection tests [10], clearly showed that the resilient responses of both sub grade and base material were highly non-linear.
The problem with empirical relations is that the models tend to assign a fixed value of resilient modulus to a given soil type thereby neglecting its dependence on stress and strain.

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Table 2.1 Summary of MR and CBR correlations [11]

Correlation Name	Equation
Heukelom and Klomp (1962) and AASHTO Design Guide	$M_R(psi) = 1500 \times CBR$
ODOT Current Practice	$M_R = 1200 \times CBR$
U S Army Corps of Engineers (Green and Hall 1975)	$M_R(psi) = 5409 \times CBR^{0.71}$
South African Council on Scientific and Industrial Research (CSRI)	$M_R = 3000 \times CBR^{0.65}$
Transportation and Road Research Laboratory (TRRL)	$M_R(psi) = 2555 \times CBR^{0.64}$

2.2.1 Significance of resilient modulus

The resilient modulus of sub grade material is an important input in the design of pavement structures. It is used for material characterization of unbounded pavement material layers and has been recognized widely in pavement design and evaluation. It has found significant use in a number of pavement evaluation models.

The 1986 AASHTO guide for design of pavement structures incorporated the resilient modulus of sub grade materials into the design process.

It is used in various design guides and also in predicting stress, strain and displacement.

2.2.2 Factors affecting Resilient Modulus

Sub grade resilient modulus depends mainly on three factors: (I) stress state, (2) soil type and structure, and (3) soil's physical properties. This observation was made by so many investigators such as [12, 13, 14, 15]. Generally speaking, for fine-grained soils, the controlling factors that govern resilient modulus values are deviator stress, density, and moisture content.

I. Effect of Confining Stress

The extent to which the confinement affects values depends on the material type and prope11ies. Resilient modulus of fine-grained soils increases slightly with increasing confining stress. This behavior is typical for cohesive soils as noted by [13, 16, 17, 18, 19]. On the other hand, the effect of confining pressure can be considered negligible as noted by [15].

2. Effect of Deviatoric Stress

Resilient modulus of subgrade soil is highly affected by the increase in deviatoric axial stress. As the deviator stress increases, the resilient modulus rapidly decreases; this behavior refers to the so-called strain softening [13,14,19,21,22].

3. Moisture content effects

For fine-grained soils it is a well known fact that the resilient modulus decreases as the water content increases. This behavior caused by the low hydraulic conductivity of the fine-grained soils which in turn causes pore water pressure to build up during cyclic loading. As a result, the effective stress will decrease resulting in excess permanent deformation of the pavement system, then a reduction in resilient modulus and strength. This observation was pointed out by [17, 23],

4. Temperature Effects

Tremendous effects can be observed due to the temperature factor. In general, the significant effect of the temperature can be classified into three different categories: frozen, unfrozen or recently thawed condition. Freezing of cohesive soils can significantly increase the resilient modulus compared to the unfrozen condition.

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5. Specimen Size and Preparation

Specimen sizes and preparation techniques have been changing over time. For cohesive soils specimen sizes have varied from 71.I mm and 101.6 mm in diameter. Besides, preparation methods have also varied. The compaction methods that are commonly used for cohesive soils are static and dynamic techniques. These methods, however, have an impact on the resilient modulus values that can be deduced from the test.

2.2.3 Determination of resilient modulus

Resilient modulus can be determined directly through laboratory test using the repeated load triaxial test or indirectly from geophysical and geotechnical methods. Laboratory tests are normally performed on physical samples and the processes of obtaining samples do inflict damage to the structure hence the test is considered to be destructive. Nondestructive tests on the other hand, refer to the procedures which use load induced deflections or wave responses from controlled agitations on structure without causing any intrusion.

2.2.3.1 Direct laboratory method (Repeated load triaxial testing procedure)

The resilient modulus for embankment soils is determined in the laboratory using a repeating or cyclical load triaxial cell. The triaxial cell itself varies from I00 mm in diameter and 200 mm depending upon the minimum required sample size. Soil samples can be taken from the field and trimmed to size or compacted in the laboratory using a variety of methods. Soil specimens for fine grained soils have a minimum diameter of 71 mm. The height of the specimen is limited to a minimum of 2 times the diameter (AASHTO, 2000). Deformation of the sample can be measured using two LVDT's attached to either side of the soil specimen. If soil samples are too soft for LVDT mounting or the triaxial cell does not permit internal mounting, an LVDT can be mounted externally on the loading piston. The load cell is located at the top of the specimen or within the loading machine. The typical triaxial setup can be seen in Figure 2.6a while detail of the triaxial chamber is shown in figure 2.6b. The loading piston can be powered pneumatically or hydraulically depending upon the equipment. In addition, computer controller and data acquisition equipment is required to properly load specimens and record test data.

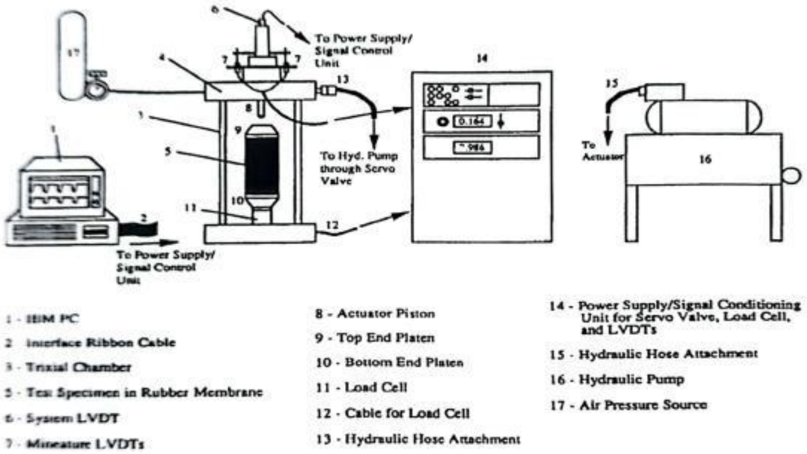

Fig 2.6 a Schematic of repeated load triaxial test system

In a triaxial resilient modulus test a repeated axial cyclic stress of fixed magnitude, load duration and cyclic duration is applied to a cylindrical test specimen. The specimen is subjected to this dynamic cyclic stress, while it is also being subjected to a static confining stress provided by a triaxial pressure chamber. The total resilient (recoverable) axial deformation response of the specimen is measured and used to calculate the resilient modulus using an equation: The following is a basic outline of the triaxial test procedure:

I. The specimen is a cylindrical sample normally 100 mm in diameter by 200 mm high. The sample is generally compacted in the laboratory; however, undisturbed samples are best if available.
2. The specimen is enclosed vertically by a thin "rubber" membrane and on both ends by rigid surfaces (platens).
3. The sample is placed in a pressure chamber and a confining pressure is applied.

4. The deviator stress is the axial stress applied by the testing apparatus minus the confining stress. In other words, the deviator stress is the repeated stress applied to the sample.

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5. The resulting strains are calculated over a gauge length.

6. Basically, the initial condition of the sample is unloaded (no induced stress). When the deviator stress is applied, the sample deforms, changing in length. This change in sample length is directly proportional to the stiffness.

2.2.3.2 Geotechnical Methods of measuring resilient modulus

2.2.3.2.1 Dynamic Cone Penetrometer

The dynamic cone penetrometer (DCP) is a test used to measure the in-situ resistance to penetration of soils. The DCP is an effective tool for assessing the in-situ strength, stiffness, and uniformity of pavements and subgrades, and is also a useful tool for quality assurance applications in highway and railway construction. As shown in figure 3.7 the DCP consists of a fixed upper 575mm travel rod with either a 4.6- or 8-kg falling weight (the lighter weight being used for weaker soils). It also has a lower rod containing the anvil and a replaceable 20mm diameter cone with an apex angle of 60°. The DCP test is conducted by dropping the weight from a height of 575mm and recording the number of blows versus the depth of penetration. From this data, the penetration rate is calculated. The DCP test can verify the level and uniformity of compaction, making it a useful tool for quality control applications. The DCP test is also capable of determining the thickness of the tested layer. The sub grade resilient modulus can also be predicted directly from the DCP results (Murad 2004). To assess the structural properties of the pavement subgrade, the DCP values are often correlated with the CBR test results in order to assess the structural properties of the pavement layers. The following correlations were developed from the results of several
studies.

log CBR = 2.62 - 1.27 *log* PR 2.3
log CBR = 2.56 - 1.15 *log* PR 2.4
log CBR = 2.2 - 0.71 (*log* PR)1.5 2.5
log CBR = 2.56 -1.16 *log* PR (for PR values> I0) 2.6
log CBR = 2.70 - 1.12 *log* PR (for PR values< 10) 2.7

The subgrade resilient modulus can also be determined from the results of the DCP test. The equations shown below relate the resilient modulus directly to the PR value determined from the DCP test.

log (Es)= 3.25- 0.89 *log* (PR) 2.8
log (Es)= 3.652-1.17 *log* (PR) 2.9
log (Es)= B - 0.4 *log* (PR) (where B is dependent on soil type) 2.10
log (Es)= 3.05 - 1.07 *log* (PR) 2.11

An equation was also developed by Chen to relate the resilient modulus backcalculated from the FWD test to the results of the DCP test.
MFwD = 338 (PR)-0.39 (for 10 < PR < 60) [29] 2.12

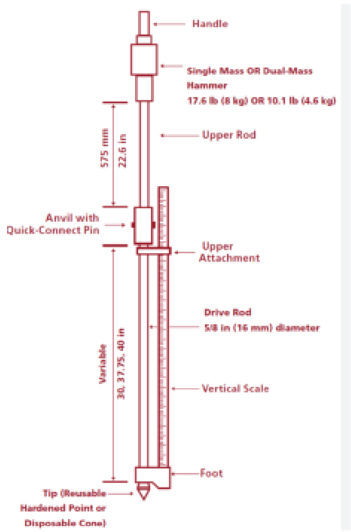

Fig 2.6 Schematic diagram of dynamic cone penetrometer

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The DCP testing equipment is simple, rugged, and inexpensive and can be operated by one or two people. Site access is not an issue due to the portability of the equipment. The test produces continuous measurements of the in-situ strength and stiffness of pavement layers and subgrade, and is non-destructive. The DCP test can also be performed in pavement core holes. The test results are accurate in many soil types including weak rocks, and are fairly reliable.

2.2.3.3 Geophysical methods of measuring resilient modulus

2.2.3.3.1 The falling weight deflectometer

The Falling Weight Deflectometer (FWD) has been developed from the "deflectometre aboulet" originally devised by Bretonniere in 1963. The theoretical basis for LWD is rooted in the **Boussinesq elastic half-space theory**. While Boussinesq assumes a static load, the LWD applies a dynamic pulse, leading researchers like [30] to argue that the LWD is fundamentally more "mechanistic" than static plate load tests because it accounts for the inertia and damping properties of the subgrade.
The device closely stimulates the deflection of pavement surface as a result of fast-moving load from traffic. A load pulse is generated by a falling weight which is transmitted to the pavement through a 300mm diameter plate. The load pulse induces a deflection on the pavement which is measured at specific radial intervals from the center of the plate with geophones. Based on the measured deflections, it is possible to estimate the stiffness of the pavement layers by a computational method known as the back analysis if the thicknesses of the layers are known. When a load is applied to the surface of a pavement, the higher the modulus in any particular layer the greater the stress gradient in the material (see Figure 2.8). However, it is not only the modulus of the layers that affects the transmission of the applied load within the pavement structure, but the thickness of the layers as well. [7]. Thus, the deflection bowl under the FWD load is the result of the combined effects of both the thickness and the modulus of the pavement layers.
In order to estimate the in situ layer moduli using back-analysis techniques a number of problems that affect the accuracy of the solution should be addressed such as:

. The determination of the optimum location of the geophones.

, The possibility of non-uniqueness of the solution.

. Errors due to the assumption of a semi-infinite subgrade where a rock layer exists at a shallow depth below the foundation.

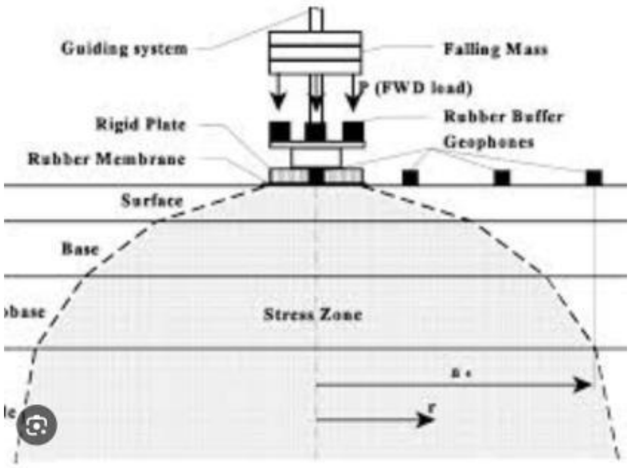

Fig 2.8 FWD setup and schematic presentation of stress bulb

Improvements to the quality of deflection data should be made, since it is desirable to place the deflection transducers at radial positions which are more sensitive to the moduli of the individual layers of the structure. Thus, if reliable values of the layer moduli are to be back-calculated, the FWD geophones should be positioned with some care. [7].

General recommendations with regard to the positioning of the geophones do not seem to be true in cases of very stiff pavements and of pavements having cement-bound road bases where it appears the problem of underestimating the distance from the load center line at which deflection is felt to be affected only by the subgrade modulus. This distance seems to be greater than the maximum distance at which the last geophone is usually placed. In practice the deflections are measured at a variety of radial

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distances but usually at intervals of 0.30 m up to 2.50 m. [7]

2.2.3.3.1.I Features of the FWD

The main features of the FWD are as follows

• Control Box

Contains connectors for the geophones, load cell, temperature sensor, and other sensors mounted on the FWD. Located on the FWD trailer, the control box sends these signals to the signal processor located in the tow vehicle through the multi signal cable. The control box also has buttons for manual control of the FWD hydraulics.

• Geophone

Device used to measure deflection. It is yellow, roughly cylindrical, and about 25mm in diameter and 50 mm high. Geophones are mounted in spring loaded sensor support brackets suspended along the sensor bar. Each geophone has a unique serial number that is used to identify critical calibration information in the FWD data collection software.

• Load Cell

Measures the force imparted to the pavement by the FWD. The load cell is located directly above the load plate and below the swivel. The load cell has a serial number' which is visible from the rear.

• Load Plate

Directly contacts the pavement surface to transmit the load. It is usually rigid and is 300mm in diameter. It consists of three layers: the topmost is steel, the middle is polyvinylchloride (PVC), and the bottommost is a ribbed rubber sheet.

2.2.3.3.2 Lightweight Deflectometer

The lightweight deflectometer is a portable version of the falling weight deflectometer. It is a light weight, portable tool used to determine the stiffness of unbound materials during construction by measuring the deflection under an applied load. This device is hand operated and takes measurements of the deflection of the compacted soil that is impacted by a falling weight. The device measures a deflection and estimates a modulus value based on the force required to generate a given deflection for that soil type. This device induces a soil response by dropping a weight onto a plate resting on the test layer. A load cell within the instrument measures the time history of the load pulse and a geophone suspended through the bottom plate measures the time history of the soil's displacement. [30]. These history files are automatically exported wirelessly to a data acquisition system, where the peak load and displacement values are used to calculate modulus value. [20]

Several LFWD models are available in the market as a result of different manufacturers and countries of origin, but they are very similar in principle. The common ones include the German dynamic plate GDP, the Transport Research Laboratory prototype foundation tester TFT and the Prima I00 LFWD.

The Dynatest 3031 LFWD was used in this study and it was developed by Carl Bro Pavement Consultants Koldinoo in Denmark.

2.2.3.3.2.1 Dynatest 3031 . .

The equipment is precision-engineered, using stainless or anodized material for all metal parts. The system is powered by a pack of four AA alkaline or rechargeable batteries, proving approximately 2000 measurements or equivalent to more than 12 hours of continuous operation.

With additional (optional) 2x5kg weights, can produce up to l5kN peak loads. The LFWD weighs about 22 kg (with the standard I0kg drop weight), and it is very portable and easily carried around construction site. There is an optional, specially designed trolley available.

The Dynatest LFWD requires no reference measurements and provides a simple, cost-effective alternative to time-consuming and expensive static plate bearing testing.

This LFWD is ideal for Quality Assurance/ Quality Control on subgrade, subbase and thin flexible pavement constructions to verify that specifications are met. It can also be used to identify weaknesses, leading to further tests using FWDs and other material analysis techniques. [34]

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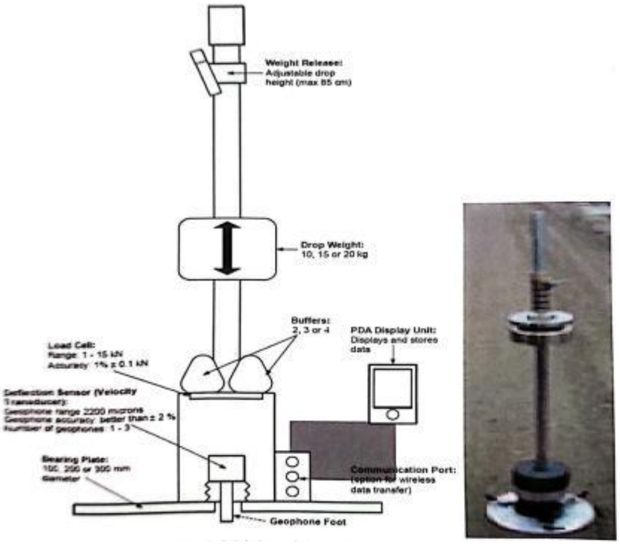

Fig 2.9 Lightweight Deflectometer

2.2.3.3.2.1.1 Key Operational Features:

The Dynatest LFWD electronics are interfaced to a handheld PDA via a wireless Bluetooth connection. The LFWD electronics are dust and splash proof (IP56) for safe outdoor use. The drop height is easily and quickly adjusted by a movable release handle. A laser engraved scale on the weight guide shaft allows for easy setting of the desired drop height. The magnitude of the impact force is determined from actual measurements by a precision loadcell measuring the time history and peak value of the impact force from the standard I0kg or the optional 15kg or 20kg drop weight setups. The loading plate diameter can quickly and easily be switched between 300mm and I50mm. A I00mm plate diameter is included and an optional 200mm plate is available. The center deflection time history and peak value is measured through a hole in the loading plate by a highly accurate, seismic transducer (geophone). An integrated lever to ensure the center geophone is correctly centered and seated. [34]

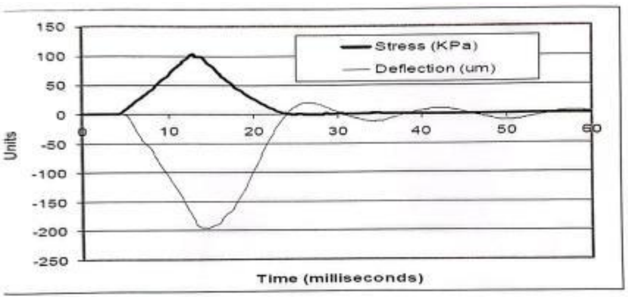

Fig 2.10 Example of LFWD Output from a laboratory test.

In general, the device software integrates the geophone (velocity transducer) signal to determine the maximum (or peak) deflection value. This has two important ramifications, the first being that under test the peak deflection may not occur at the same instant as the peak load (Figure 2.1b) and usually does not specifically for lower stiffness materials. The second is that the maximum deflection may include an element of permanent/plastic in addition to recoverable/elastic deflection. This depends upon the 'strength' of the materials under test, and the efficacy of the contact between the geophone foot and the material under test. Thus, it is apparent that the term 'elastic' stiffness (E) should be applied very carefully to all LFWDs, and the use of such 'elastic' values in elastic pavement analysis needs careful consideration. [31]

3.0 METHODOLOGY

There are several methods of obtaining Resilient Modulus of soil. This work investigates the use of one of these methods, namely the light weight deflectometer based methodology.
This will be achieved by performing a laboratory-based investigation which will focus on the following aspects.
I. An investigation of the depth to which the LWD can be used to infer the Resilient Modulus.
2.The repeatability of LWD results.

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3. Similarity of the Resilient Modulus values obtained by the LWD with laboratory-based methods under a variety of conditions.

3.2 An investigation of the depth to which the LWD can be used to infer the Resilient Modulus.

Road and railway structures are made of layers of materials with each layer having different physical prope11ies. The combined action of the constituent layers provides for the overall performance of the structure. It is therefore important to be able to assess each of these layers. The depth of influence of the lightweight deflectometer defines the limit to which the instrument can be able to obtain sensible readings.
By building a multi-layer system of compacted sand and ballast and progressively measuring deflections and surface modulus with the three geophones fitted to the lightweight deflectometer, the depth of influence can be ascertained.

3.3 Repeatability of LWD results

Resilient Modulus is a stress related property which implies that the value changes according to the stress in the system. This response of sub grade to load is fundamental to the mechanistic design methodology. If mechanistic design of roads and railways is to be effective, reliable measurements of Resilient Modulus are of great importance. Laboratory measurements of Resilient Modulus are based on samples which in most cases are reconstituted and therefore are not purely representative of the field situation. The LWD measurements being based on in situ conditions are of great importance and so is the repeatability of its measurements. To assess the repeatability of the LWD the following was done.
I. A series of measurements were taken from a designated spot in the laboratory for a period of four days using the same drop weight, same drop height, same assembly of damper and under similar ambient temperature conditions.
2. In the test tank readings are taken from defined spots on each layer of material in the test box. The readings from each spot are analyzed to determine the variability.

3.4 Similarity of the Resilient Modulus values obtained by the LWD with laboratory based methods under a variety of conditions.

Several correlations have been developed by other researchers which associate Resilient Modulus values with measures of other parameter of soil. Although these correlations tend to assign a fixed value of Resilient Modulus to a particular soil type, they are useful for the validation of values obtained from LWD measurements. To this end, in place density test was performed using the sand replacement method, DCP and the repeated load triaxial tests were performed.
Using the results from these tests, values of Resilient Modulus are obtained and compared with those from LWD measurements.

4.0 Laboratory investigations

A laboratory testing program had to be planned and carried out to fulfill the objectives of this study. The suitability of LWD can be investigated in a number of ways using different parameters however; this study assesses the suitability of LWD based on the repeatability of its measurements and the similarity of its measurements with other methods. An appropriate test plan will have to be worked out to achieve the objective.
The testing program was divided into two groups. The first group deals with indirect tests involving the use of LWD and DCP to test samples prepared in a test box. The main goal of this group of tests was to have two parallel sets of Resilient Modulus values from in situ applicable tests which are to be compared. It was also intended to obtain the compacted density of each layer of sand in the test box in order to see what relationship exist between density and Resilient Modulus. The second group of tests had to do with obtaining Resilient Modulus directly by the Repeated Load Triaxial tests on sample at same moisture contents, densities and confining pressures as the samples in the test box. These tests were to provide direct MR results for comparison with those from LWD measurements. The layout of the test box is shown in figure 4.1.

4.2 Test procedures

4.2.1 Lightweight deflectometer test
A tank measuring 1000 x 1500 x I 000mm made of assembled precast concrete elements. The tank was lined internally with two layers of plastic sheet in order for it to retain water. Two Pvc pipes of 50mm diameter are securely placed at two diagonally opposite corners. The pipes are used to monitor water level in the tank and also as shaft to insert suction pipe used for draining water. Each of these pipes is perforated and fitted with filter to prevent blockage by sand particles.

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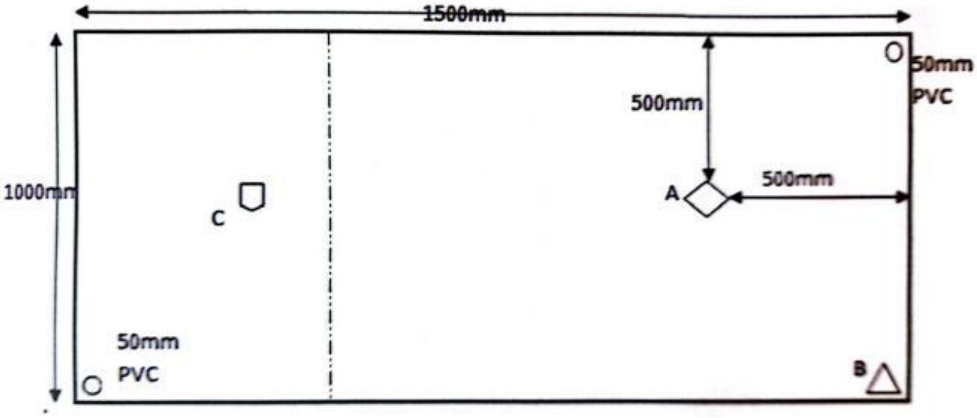

Fig 4.1 Textbox layout

Sand is built up in layers of 150mm (see figure 4.2). Each layer of sand is plate compacted with a motor compactor before deflection measurements are taken with the LWD. The LWD measurements were obtained in accordance with ASTM E2583-07 standards. In total four layers of sand amounting to an overall depth of 600mm were placed before a layer made of 300mm of ballast was placed and compacted. Measurements are taken from three spots (points A, B and C) as indicated in figure 4.1.

Figure 4.2 Layer 1 compaction in Test box

In order to investigate the effect of overburden pressure on Resilient Modulus, a 400mm diameter PVC pipe was used as a casing to enable assess to two buried layers. See figure 4.3.
Readings were then taken from these layers to compare with previously recorded readings from the spot.

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Figure 4.3 Testing of buried layer

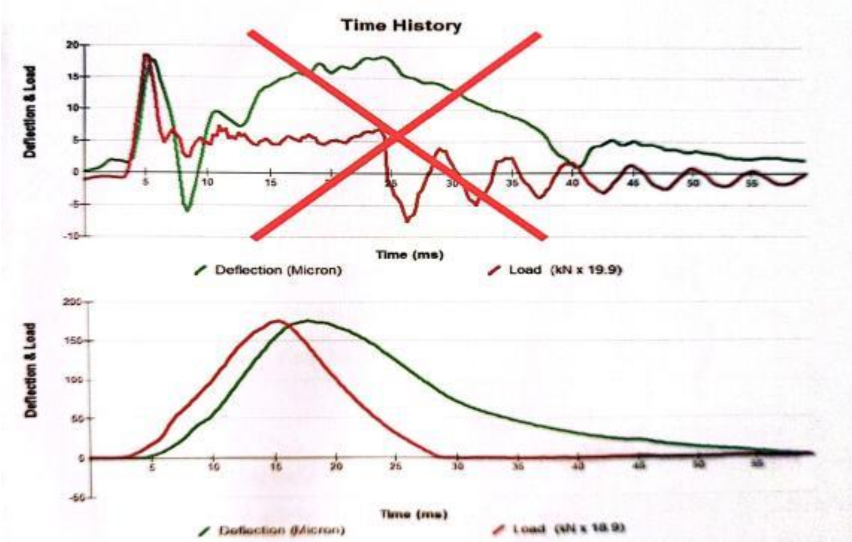

Fig 4.4 Deflection-load time graph

The Dynatest light weight deflectometer is linked by Bluetooth to a PDA from which the readings are taken. It provides values for deflection, pulse, stress and surface modulus. It also plots the load-time and deflection-time graphs as shown in figure 4.4. From this plot, unreasonable drops are identified or discarded by ensuring that the peak deflection occurred at about same time as the peak force. Several drops are taken from each point using varying drop weights and drop heights. In each case, the first three drops are considered as seating drops to normalize base plate contact with the material.

4.2.2 Dynamic cone penetrometer.

The DCP tests were done at two stages. Firstly, after the last layer of sand was placed to pick out the penetration indices of the sand layers without the influence of ballast. The second one was after the ballast was placed in order to get the penetration indices through the whole system. The tests are in accordance with the procedure stipulated in ASTMDl586.

4.2.3 Repeated load triaxial test.

Repeated load triaxial test machine manufactured to ASTMT307 was used. It is a fully automated system that calculates Resilient Modulus after an assigned number of load cycles and test sequence.
The samples were prepared using cylindrical mould of I00mm diameter and height of 200mm and following the steps already stated in the literature review.

4.2.4 Other tests.

Particle size analysis of sample was done using seven number sieves ranging from 0.45mm to 2mm after sample has been dried overnight in the oven. A mechanical shaker was used for ten minutes as stipulated in ASTMD 433. The compacted density tests were also performed in accordance with the modified AASHTOT191.

4.3 Test results

4.3.1 Results from LWD tests

In layer I, the effect of using a constant drop weight with varying drop heights was investigated for points A and B. The tests carried out were numbered from I to 15 and the results are in Appendix A.

Table 4.1(extract from test no 2 and 4 in Appendix A) shows the average readings taken from point A using three geophones and a constant weight of 10kg while Table 4.2(extract from test no 5 and 6 in Appendix A) shows average readings using the 15kg weight.

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Table 4.1 LWD readings at point A from two drop heights using 10kg drop weight and three geophones

Drop height(cm)	DI(micron)	D2(micron)	D3(micron)	Em1(mpa)	Em2(mpa)	Em3(mpa)
60	262	1.75	2.25	45.75	2076	722
120	353.4	2.2	3.6	48.6	2400	680.8

Table 4.2 LWD readings at point A from two drop heights using 15kg drop weight and three geophones

Drop height(cm)	D1(micro)	D2(micro)	D3(micro)	Eml(mpa)	Em2(mpa)	Em3(mpa)
60	261	1.25	1.75	43.25	2434.75	759.75
120	346.25	0.75	1.5	49	10216.5	1504.75

Table 4.3a shows the result using one geophone and I0kg drop weight at point A (test nos1 and 3) while table 4.3b shows that at point B (test nos7 and 8).

Table 4.3a LWD readings at point A from two drop heights using 10kg drop weight and one geophone

Drop height(cm)	DI (micron)	Em1(mpa)
60	302.8	40.6
120	379.6	45.6

Table 4.3b LWD readings at point B from two drop heights using 10kg drop weight and one geophone

Drop height(cm)	DI (micron)	Em1(mpa)
60	338.6	36.6
120	393.2	44.8

In layer 2, the surface modulus at the top is examined to see how the value obtained using one geophone compares with using three geophones. Figure 4.5 shows how layer 1 was prepared before the placement of layer 2. A section was separated with polythene in order to examine the effect of a different layer boundary condition. The results for points A and C (see figure 4.1) are in Appendix B.

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Figure 4.5 Top of layer 1 showing section separated with membrane

In layer 3, the effect of varying drop heights while using a given drop weight was examined further using one geophone (results from test no 16 to 21 in Appendix C)

In layer 4, the end/corner effect is examined again at point B (test no 25 to test no27). The results are in Appendix D. Also, test 28 and 29 with results included in Appendix D are used to examine the effect of overburden pressure.

The final layer (5) was made of ballast. The three geophones are used in test no 33 to examine what effects the flooding of the tank might have on the resilient modulus. Results are in Appendix E which also includes the results for test numbers 30 to 32 (tests on ballast layer before flooding). It is observed from the results that computed resilient modulus initially increased considerably from 95mpa to l 20mpa with increase of about l 2kpa. It shows from table 4.4 that the RM remained unchanged with subsequent increase of about S0kpa in test 32. After flooding to a depth of 600mm, the resilient modulus obtained from test 33 dropped sharply to 80mpa from 120mpa.

Table 4.4 Summary of test results from Layer5

Test No	σ° (kpa)	MRtop (mpa)
30	86.38	**95.0**
31	98.93	**120.0**
32	148.16	**120.0**
33	148.08	**80.0**

4.3.2 Results from DCP tests

The results of the dynamic cone penetration tests are shown in Appendix J. Using equation 4.1 which was devised by George and Uddin (cited by Amini, 2003), values of MR are computed and presented in table 4.5

$$MR = 235.3DCPI^{-0.475} \quad (4.1)$$

Table 4.5 DCP with correlated MR values

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Blow	Penetration (mm)	MR(mpa) correlation 4.1		MR(mpa) correlation 4.2	
1	147	22	Layer 5 average 42.5	19	Layer 5 average 52
2	38	42		49	
3	20	57		78	
4	22	54		73	
5	49	37		41	
6	105	26	Layer 4 average 39	24	Layer 4 average 45.3
7	44	39		44	
8	24	52		68	
9	24	52	layer 3 51.3	68	Layer 3 67
10	25	51		66	
11	27	49		63	
12	26	50		64	
13	27	49		63	
14	20	57		78	
15	19	58	Layer 2 56.7	81	Layer 2 77.9
16	20	57		78	
17	18	60		84	
18	20	57		78	
19	23	53		70	
20	22	54		73	
21	19	58		81	
22	21	55	Layer 1 49.6	75	Layer 1 64
23	20	57		78	
24	28	48		61	
25	35	43		52	
26	33	45		54	

The average resilient modulus for each Iayer of material is calculated from the average of
resilient modulus due to the penetration from every single blow. Figure4 6. shows the rates of penetration in mm/blow though the layers of materials.

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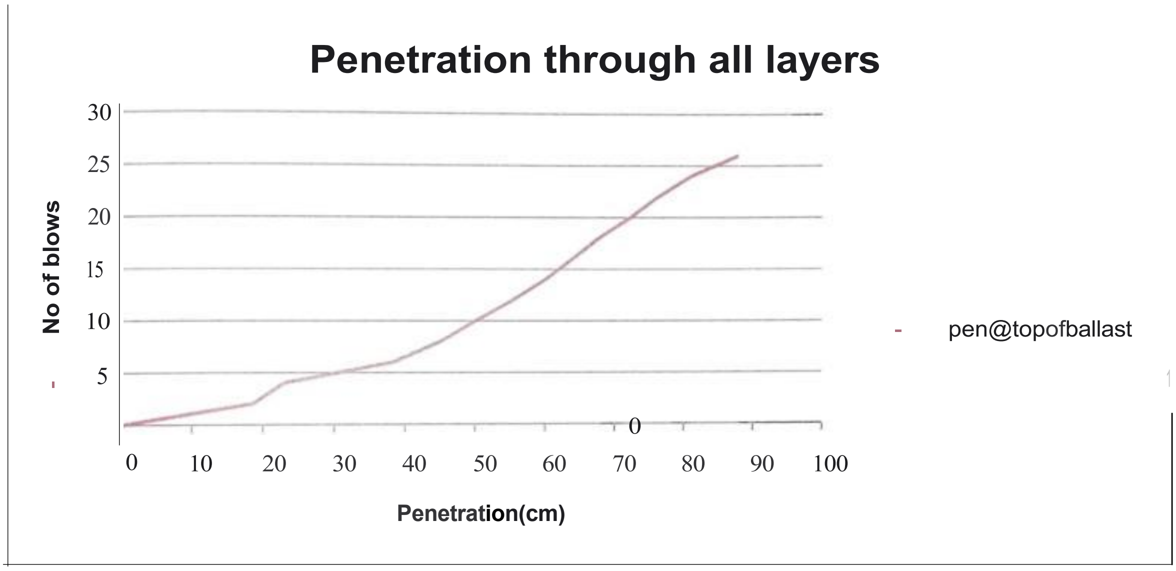

Figure 4.6 Penetration vs no. of blows

As indicated in table 4.4, the initial penetration rate on the ballast was very high. (147mm from the first blow). The same was experienced with the 6th blow (just as sand is being encountered). This may be due to the lateral shifting of particles at the top and may influence the correlated resilient modulus value.

4.3.2 Results from Repeated load triaxial tests

In the triaxial test, four representative samples were tested. Each sample was to be made to meet the moisture content and density corresponding to those of each layer of sand in the test box. The result of the repeated load triaxial test is attached in Appendix F. Normally each sample should go through sixteen sequence of loading in the triaxial test chamber but due to difficulties encountered during the testing process, only one sample was tested and for only two sequence of loading.
The result shows that the sample failed under a confining pressure of 42kpa and at a permanent strain of 1.8% and at this point the resilient modulus was 32.89kpa.

4.4 Analysis of results

4.4.1 Accuracy and repeatability of measurements

The lightweight deflectometer measures a number of parameters which are necessary for the computation for Resilient Modulus. These include force, pulse, contact pressure, deflection and surface modulus. The accuracy of the overall process is affected by the accuracy of each of these measures. Accuracy, which is the difference between a true value and the measured value, is largely a function of calibration and repeatability of measurements. As stated in the manual [33] 3031can only be calibrated by the manufacturers and it is done after a total of 25,000 drops or after two years of use. Since the particular instrument used for this study was less than two years old and had not been used for up to 10,000 drops, it is assumed that the manufacturer's calibration was still valid. To quantify the working precision of this instrument therefore, the focus was on repeatability.
Figures 4.7 to 4.10 show the variability of measurements taken over a 5-day period under same conditions from a spot on the laboratory floor.

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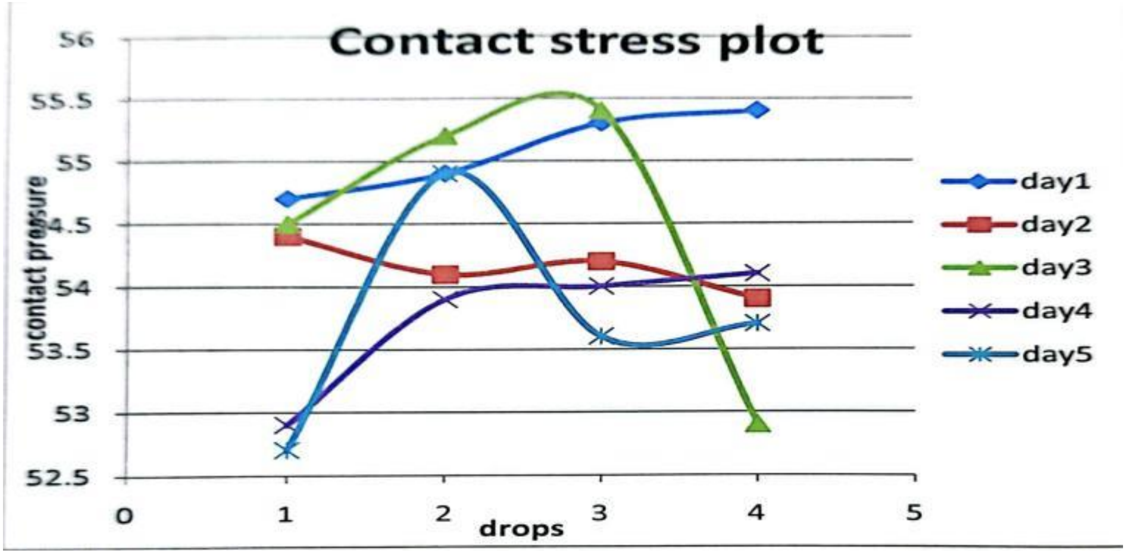

Figure 4.7 Contact stress vs drop numbers on Lab. floor.

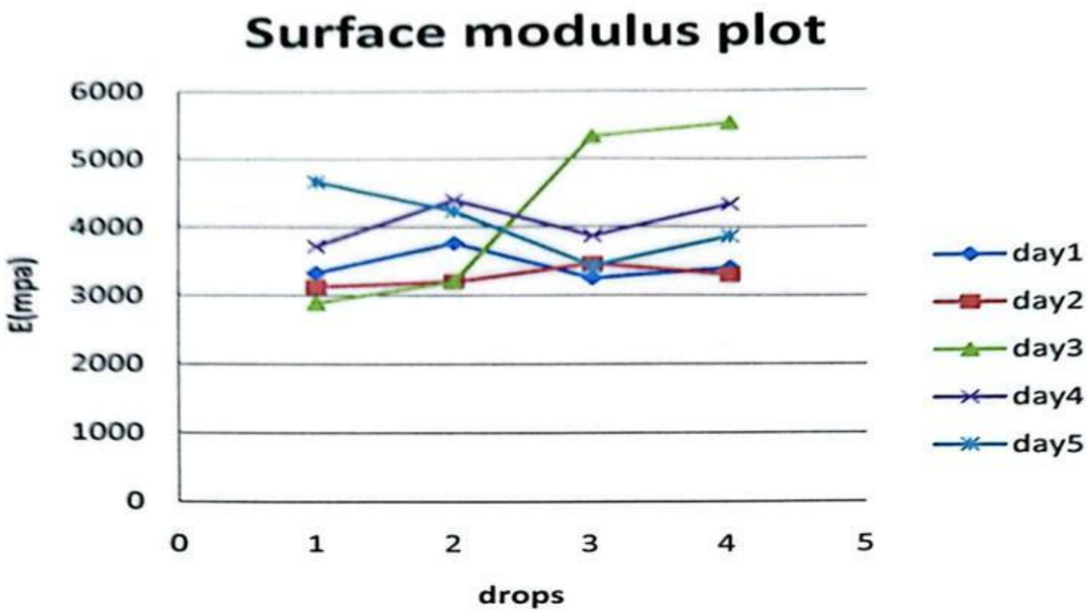

Figure 4.8 Surface modulus vs drop numbers on Lab. floor.

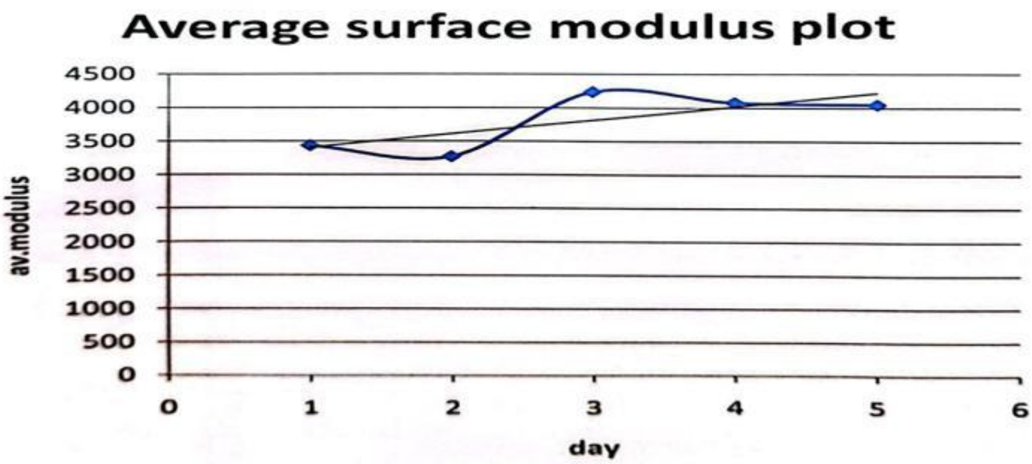

Figure 4.9 Average daily surface modulus vs day number.

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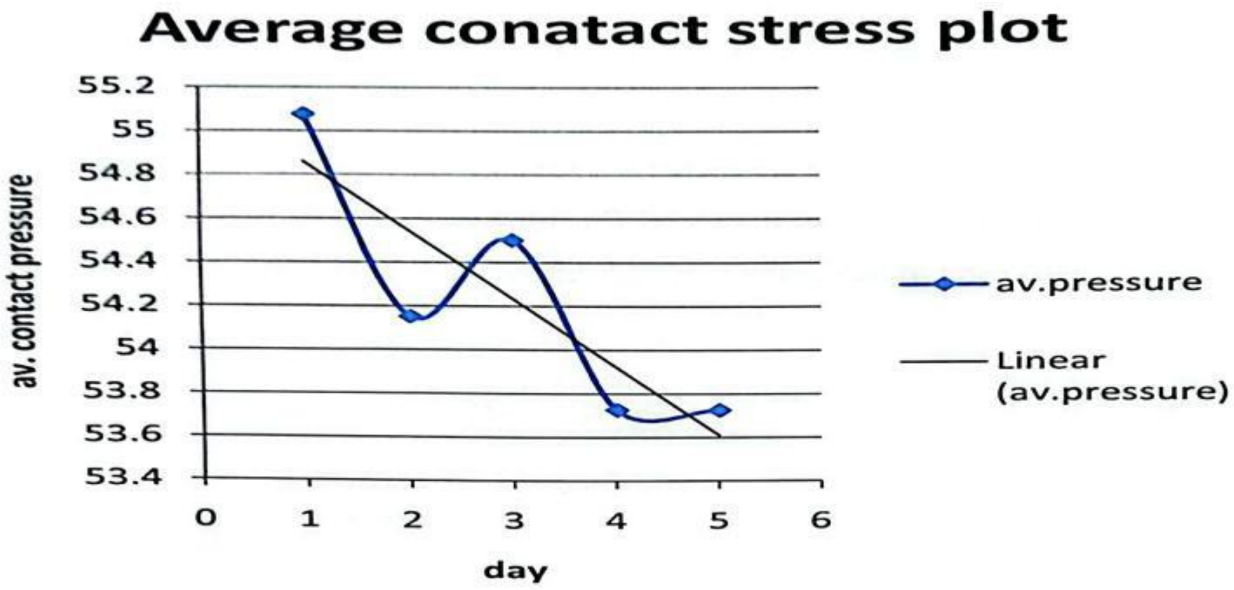

Figure 4.10 Average daily contact stress vs day number

From figure 4.7 the variability of the contact stress measurements appears to be high with no apparent trend but the plot for the average daily contact pressure (figure 4.10) showed a downward trend as the days went by although the daily surface modulus plot seems scattered (figure 4.8). As indicated in figure 4.9 the average surface modulus is consistent. The summary statistics of the daily C.O.V in table 4.6 which is extracted from Appendix G shows that the maximum C.O.V's for force and contact stress measurements were less than
3%.

Table 4.6 Summary statistics for COV for tests on Lab floor

Days	force(%)	stress(%)	Defl (%)	Eml(%)
I	0	0.59991	13.333333	6.636196
2	0	0.38442	0	4.409594
3	0	2.08130	28.867513	32.72333
4	1.3245	1.03495	16.495722	8.30694
5	2.14868	1.68121	16.495722	13.06501

In the case of deflection (DI) and surface modulus (Em I), over 25% were recorded.

On the other hand, in the summary statistics for all the 33 tests on the test box (see table 4.7), the max C.O.V recorded for contact stress measurements was about 3% while that for deflection (DI) and surface modulus (Em I) reduced by about I0% to 14.32% from the 32.7% recorded on the laboratory floor test. This suggests that there may be the likelihood that the stiffness of the concrete floor affected the deflection readings and consequently, the surface modulus (Em I)

Table 4.7 Summary statistics for COV for tests on test box

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TEST No	Stress(%)	PULSE(%)	D1(%)	D2(%)	D3(%)	Em1(%)	Em2(%)	Em3(%)
1	0.27	0.00	3.87			3.74		
2	0.11	0.00	1.79	54.71	22.22	1.09	39.80	17.43
3	0.74	0.00	3.62			3.33		
4	1.00	0.00	0.89	59.27	31.67	1.13	50.50	39.75
5	2.91	2.57	3.84	76.59	54.71	5.46	54.04	40.37
6	1.17	0.00	1.83	127.66	38.49	2.36	57.18	39.26
7	0.28	0.00	4.47			4.57		
8	0.78	0.00	4.01			3.67		
9	0.75	0.00	2.67			2.76		
10	1.14	2.83	9.55	22.02	35.36	9.45	18.65	18.07
11	1.55	2.83	15.07	10.65	26.15	14.32	11.48	31.31
12	0.93	1.77	3.87	34.23	63.89	3.95	50.99	52.04
13	1.19	0.00	9.18	46.48		9.50	46.46	
14	2.21	1.26	2.27	7.21	43.85	3.30	7.08	42.91
15	1.20	1.23	2.97	7.75	16.11	4.57	6.14	15.22
16	0.54	0.00	0.65			0.96		
17	0.75	0.00	1.03			1.50		
18								
19	1.26	1.27	0.60			1.77		
20	0.98	0.00	2.13			2.88		
21	0.13	0.00	1.46	17.89	3.67	1.41	1.81	3.04
22	0.28	0.00	3.80			4.06		
23	0.35	0.00	0.79			1.34		
24	3.45	0.00	2.75			1.27		
25	0.75	1.85	1.13			0.63		
26	0.36	0.00	0.59			0.00		
27	0.34	0.00	0.34			0.80		
28	0.50	2.24	1.82			1.64		
29	1.04	1.85	2.87			3.53		
30	1.40	0.00	4.02	2.57	1.77	3.10	1.54	3.64
31	0.39	0.00	4.97	4.37	2.06	3.23	3.12	1.77
32	0.22	1.48	2.64	1.20	1.86	2.75	0.87	1.04
33	0.63	1.45	3.31	2.33	5.57	3.70	3.23	4.60
MAX	3.45	2.83	15.07	127.66	63.89	14.32	57.18	52.04
MIN	0.11	0.00	0.34	1.20	1.77	0.00	0.87	1.04

Effect of varying drop heights

The force generated by the falling weight depends on both the drop height and the drop weight. For any given diameter of loading plate, the force determines the stress delivered to the material being tested. Deflection of the material and the surface modulus are related to
the amount of stress. Figure 4.13 shows that while using a fixed drop weight of I0kg at
layer 3 (point A), varying drop heights does not result in any appreciable change in the slope of the curves. The curves are approximately parallel but are slightly steeper than the graphs from a similar plot at same layer 3 (point B) as shown in figure 4.14. This may suggest that sensitivity to drop height variation may have something to do with the corner where compaction may not have been as effective.

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Effect of layer boundary condition

Comparing results at points A and C using test 10 and it appears from figure 4.11 and 4.12 that the readings from point C (for DI and D2) where a membrane has been used to separate the layers have exhibited better consistency than those from point A where layers are not separated with membrane.

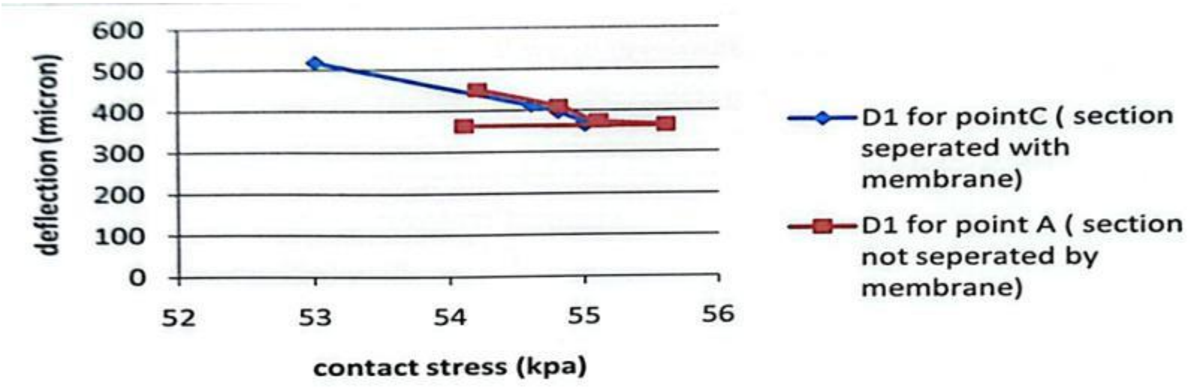

Figure 4.11 Deflection DI vs contact stress at layer 2

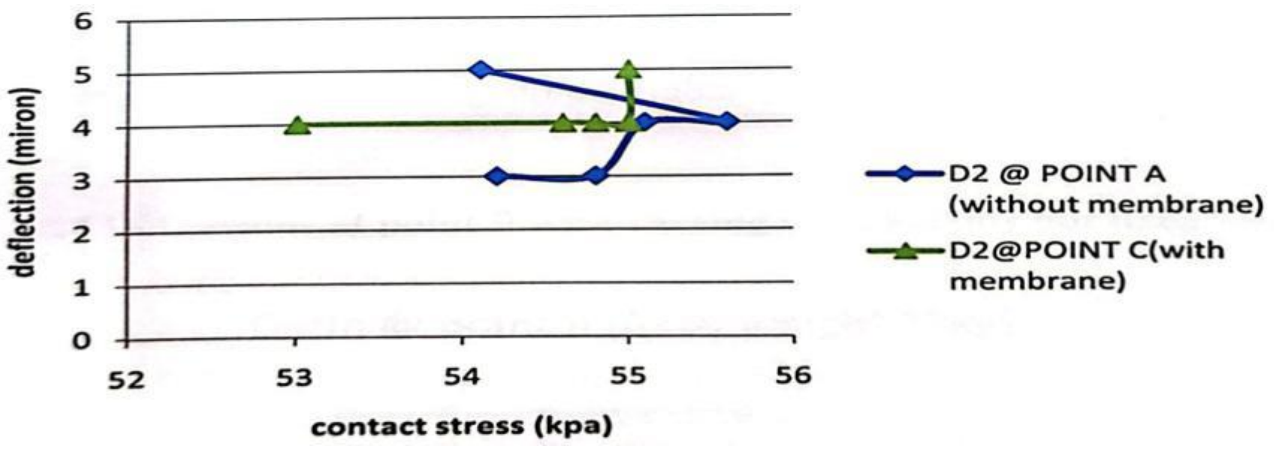

Figure 4.12 Deflection D2 vs contact stress at layer 2

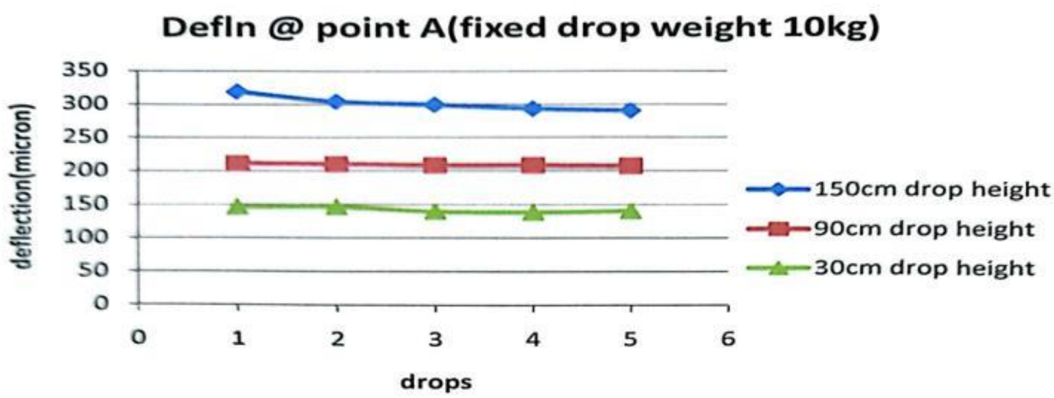

Figure 4.13 Deflections at point A with varying drop heights but fixed weight

Effect of varying drop weight

Under a fixed drop height of 150cm, the readings from point A in layer 5 using varying drop weights indicated more variability (see figure 4.15) than that observed using fixed drop weight. With each drop weight's curve looking different from the other, it appears that using a fixed drop weight at varying drop heights gives a more consistent variation in deflection.

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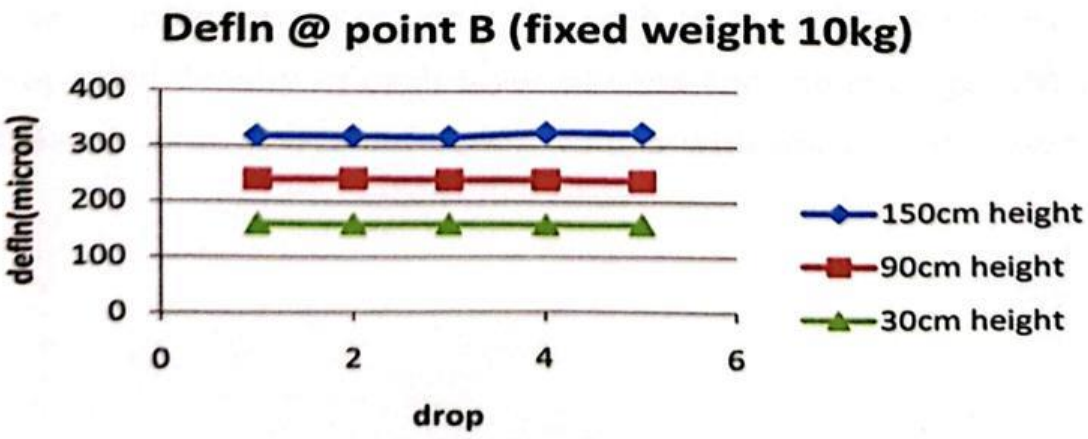

Figure 4.14 Deflections at point B with varying drop heights but fixed weight

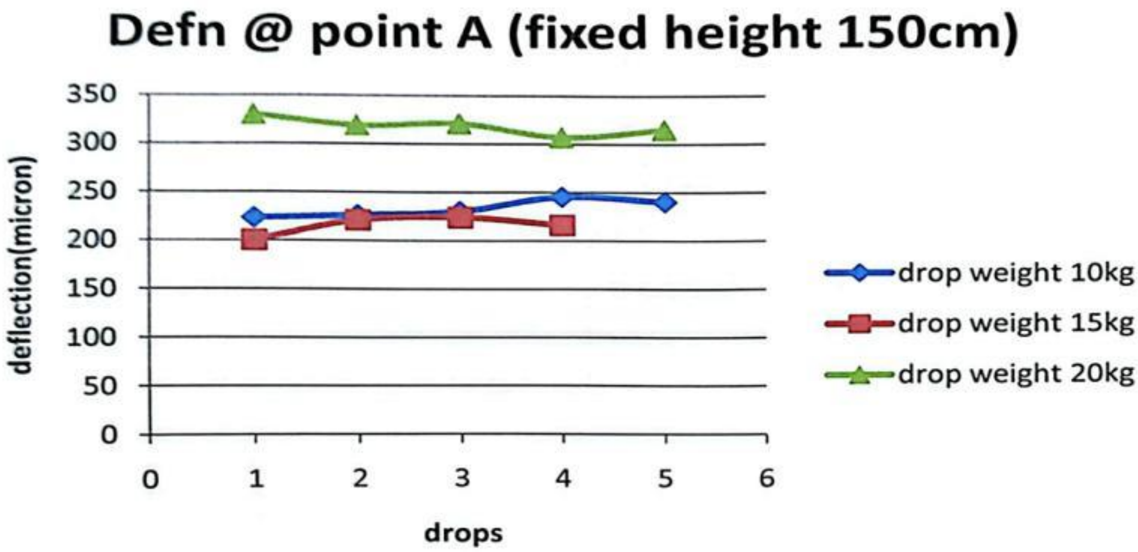

Figure 4.15 Deflections at point B with varying drop weights but fixed height

4.4.2 Similarity of measurement

DCP and Repeated Load Triaxial tests have been selected as comparative tests for this research. To this end, these tests were conducted on the same sample in order to obtain parallel values of MR to be compared. As have been pointed out in the literature review chapter, MR is affected by both factors related to the structure of material and factors related to the physical state of material which includes density, moisture content and temperature. In order to have a fair comparison, it is important to consider these factors.

Inside the test box the density and moisture content, which are the main variables relating to the physical state of material are constant for each layer. Table 4.8 shows the Moisture content (MC), compacted density of each layer of sand and the average MR for each layer (point A) as calculated using LWD deflection values with the numeric model as attached in Appendix I.

Table 4.8 MR(LWD), moisture content and in place density for sand layers

Sand layer	Average MR(Mpa)	In-place Density (g/cm3)	In-place MC(%)

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1	39.5	1.744	5.4
2	29.75	1.67	6.14
3	67.3	1.96	6.01
4	63.33	1.89	7.8

From table, the relationship between density and MR can be seen in figure 4.16

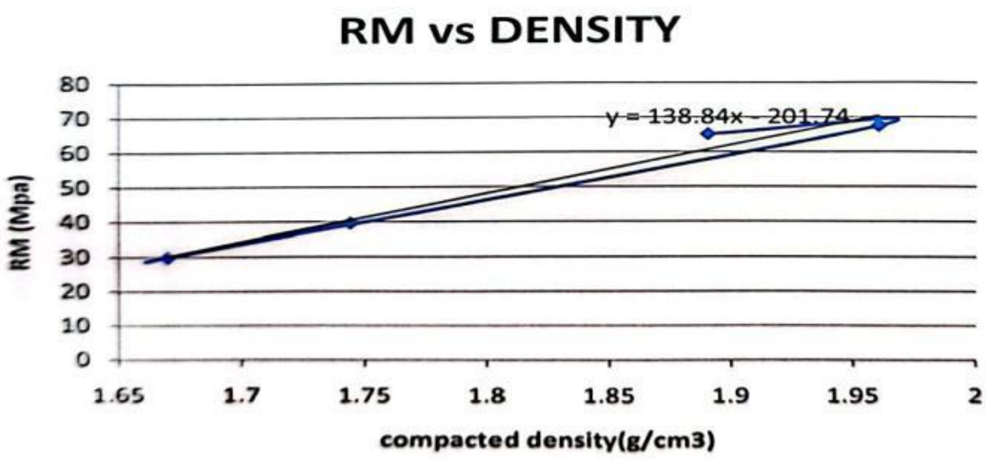

Figure 4.16 LWD Resilient modulus vs in place density

Since density is mass/volume, the compaction process that took place in the test box actually increased density by reducing the material volume. The compaction effort brings
the soil particles together by reducing the void and thereby increasing confinement. The
amount of confinement on materials in the test box may therefore be loosely associated with compacted density. The resilient modulus as indicated by the linear trend shown in figure 4.16 appear to be increasing with increasing density.
Comparing the vertical continuity of the resilient modulus and density across the four layers of sand, the similarity in the shape of the graphs figures 4.17 and 4.18 seems to confirm the trend.

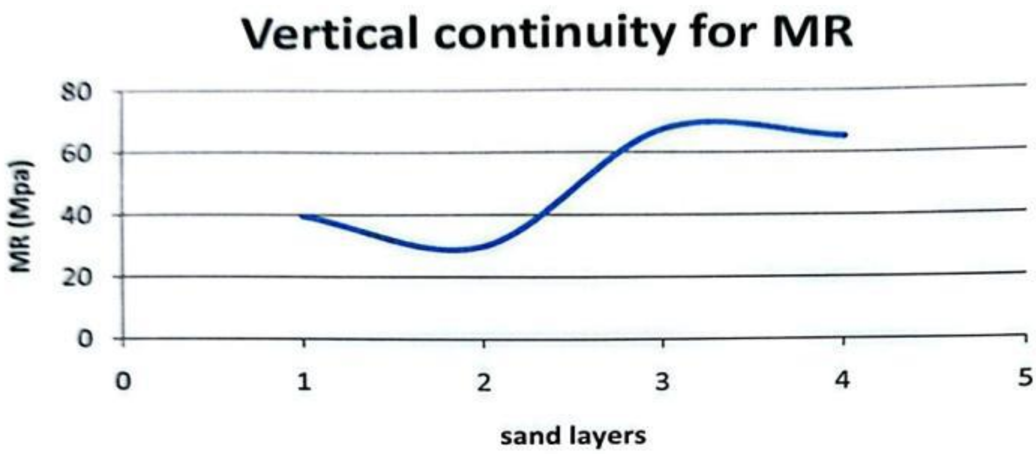

Figure 4.17 LWD Resilient modulus profiles of sand layers

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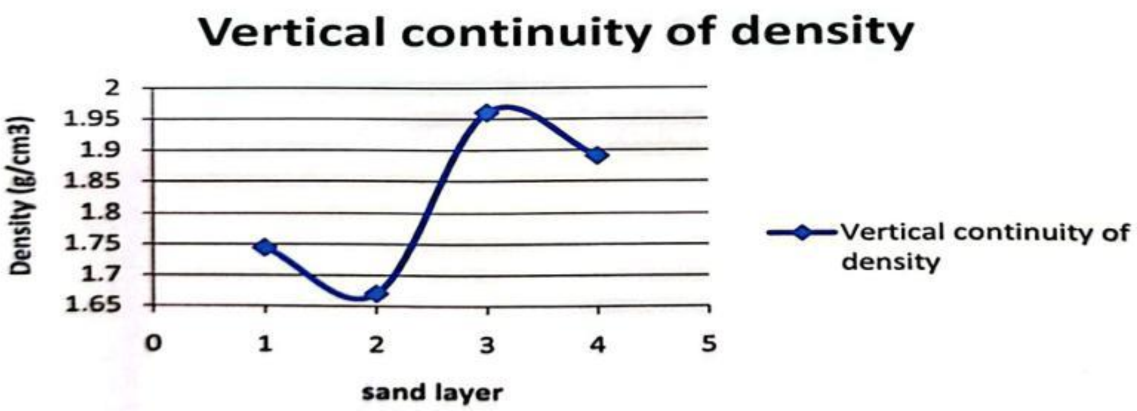

Figure 4.18 In-place density profiles of sand layers

It seems right then to consider the resilient moduli according to the different layers of the rnaterial since there are variations in their density and moisture content. The DCP test provided average MR value for each layer of sand. The challenge here is that there is only one set of MR result from the triaxial test which is the one reflecting the same density and moisture content as layer 1 (see table 4.9). Even then the question arose. Which of the MR values from triaxial test will be representative for layer 1 considering that only two sequence of loading was conclusive? It was thought that the average of the last sequence before failure (32.98Mpa) should be used.

Table 4.9 Resilent modulus from three tests

Sand layer	MR(DCP), (Mpa)		MR(LWD) (Mpa)	MR(Triaxial) (Mpa)
	Cor 4.1	Cor 4.2		
1	49.6	64	39.5	32.98
2	56.7	77.9	29.75	
3	53.3	67	67.33	
4	39	45.3	63.33	
average	49.65	63.4	49.98	32.98

Table 4.9 is the summary of MR results from the tests conducted in this research. The graphical representation in figure C shows some similarity in the curves for DCP 1 and DCP 2. The LWD curve is clearly different but on comparing the average MR for all layers of sand, the values can be said to be close. The average MR value from DCP test using the correlation equation 4.1 is particularly close to the value from LWD test.

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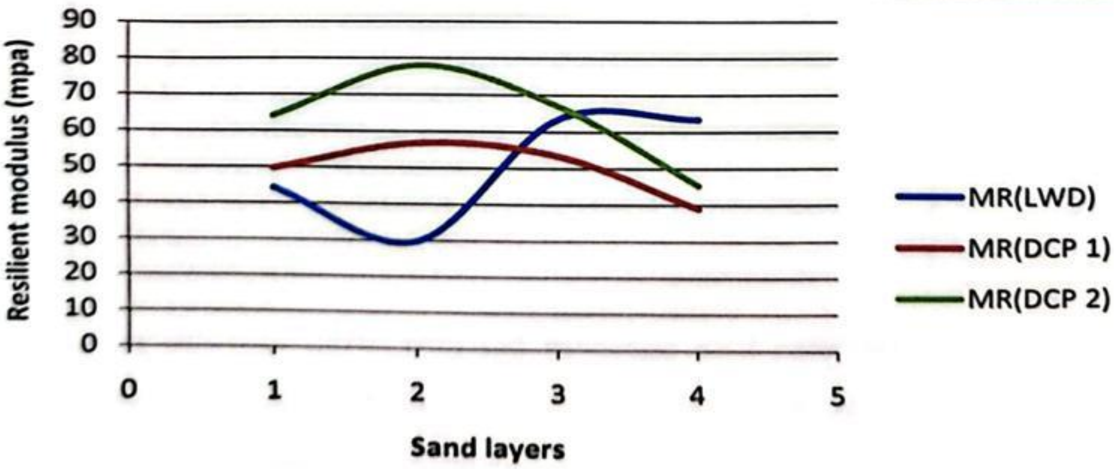

Figure 4.19 Resilient modulus vs sand layers

For the effect of overburden pressure, it was observed that the average value of MR obtained from point A at layer 2 which was 29.75 Mpa (table 4.8) is considerably less than the 85Mpa obtained from same spot in test 29. (see MR value from test 29 in Appendix I). The sharp increase in the MR can be attributed to the overburden pressure due to the weight of the layers of sand on top.

4.4.3 Depth of influence

In estimating the extent or depth of influence, the assumption is made that since the measured deflection at any distance from center of the loading plate is the direct result of deflection below a specific depth it means that only the portion that is stressed contributes to the measured deflection. Therefore, it is reasonable to say that the depth at which deflection is zero is related to the offset at which zero surface deflection will occur. In figure 4.20, it will be the depth at which De= 0.

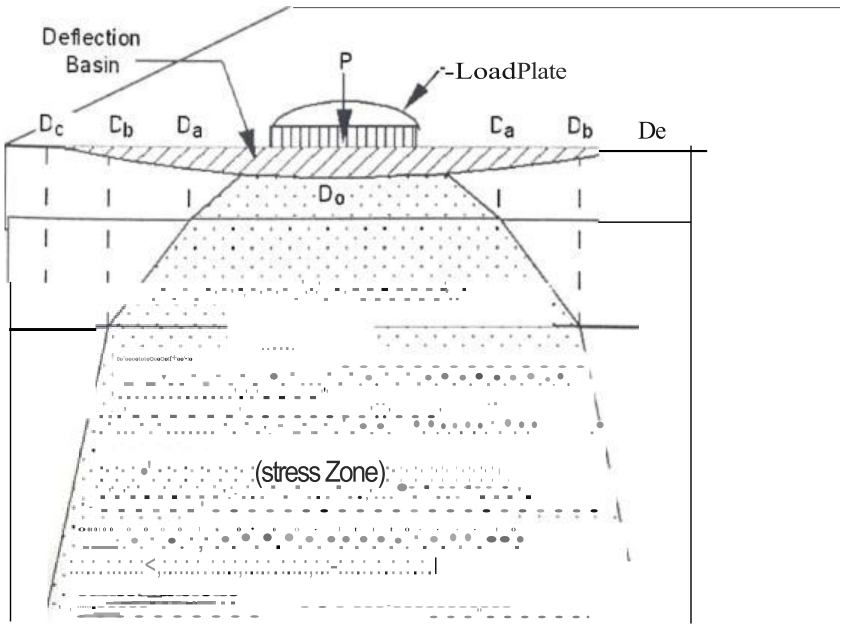

Figure 4.20 Deflection bowl

It Was thought that the low deflection D2 (average of 2 micron) recorded in layer 1 was because of the concrete floor which formed the base of the test box. It was taken as an indication that the second geophone picked up the deflection on the concrete layer which was 150mm below the contact level at that time. At this point, 1t was not clear what was accounting for the deflection recorded by the third geophone (D3). However, the same effect was noticed in layer 2 where the third geophone 03 was thought to have picked up deflection on the concrete floor which was now 300mm below the contact level. When layer4 was added, an increase in 03 (test no 21) was recorded. This increase in the deflection reading 03 confirmed that the concrete floor at this point (450mm) was beyond

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its influence. Therefore, the limit for the depth of influence must be between 300mm and 450mm.

5.0 DISCUSSION

The main focus of this study was to investigate the suitability of the lightweight deflectometer. To this end, the performance of a Dynatest (3031) with respect to its accuracy and repeatability of measurements was investigated. Also, investigated was the similarity of values of Resilient Modulus measured with those from dynamic cone penetrometer and the Repeated Load triaxial test. The depth of influence of this instrument was also studied in the process of these investigations.
A comparative, statistical analysis was conducted on the data generated from the series of tests already described in the previous chapter. The results of these analysis provided the main bases for the assessment of this instrument.
Repeatability of measurement is very important to the road engineer. At every stage of the engineer's work (design, construction and maintenance), accurate measurements are needed to quantify important parameters necessary for efficient delivery of engineering services.
The road or railway engineer must have reliable resilient modulus which is a very important factor in mechanistic designs. As a non-destructive pavement evaluation device, the lightweight deflectometer offers to its users, a valuable measurement tool of high degree of repeatability of measurement without the inflicting of damage on pavement structures. This research has shown that a coefficient of variance of less than 15% is possible when used on granular materials. However, the experience of the operator can be a big factor. Poor contact between loading plate and road surface can greatly affect readings as there is hardly any tolerance for uneven surfaces. The use of a thin sand layer applied to provide a level surface to uniformly distribute the impact may be a good practice. The experience of the operator is always called upon even in things as basic as maintaining verticality of guide rod during measurements. This may be an issue when measuring on slopes as there is no spirit bulb to guide. Also, the recognition of bad drops requires operator's observance of the force-deflection time history. The operator also needs to make judgment on the number of seating drops to accommodate on a given spot. The instrument does not alert its user when wrong combinations of dampers are used. Dampers control the load pulse which in turn affects almost all the readings. Damper stiffness can also be affected by temperature. Overall, the huge dependence on the operator's skills and experience can be a setback. The instrument was not checked for reproducibility as only
one person was involved in the study.

Concerning the similarity of measurements, the results show considerable agreement with those of the DCP and triaxial test. However, the closeness of values depend greatly on the DCP/MR correlation equation utilized. Even then, the accuracy of the back calculation model can have profound effect the resultant resilient moduli. The method of equivalent thickness application for a multi-layer system assumes the subgrade layer to be semi-infinite which makes the incidence of rock layer beneath a subgrade to have influence on results. It should be pointed out that according to this study, the DCP results on layer to layer bases had very weak correlation with the LWD but the average across layers proved to be different. As comparing with the repeated load triaxial test results, it is noteworthy that according to Miller (2009) the recommended axial load pulse during resilient modulus testing is haversine in shape and 100ms in duration. Applied deviator stresses range from 15 to 70 kPa for subgrade soils and from 20 to 280 kPa for base course materials while LWD testing involves three to four repeated impulse loading cycles with 15-20ms duration and due to confinement, the soil experiences simultaneous vertical and horizontal load pulses. This difference in stress path has a significant influence on resulting modulus. It has been documented that vertical compaction especially under a compactor causes lateral stress to increase with only partial recovery when the compactor "walks out". This may be even worse in a test box such as the one used for this research because of the restrain from the box sides. The stress remaining, otherwise known as residual stress, has a profound effect on the deflection tests in-situ, whereas it has minimal effect on reconstituted samples recommended in T-307 protocol. Residual stresses are partially removed when the sample is extruded from the mold, an explanation for residual stress being not significant in T-307 samples. That the residual stress, relevant in material in-situ, could cause the resulting modulus to be larger than that obtained from reconstituted sample in which residual stress is practically nonexistent. These factors may have contributed to the low value of resilient modulus recorded from the triaxial test.
Also, Triaxial test involves the use of samples and sometimes samples are not true representatives due to poor sampling techniques. It is also a well known fact that soil properties vary spatially and the modeling field conditions inside the triaxial chamber are very difficult
Roads and railway structures are mostly composed of layers of materials of different properties engineered to provide safe support for traffic in an efficient manner. The ability to assess the condition of the lower layers without having to physically access them can help save valuable time and also eliminate the problems associated with digging up and patching. According to the finding of this study (using Dynatest 3031), the lightweight deflectometer is able to investigate the condition of a road up to a depth of between 300 to 450mm which seems shallow but since most pavement materials are applied in layers of manageable thicknesses (in order to allow for effective compaction), each layer of material can easily be tested. Testing process takes only about 5 minutes which makes it suitable for quality assurance tests were quick results are required to enable another stage of work to commence.

6.0 CONCLUSIONS AND FURTHER RESEARCH

This research work has investigated the suitability of lightweight deflectometer with focus on the three aspects namely;

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repeatability of measurements, depth of influence and similarity of resilient modulus values with other methods of measurement. To this end, the following works have been accomplished.
. Determining resilient modulus using deflection and surface modulus reading obtained with a lightweight deflectometer.
. Determining resilient modulus using correlation equations applied to readings obtained with a dynamic come penetrometer.
. Measuring resilient modulus using the repeated load triaxial test.
. Determining resilient modulus using density/particle size distribution
. Statistical analyses of results.
. Coarse comparison of resilient modulus values obtained from the different methods employed in this research:
The main conclusions from this work are as follows:
1.The repeatability of measurements by the lightweight deflectometer can be assessed.
2. The depth to which the lightweight deflectometer is determinable but only within a range.
3. Resilient moduli values obtained using lightweight deflectometer is comparable to those obtained from other methods namely DCP and repeated load triaxial test and it was found that
I. The coefficient of variation of measurements for LWD contact pressure was less than
4%
2. The coefficient of variation for LWD deflection measurements was less than 4%
3. The depth of influence of the lightweight deflectometer is between 300 and 450mm but may depend on the applied stress and the stiffness of material being measured.
4.Flooding of subgrade can greatly affect the resilient modulus of materials in the upper layer of a pavement structure.
5.Boundary condition between layers can affect deflection.
6.Resilient modulus is a function of compacted density.
7.Overburden pressure affects resilient modulus.
8.Resilient modulus obtained using the LWD correlates well with that obtained from DCP.

Further works

I. The stress dependency of resilient modulus is a big issue. The resilient modulus from triaxial test is only calculated as the average secant modulus of five unloading cycles while the lightweight deflectometer uses about four repeated loading cycles within about 20 milliseconds which induces both vertical and horizontal load pulses due to confinement. It may be beneficial to measure the difference in these stress parts as it may have consequence on the measured resilient modulus.
2. Due to the sharp variability observed in the daily average COV on the tests conducted on the concrete floor of the laboratory, it might be useful to conduct research that can ascertain the effect of using the lightweight deflectometer to measure bound materials as against unbound materials.

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Appendix A

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TEST No 1

MATERIAL	sand
LAYER	1
LOCATION	A
DROP Height(cm)	60
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	54.6	30	316	-	-	39	-	-
2	54.4	30	315	-	-	39	-	-
3	54.6	30	297	-	-	41	-	-
4	54.8	30	293	-	-	42	-	-
5	54.7	30	293	-	-	42	-	-
MEAN	54.62	30	302.8			40.6		
STDEV	0.148324	0	11.71324037			1.51657509		
C.O.V(%)	0.2715562	0	3.868309238			3.73540662		

TEST No 2

MATERIAL	sand
LAYER	1
LOCATION	A
DROP Height(cm)	60
DROP Wt(kg)	10
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	53.4	30	269	3	3	45	1092	594
2	53.3	30	260	1	2	46	3062	756
3	53.3	30	260	1	2	46	2307	882
4	53.4	30	259	2	2	46	1843	656
MEAN	53.35	30	262	1.75	2.25	45.75	2076	722
STDEV	0.057735	0	4.69041576	0.9574271	0.5	0.5	826.257	125.8253
C.O.V(%)	0.1082194	0	1.790235023	54.71012	22.22222222	1.09289617	39.80043	17.42732

TEST No 3

MATERIAL	sand
LAYER	1
LOCATION	A
DROP Height(cm)	120
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	76.8	25	394	-	-	44	-	-
2	77.1	25	395	-	-	44	-	-
3	75.6	25	373	-	-	46	-	-
4	76.6	25	368	-	-	47	-	-
5	76.6	25	368	-	-	47	-	-
MEAN	76.54	25	379.6			45.6		
STDEV	0.5639149	0	13.75863365			1.51657509		
C.O.V(%)	0.7367584	0	3.624508339			3.32582256		

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TEST No 4

MATERIAL	sand
LAYER	1
LOCATION	A
DROP Height(cm)	120
DROP Wt(kg)	10
No of geophones	3
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	75.6	25	358	1	4	48	3749	548
2	75	25	355	3	5	48	1678	421
3	77	25	350	4	4	49	1120	538
4	76.3	25	352	1	3	49	3646	800
5	76.3	25	352	2	2	49	1811	1097
MEAN	76.04	25	353.4	2.2	3.6	48.6	2400.8	680.8
STDEV	0.7635444	0	3.130495168	1.3038405	1.140175425	0.54772256	1212.324	270.6265
C.O.V(%)	1.0041351	0	0.885822062	59.265476	31.67153959	1.12700115	50.49667	39.75125

TEST No 5

MATERIAL	sand
LAYER	1
LOCATION	A
DROP Height(cm)	60
DROP Wt(kg)	15
No of geophones	3
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	48.6	44	276	0	3	40	4307	437
2	49.5	44	257	2	2	43	1357	562
3	51.5	46	256	2	1	45	1712	978
4	51.5	46	255	1	1	45	2363	1062
MEAN	50.275	45	261	1.25	1.75	43.25	2434.75	759.75
STDEV	1.4614491	1.154701	10.03327796	0.9574271	0.957427108	2.36290781	1315.85	306.7359
C.O.V(%)	2.9069101	2.566001	3.844167802	76.594169	54.71012044	5.46337067	54.04455	40.37327

TEST No 6

MATERIAL	sand
LAYER	1
LOCATION	A
DROP Height(cm)	120
DROP Wt(kg)	15
No of geophones	3
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	75.9	35	340	0	1	50	15352	2321
2	76.2	35	344	0	1	50	14368	1542
3	74.2	35	346	2	2	48	2777	991
4	75.5	35	355	1	2	48	8369	1165
MEAN	75.45	35	346.25	0.75	1.5	49	10216.5	1504.75
STDEV	0.8812869	0	6.34428877	0.9574271	0.577350269	1.15470054	5841.453	590.7681
C.O.V(%)	1.168041	0	1.832285565	127.65695	38.49001795	2.35653171	57.17666	39.26021

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TEST No 4

MATERIAL	sand
LAYER	1
LOCATION	A
DROP Height(cm)	120
DROP Wt(kg)	10
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	75.6	25	358	1	4	48	3749	548
2	75	25	355	3	5	48	1678	421
3	77	25	350	4	4	49	1120	538
4	76.3	25	352	1	3	49	3646	800
5	76.3	25	352	2	2	49	1811	1097
MEAN	76.04	25	353.4	2.2	3.6	48.6	2400.8	680.8
STDEV	0.7635444	0	3.130495168	1.3038405	1.140175425	0.54772256	1212.324	270.6265
C.O.V(%)	1.0041351	0	0.885822062	59.265476	31.67153959	1.12700115	50.49667	39.75125

TEST No 5

MATERIAL	sand
LAYER	1
LOCATION	A
DROP Height(cm)	60
DROP Wt(kg)	15
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	48.6	44	276	0	3	40	4307	437
2	49.5	44	257	2	2	43	1357	562
3	51.5	46	256	2	1	45	1712	978
4	51.5	46	255	1	1	45	2363	1062
MEAN	50.275	45	261	1.25	1.75	43.25	2434.75	759.75
STDEV	1.4614491	1.154701	10.03327796	0.9574271	0.957427108	2.36290781	1315.85	306.7359
C.O.V(%)	2.9069101	2.566001	3.844167802	76.594169	54.71012044	5.46337067	54.04455	40.37327

TEST No 6

MATERIAL	sand
LAYER	1
LOCATION	A
DROP Height(cm)	120
DROP Wt(kg)	15
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	75.9	35	340	0	1	50	15352	2321
2	76.2	35	344	0	1	50	14368	1542
3	74.2	35	346	2	2	48	2777	991
4	75.5	35	355	1	2	48	8369	1165
MEAN	75.45	35	346.25	0.75	1.5	49	10216.5	1504.75
STDEV	0.8812869	0	6.34428877	0.9574271	0.577350269	1.15470054	5841.453	590.7681
C.O.V(%)	1.168041	0	1.832285565	127.65695	38.49001795	2.35653171	57.17666	39.26021

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TEST No 7

MATERIAL	sand
LAYER	1
LOCATION	B
DROP Height(cm)	60
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em:
1	54.9	31	361	_	_	34	
2	55	31	345	_	_	36	
3	55.1	31	337	_	_	37	
4	55	31	326	_	_	38	
5	55.3	31	324	_	_	38	
MEAN	55.06	31	338.6			36.6	
STDEV	0.151658	0	15.14265			1.67332	
C.O.V(%)	0.27544	0	4.472137			4.571913	

TEST No 8

MATERIAL	sand
LAYER	1
LOCATION	B
DROP Height(cm)	120
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2
1	78.2	25	409	_	_	43	
2	79	25	407	_	_	44	
3	77.8	25	395	_	_	44	
4	77.4	25	372	_	_	47	
5	78.4	25	383	_	_	46	
MEAN	78.16	25	393.2			44.8	
STDEV	0.60663	0	15.78607			1.643168	
C.O.V(%)	0.776139	0	4.014769			3.667785	

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Appendix B

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TEST No 9

MATERIAL	sand
LAYER	2
LOCATION	A
DROP Height(cm)	60
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	54.3	31	392	_	_	31	_	_
2	55.3	31	384	_	_	32	_	_
3	55	31	374	_	_	33	_	_
4	54.5	31	366	_	_	33	_	_
5	55	31	374	_	_	33	_	_
MEAN	54.82	31	378			32.4		
STDEV	0.408656	0	10.0995			0.894427		
C.O.V	0.745451	0	2.671827			2.760578		

TEST No 10

MATERIAL	sand
LAYER	2
LOCATION	A
DROP Height(cm)	60
DROP Wt(kg)	10
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	54.2	31	450	3	2	27	881	775
2	54.8	31	409	3	1	30	970	1114
3	55.1	32	374	4	2	32	746	756
4	55.6	33	364	4	3	34	751	882
5	54.1	31	363	5	2	34	585	748
MEAN	54.76	31.6	392	3.8	2	31.4	786.6	855
STDEV	0.626897	0.894427	37.42325	0.83666	0.707107	2.966479	146.7184	154.483
C.O.V	1.144808	2.830466	9.546749	22.01737	35.35534	9.447387	18.65223	18.06819

11 TO 15 WITH MEMBRANE

TEST No 11

MATERIAL	sand
LAYER	2
LOCATION	C
DROP Height(cm)	60
DROP Wt(kg)	10
No of geophones	3
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	53	31	517	4	3	23	673	560
2	54.6	31	411	4	3	30	857	513
3	54.8	32	395	4	2	31	782	823
4	55	33	370	4	4	33	801	407
5	55	31	364	5	4	34	655	411
MEAN	54.48	31.6	411.4	4.2	3.2	30.2	753.6	542.8
STDEV	0.843801	0.894427	62.01048	0.447214	0.83666	4.32434966	86.54941	169.9329
C.O.V(%)	1.548827	2.830466	15.07304	10.64794	26.14563	14.3190386	11.48479	31.30673

TEST No 12

MATERIAL	sand
LAYER	2
LOCATION	C
DROP Height(cm)	120
DROP Wt(kg)	10
No of geophones	3
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	77.2	25	589	1	1	30	7729	3324
2	77.3	25	583	2	1	30	2844	3434
3	78.2	26	563	2	1	31	2885	1876
4	78.3	25	536	1	1	33	4657	4026
5	76.6	25	552	2	3	31	2798	628
MEAN	77.52	25.2	564.6	1.6	1.4	31	4182.6	2657.6
STDEV	0.719027	0.447214	21.87007	0.547723	0.894427	1.22474487	2132.765	1382.894
C.O.V(%)	0.927538	1.774657	3.873551	34.23266	63.88766	3.95078991	50.99136	52.03543

TEST No 13

MATERIAL	sand
LAYER	2
LOCATION	C
DROP Height(cm)	120
DROP Wt(kg)	15
No of geophones	3
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	85	34	607	1	0	32	3299	65707
2	85.4	34	633	1	0	30	5275	8904
3	85.5	34	647	2	0	30	2834	0
4	83.7	34	534	3	0	35	1571	15125
5	86.5	34	533	2	0	37	2204	10865
MEAN	85.22	34	590.8	1.8	0	32.8	3036.6	20120.2
STDEV	1.01341	0	54.24205	0.83666	0	3.1144823	1410.81	26073.9
C.O.V(%)	1.189169	0	9.181119	46.48111	#DIV/0!	9.49537287	46.46019	129.5907

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TEST No 14

MATERIAL	sand
LAYER	2
LOCATION	C
DROP Height(cm)	60
DROP Wt(kg)	15
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	52.2	44	357	6	3	33	502	526
2	52.4	43	354	6	3	34	542	501
3	53	44	341	7	4	35	447	383
4	54.4	43	350	6	2	35	477	836
5	54.8	43	339	6	1	36	491	1078
MEAN	53.36	43.4	348.2	6.2	2.6	34.6	491.8	664.8
STDEV	1.178134	0.547723	7.918333	0.447214	1.140175	1.14017543	34.82384	285.2853
C.O.V(%)	2.207898	1.262034	2.274076	7.213123	43.8529	3.2953047	7.080895	42.91295

TEST No 15

MATERIAL	sand
LAYER	2
LOCATION	C
DROP Height(cm)	30
DROP Wt(kg)	15
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em 2(Mpa)	Em3(Mpa)
1	40	45	261	10	3	35	225	428
2	39.1	44	252	10	3	35	217	366
3	40	44	244	11	3	37	202	335
4	39.8	44	245	12	4	37	194	299
5	40.4	45	244	11	4	39	201	305
MEAN	39.86	44.4	249.2	10.8	3.4	36.6	207.8	346.6
STDEV	0.477493	0.547723	7.395945	0.83666	0.547723	1.67332005	12.75539	52.75699
C.O.V(%)	1.197926	1.233609	2.967875	7.746852	16.10949	4.57191271	6.138302	15.22129

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Appendix C

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TEST No 16

MATERIAL	sand
LAYER	3
LOCATION	A
DROP Height(cm)	150
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	65.6	26	201	–	–	86	–	–
2	66.2	26	199	–	–	88	–	–
3	66.6	26	201	–	–	87	–	–
4	66.1	26	200	–	–	87	–	–
5	66.1	26	198			88		
MEAN	66.12	26	199.8			87.2		
STDEV	0.356371	0	1.30384			0.83666		
C.O.V(%)	0.538975	0	0.652573			0.959473		

TEST No 17

MATERIAL	sand
LAYER	3
LOCATION	A
DROP Height(cm)	90
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	41.7	33	127	–	–	86	–	–
2	42.5	33	126	–	–	89	–	–
3	41.9	33	126	–	–	88	–	–
4	41.8	33	126	–	–	87	–	–
5	42.1	33	129			86		
MEAN	42	33	126.8			87.2		
STDEV	0.316228	0	1.30384			1.30384		
C.O.V(%)	0.752923	0	1.028265			1.49523		

TEST No 18

MATERIAL	sand
LAYER	3
LOCATION	A
DROP Height(cm)	30
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	27.9	36	81	–	–	90	–	–
2	42.5	33	126	–	–	84	–	–
3	41.9	33	126	–	–	88	–	–
4	41.8	33	126	–	–	87	–	–
5	42.1	33	129			86		
MEAN	39.24	33.6	117.6			87		
STDEV	6.344919	1.341641	20.50122			2.236068		
C.O.V(%)	16.16952	3.992979	17.43301			2.570193		

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Appendix D

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TEST No 22

MATERIAL	sand
LAYER	4
LOCATION	A
DROP Height(cm)	150
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
			DEFLECTION(micron)					
1	87.6	24	319	–	–	72	–	–
2	87.9	24	304	–	–	76	–	–
3	87.9	24	299	–	–	77	–	–
4	87.9	24	293	–	–	79	–	–
5	88.3	24	290			80		
MEAN	87.92	24	301			76.8		
STDEV	0.248998	0	11.42366			3.114482		
C.O.V(%)	0.28321	0	3.795236			4.055315		

TEST No 23

MATERIAL	sand
LAYER	4
LOCATION	A
DROP Height(cm)	90
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
			DEFLECTION(micron)					
1	64.6	26	211	–	–	80	–	–
2	65	26	210	–	–	82	–	–
3	64.9	26	208	–	–	82	–	–
4	65.1	26	208	–	–	82	–	–
5	65.2	26	207			83		
MEAN	64.96	26	208.8			81.8		
STDEV	0.230217	0	1.643168			1.095445		
C.O.V(%)	0.354399	0	0.786958			1.339175		

TEST No 24

MATERIAL	sand
LAYER	4
LOCATION	A
DROP Height(cm)	30
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
			DEFLECTION(micron)					
1	44.1	32	146	–	–	80	–	–
2	44.1	32	146	–	–	80	–	–
3	41.4	32	139	–	–	78	–	–
4	41.6	32	138	–	–	79	–	–
5	41.3	32	140			78		
MEAN	42.5	32	141.8			79		
STDEV	1.464582	0	3.898718			1		
C.O.V(%)	3.446075	0	2.749448			1.265823		

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TEST No 25

MATERIAL	sand
LAYER	4
LOCATION	B
DROP Height(cm)	150
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	86.5	24	319	–	–	71	–	–
2	86.5	24	320	–	–	71	–	–
3	86.1	25	318	–	–	71	–	–
4	86.9	24	326	–	–	70	–	–
5	87.8	24	325			71		
MEAN	86.76	24.2	321.6			70.8		
STDEV	0.646529	0.447214	3.646917			0.447214		
C.O.V(%)	0.745193	1.84799	1.133991			0.631658		

TEST No 26

MATERIAL	sand
LAYER	4
LOCATION	B
DROP Height(cm)	90
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	64.7	26	241	–	–	71	–	–
2	65.1	26	243	–	–	71	–	–
3	65.2	26	241	–	–	71	–	–
4	65.2	26	241	–	–	71	–	–
5	64.8	26	239			71		
MEAN	65	26	241			71		
STDEV	0.234521	0	1.414214			0		
C.O.V(%)	0.360801	0	0.586811			0		

TEST No 27

MATERIAL	sand
LAYER	4
LOCATION	B
DROP Height(cm)	30
DROP Wt(kg)	10
No of geophones	1
PLATE diameter(mm)	300

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	41.4	32	160	–	–	68	–	–
2	41.5	32	160	–	–	68	–	–
3	41.7	32	160	–	–	69	–	–
4	41.7	32	159	–	–	69	–	–
5	41.7	32	159			69		
MEAN	41.6	32	159.6			68.6		
STDEV	0.141421	0	0.547723			0.547723		
C.O.V(%)	0.339955	0	0.343185			0.798429		

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28 AND 29 (IN THE PIT)

TEST No 28

MATERIAL	sand	
LAYER	3	(excavate 150mm below layer 4)
LOCATION	A	
DROP Height(cm)	150	
DROP Wt(kg)	10	
No of geophones	1	
PLATE diameter(mm)	300	

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	88.3	25	264	–	–	88	–	–
2	88.3	24	273	–	–	85	–	–
3	88.6	25	276	–	–	85	–	–
4	89	24	271	–	–	87	–	–
5	89.3	24	276	–	–	85	–	–
MEAN	88.7	24.4	272			86		
STDEV	0.441588	0.547723	4.949747			1.414214		
C.O.V(%)	0.497844	2.244765	1.81976			1.644434		

TEST No 29

MATERIAL	sand	
LAYER	2	(excavate 300mm below layer 4)
LOCATION	A	
DROP Height(cm)	150	
DROP Wt(kg)	10	
No of geophones	1	
PLATE diameter(mm)	300	

DROP No	Stress(kpa)	PULSE	DEFLECTION(micron) D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	89.3	25	220	–	–	107	–	–
2	88.3	24	223	–	–	104	–	–
3	90.1	24	225	–	–	105	–	–
4	89.5	24	210	–	–	112	–	–
5	90.8	24	214	–	–	112	–	–
MEAN	89.6	24.2	218.4			108		
STDEV	0.932738	0.447214	6.268971			3.807887		
C.O.V(%)	1.041002	1.84799	2.870408			3.525821		

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TEST No 30

MATERIAL	ballast
LAYER	5
LOCATION	A
DROP Height(cm)	2.5
DROP Wt(kg)	10
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	84.4	25	223	56	26	100	99	106
2	86.2	25	226	58	25	100	98	112
3	86.9	25	230	57	25	100	100	116
4	87.6	25	245	58	25	94	99	116
5	86.8	25	240	60	25	95	96	113
MEAN	86.38	25	232.8	57.8	25.2	97.8	98.4	112.6
STDEV	1.2132601	0	9.364827815	1.4832397	0.4472136	3.03315018	1.516575	4.09878
C.O.V(%)	1.4045613	0	4.02269236	2.5661586	1.77465713	3.10138055	1.541235	3.640125

TEST No 31

MATERIAL	ballast
LAYER	5
LOCATION	A
DROP Height(cm)	2.5
DROP Wt(kg)	15
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	99.5	33	200	54	24	125	116	134
2	98.7	33	221	57	24	118	114	138
3	98.7	33	224	60	24	116	108	133
4	98.8	33	216	58	25	120	111	133
MEAN	98.925	33	215.25	57.25	24.25	119.75	112.25	134.5
STDEV	0.386221	0	10.68877916	2.5	0.5	3.86221008	3.5	2.380476
C.O.V(%)	0.390418	0	4.965751063	4.3668122	2.06185567	3.22522762	3.11804	1.769871

TEST No 32

MATERIAL	ballast
LAYER	5
LOCATION	A
DROP Height(cm)	2.5
DROP Wt(kg)	20
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	147.8	30	330	71	29	118	138	165
2	148.2	30	319	70	30	122	140	165
3	147.9	30	321	69	29	121	141	169
4	148.3	30	307	69	30	127	141	165
5	148.6	31	315	70	29	124	140	166
MEAN	148.16	30.2	318.4	69.8	29.4	122.4	140	166
STDEV	0.3209361	0.447214	8.414273587	0.83666	0.54772256	3.36154726	1.224745	1.732051
C.O.V(%)	0.2166146	1.48084	2.642673865	1.1986533	1.8630019	2.74636214	0.874818	1.043404

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Appendix E

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TEST No 30

MATERIAL	ballast
LAYER	5
LOCATION	A
DROP Height(cm)	2.5
DROP Wt(kg)	10
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	84.4	25	223	56	26	100	99	106
2	86.2	25	226	58	25	100	98	112
3	86.9	25	230	57	25	100	100	116
4	87.6	25	245	58	25	94	99	116
5	86.8	25	240	60	25	95	96	113
MEAN	86.38	25	232.8	57.8	25.2	97.8	98.4	112.6
STDEV	1.2132601	0	9.364827815	1.4832397	0.4472136	3.03315018	1.516575	4.09878
C.O.V(%)	1.4045613	0	4.02269236	2.5661586	1.77465713	3.10138055	1.541235	3.640125

TEST No 31

MATERIAL	ballast
LAYER	5
LOCATION	A
DROP Height(cm)	2.5
DROP Wt(kg)	15
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	99.5	33	200	54	24	125	116	134
2	98.7	33	221	57	24	118	114	138
3	98.7	33	224	60	24	116	108	133
4	98.8	33	216	58	25	120	111	133
MEAN	98.925	33	215.25	57.25	24.25	119.75	112.25	134.5
STDEV	0.386221	0	10.68877916	2.5	0.5	3.86221008	3.5	2.380476
C.O.V(%)	0.390418	0	4.965751063	4.3668122	2.06185567	3.22522762	3.11804	1.769871

TEST No 32

MATERIAL	ballast
LAYER	5
LOCATION	A
DROP Height(cm)	2.5
DROP Wt(kg)	20
No of geophones	3
PLATE diameter(mm)	300

			DEFLECTION(micron)					
DROP No	Stress(kpa)	PULSE	D1	D2	D3	Em1(Mpa)	Em2(Mpa)	Em3(Mpa)
1	147.8	30	330	71	29	118	138	165
2	148.2	30	319	70	30	122	140	165
3	147.9	30	321	69	29	121	141	169
4	148.3	30	307	69	30	127	141	165
5	148.6	31	315	70	29	124	140	166
MEAN	148.16	30.2	318.4	69.8	29.4	122.4	140	166
STDEV	0.3209361	0.447214	8.414273587	0.83666	0.54772256	3.36154726	1.224745	1.732051
C.O.V(%)	0.2166146	1.48084	2.642673865	1.1986533	1.8630019	2.74636214	0.874818	1.043404

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Appendix F

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Cyclic Triaxial Test

Test date = 14-8-2009
Sample number = Sand- 80 -1
Material type = Sand
Specimen dia (mm) = 100.0
Specimen ht (mm) = 150.0

Confining stress kPa	Target max.ax. stress kPa	Cycle No.	Actual maximum load kN	Actual cyclic load kN	Actual contact load kN	Actual max.ax. stress kPa	Actual cyclic stress kPa	Actual contact stress kPa	Recov.Def. LVDT 1 mm	Recov.Def. LVDT 2 mm	Average recov.def. mm	Resilient strain mm/mm	Resilient modulus MPa
Sequence No. = 1 Last 5 pulses of 100													
40.9	13.8	1	0.109	0.098	0.011	13.9	12.5	1.4	0.065768	0.067685	0.066727	0.000445	28.034
41.7	13.8	2	0.108	0.097	0.011	13.7	12.3	1.4	0.065768	0.066371	0.066069	0.000440	28.015
41.7	13.8	3	0.108	0.097	0.011	13.8	12.4	1.4	0.064452	0.066207	0.065330	0.000436	28.344
41.1	13.8	4	0.109	0.098	0.011	13.9	12.5	1.4	0.066097	0.066700	0.066398	0.000443	28.160
40.7	13.8	5	0.108	0.097	0.011	13.8	12.4	1.4	0.068234	0.069492	0.068863	0.000459	27.009
Permanent strain (%) =		1.4											
Sequence No. = 2 Last 5 pulses of 100													
41.7	27.6	1	0.216	0.194	0.022	27.6	24.7	2.8	0.110654	0.113028	0.111841	0.000746	33.173
41.2	27.6	2	0.217	0.195	0.022	27.6	24.9	2.8	0.111970	0.114506	0.113238	0.000755	32.922
40.8	27.6	3	0.216	0.194	0.022	27.6	24.8	2.8	0.111970	0.114342	0.113156	0.000754	32.842
42.0	27.6	4	0.217	0.195	0.022	27.6	24.8	2.8	0.111476	0.113685	0.112581	0.000751	33.077
42.0	27.6	5	0.217	0.195	0.022	27.6	24.8	2.8	0.112134	0.114013	0.113074	0.000754	32.893
Permanent strain (%) =		1.8											

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		drop	force(kN)	stress(kpa)	defl(micron)	E(Mpa)
day1		1	3.9	54.7	4	3324
		2	3.9	54.9	3	3760
		3	3.9	55.3	4	3244
		4	3.9	55.4	4	3400
	1	MEAN	3.9	55.075	3.75	3432
		STDEV	0	0.330404	0.5	227.7543
		C.O.V	0	0.599916	13.3333333	6.636196
day2		1	3.8	54.4	4	3124
		2	3.8	54.1	4	3195
		3	3.8	54.2	4	3456
		4	3.8	53.9	4	3298
	2	MEAN	3.8	54.15	4	3268.25
		STDEV	0	0.208167	0	144.1166
		C.O.V	0	0.384426	0	4.409594
day3		1	3.9	54.5	5	2882
		2	3.9	55.2	5	3197
		3	3.9	55.4	3	5326
		4	3.9	52.9	3	5521
	3	MEAN	3.9	54.5	4	4231.5
		STDEV	0	1.134313	1.15470054	1384.688
		C.O.V	0	2.081309	28.8675135	32.72333
day4		1	3.7	52.9	4	3714
		2	3.8	53.9	3	4393
		3	3.8	54	4	3861
		4	3.8	54.1	3	4333
	4	MEAN	3.775	53.725	3.5	4075.25
		STDEV	0.05	0.556028	0.57735027	338.5286
		C.O.V	1.3245	1.034951	16.495722	8.30694
day5		1	3.7	52.7	3	4663
		2	3.9	54.9	3	4229
		3	3.8	53.6	4	3423
		4	3.8	53.7	4	3859
	5	MEAN	3.8	53.725	3.5	4043.5
		STDEV	0.08165	0.903235	0.57735027	528.2837
		C.O.V	2.14868	1.681219	16.495722	13.06501

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Appendix H

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SUMMARY COV FOR TESTS IN THE TEST BOX

TEST No	Stress(%)	PULSE(%)	D1(%)	D2(%)	D3(%)	Em1(%)	Em2(%)	Em3(%)
1	0.27155615	0	3.868309			3.7354066		
2	0.10821936	0	1.790235	54.71012	22.22222	1.0928962	39.800435	17.427324
3	0.73675841	0	3.624508			3.3258226		
4	1.00413515	0	0.885822	59.26548	31.67154	1.1270011	50.496672	39.751248
5	2.9069101	2.566001	3.844168	76.59417	54.71012	5.4633707	54.044548	40.373268
6	1.168041	0	1.832286	127.6569	38.49002	2.3565317	57.176658	39.260214
7	0.27544044	0	4.472137			4.5719127		
8	0.77613874	0	4.014769			3.667785		
9	0.74545118	0	2.671827			2.7605777		
10	1.14480847	2.830466	9.546749	22.01737	35.35534	9.4473866	18.65223	18.068188
11	1.54882695	2.830466	15.07304	10.64794	26.14563	14.319039	11.484794	31.30673
12	0.92753757	1.774657	3.873551	34.23266	63.88766	3.9507899	50.991362	52.035432
13	1.18916931	0	9.181119	46.48111		9.4953729	46.460191	
14	2.20789752	1.262034	2.274076	7.213123	43.8529	3.2953047	7.0808952	42.912951
15	1.19792638	1.233609	2.967875	7.746852	16.10949	4.5719127	6.1383017	15.22129
16	0.53897549	0	0.652573			0.9594725		
17	0.75292325	0	1.028265			1.4952299		
18								
19	1.25703825	1.270493	0.595905			1.7716999		
20	0.98097864	0	2.129133			2.8834146		
21	0.12515144	0	1.462706	17.88745	3.665685	1.4146097	1.8092287	3.0416945
22	0.28320973	0	3.795236			4.0553155		
23	0.35439854	0	0.786958			1.339175		
24	3.44607494	0	2.749448			1.2658228		
25	0.74519271	1.84799	1.133991			0.6316576		
26	0.36080121	0	0.586811			0		
27	0.33995518	0	0.343185			0.7984294		
28	0.49784447	2.244765	1.81976			1.6444344		
29	1.04100213	1.84799	2.870408			3.5258209		
30	1.40456132	0	4.022692	2.566159	1.774657	3.1013805	1.5412348	3.6401246
31	0.390418	0	4.965751	4.366812	2.061856	3.2252276	3.1180401	1.7698707
32	0.21661456	1.48084	2.642674	1.198653	1.863002	2.7463621	0.8748178	1.0434041
33	0.63061143	1.451992	3.312249	2.329129	5.567022	3.7009589	3.230498	4.6047406
MAX	3.44607494	2.830466	15.07304	127.6569	63.88766	14.319039	57.176658	52.035432
MIN	0.10821936	0	0.343185	1.198653	1.774657	0	0.8748178	1.0434041

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Appendix I

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LAYER 1

Location	Test No	d(1)	d(2)	d(3)	Load σ_o	α	r_1	r_2	t_1	t_2	f_1	f_2	f_3	μ	Z_{equi2} @ t_{SM}	Z_{equi1} @ t_{SM1}	SM1	SM2	SM3	RM_{top}	R	σ_r	σ_r/σ	ε_c	Def 3rd	Com 2nd	Com top	Σ Def	Act d
		Deflections (microns)			kpa	m	m	m	m	m					m	m													
A	1	302.80	0.00	0.00	54.62	0.15	0.3	0.6	0.15	0.2	1	0.9	0.8	0.35	0.100	0.325724	47	NA	NA	35.0	377.754	45.345	15.27[illegible]	0.000289	0.000113	4.42E-05	0.000148	305	303
	2	262.00	1.75	2.25	53.35	0.15	0.3	0.6	0.15	0.2	1	0.9	0.8	0.35	0.100	0.32599	54	2006	780	40.0	436.2455	44.197	9.95[illegible]	0.00025	9.75E-05	3.82E-05	0.000127	262	262
	3	379.60	0.00	0.00	76.54	0.15	0.3	0.6	0.15	0.2	1	0.9	0.8	0.35	0.100	0.3256	53	NA	NA	39.0	301.1854	63.573	14.36[illegible]	0.000363	0.000141	5.54E-05	0.000186	383	380
	4	353.40	2.20	3.60	76.04	0.15	0.3	0.6	0.15	0.2	1	0.9	0.8	0.35	0.100	0.325968	57	2275	695	42.0	323.9975	63.978	14.19[illegible]	0.000337	0.000132	5.15E-05	0.000172	355	353
	5	261.00	1.25	1.75	50.275	0.15	0.3	0.6	0.15	0.2	1	0.9	0.8	0.35	0.100	0.326281	51	2647	945	28.0	438.8663	41.636	9.32[illegible]	0.000249	9.7E-05	3.8E-05	0.000126	261	261
	6	346.23	0.75	1.50	75.45	0.15	0.3	0.6	0.15	0.2	1	0.9	0.8	0.35	0.100	0.325948	57	6621	1655	43.0	329.466	62.440	13.94[illegible]	0.000331	0.000129	5.06E-05	0.000167	346	346
B	7	338.80	0.00	0.00	55.06	0.15	0.3	0.6	0.19	0.2	1	0.9	0.8	0.35	0.132	0.360686	43	NA	NA	36.0	391.5184	39.155	5.617[illegible]	0.000277	0.000116	4.27E-05	0.000178	337	339
	8	393.20	0.00	0.00	78.16	0.15	0.3	0.6	0.15	0.2	1	0.9	0.8	0.35	0.100	0.326051	52	NA	NA	39.0	291.0124	64.776	14.53[illegible]	0.000375	0.000146	5.73E-05	0.00019	394	393

LAYER 2

Location	Test No	d(1)	d(2)	d(3)	Load σ_o	α	r_1	r_2	t_1	t_2	f_1	f_2	f_3	μ	Z_{equi2} @ t_{SM}	Z_{equi1} @ t_{SM1}	SM1	SM2	SM3	RM_{top}	R	σ_r	σ_r/σ	ε_c	Def 3rd	Com 2nd	Com top	Σ Def	Act d
		Deflections (microns)			kpa	m	m	m	m	m					m	m													
A	9	378.00	0.00	0.00	54.84	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.103	0.273924	38	NA	NA	30.5	303.556	44.950	9.731[illegible]	0.000464	0.000162	4.57E-05	0.000171	378	378
	10	392.00	3.80	2.00	54.76	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.273769	37	948	901	29.0	293.7228	45.007	9.829[illegible]	0.000481	0.000168	4.72E-05	0.000179	394	392
C	11	411.40	4.20	3.20	54.48	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.103	0.274316	35	854	560	28.0	279.9172	44.638	9.652[illegible]	0.000504	0.000176	4.95E-05	0.000185	410	411
	12	564.60	1.60	1.40	77.52	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.103	0.274154	36	3189	1822	29.0	203.5363	63.505	13.72[illegible]	0.000692	0.000242	6.81E-05	0.000254	564	565
	13	590.80	1.80	0.00	85.22	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.273838	38	3116	NA	30.0	194.9365	70.023	15.27[illegible]	0.000725	0.000253	7.11E-05	0.00027	594	591
	14	348.20	6.20	2.60	53.36	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.274026	40	566	675	32.0	331.1274	43.823	9.547[illegible]	0.000427	0.000149	4.19E-05	0.000158	349	348
	15	249.20	10.80	3.40	39.86	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.103	0.27447	42	243	386	34.0	462.1013	32.630	7.035[illegible]	0.000305	0.000107	3E-05	0.000111	248	249

LAYER 3

Location	Test No	d(1)	d(2)	d(3)	Load σ_o	α	r_1	r_2	t_1	t_2	f_1	f_2	f_3	μ	Z_{equi2} @ t_{SM}	Z_{equi1} @ t_{SM1}	SM1	SM2	SM3	RM_{top}	R	σ_r	σ_r/σ	ε_c	Def 3rd	Com 2nd	Com top	Σ Def	Act d
		Deflections (microns)			kpa	m	m	m	m	m					m	m													
A	16	199.80	0.00	0.00	66.12	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.273944	87	NA	NA	69.0	576.7117	54.311	11.8[illegible]16	0.000245	8.56E-05	2.4E-05	9.09E-05	201	200
	17	126.80	0.00	0.00	42	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.273322	87	NA	NA	68.0	906.2698	34.573	7.58[illegible]32	0.000156	5.44E-05	1.53E-05	5.86E-05	128	127
	18	117.60	0.00	0.00	39.24	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.101	0.273149	88	NA	NA	68.0	977.8209	32.345	7.13[illegible]95	0.000145	5.05E-05	1.42E-05	5.48E-05	119	118
	19	218.80	0.00	0.00	71.02	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.274165	85	NA	NA	68.0	527.3284	58.302	12.6[illegible]27	0.000268	9.37E-05	2.63E-05	9.91E-05	219	219
	20	336.40	0.00	0.00	105.84	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.274101	83	NA	NA	66.0	342.416	86.842	18.9[illegible]84	0.000412	0.000144	4.05E-05	0.000152	337	336
	21	508.40	29.00	12.00	155.76	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.103	0.274637	81	353	427	65.0	227.3176	127.626	27.5[illegible]74	0.000621	0.000217	6.1E-05	0.000227	506	508

LAYER 4

Location	Test No	d(1)	d(2)	d(3)	Load σ_o	α	r_1	r_2	t_1	t_2	f_1	f_2	f_3	μ	Z_{equi2} @ t_{SM}	Z_{equi1} @ t_{SM1}	SM1	SM2	SM3	RM_{top}	R	σ_r	σ_r/σ_r	ε_c	Def 3rd	Com 2nd	Com top	Σ Def	Act d
		Deflections (microns)			kpa	m	m	m	m	m					m	m													
A	22	301.00	0.00	0.00	87.92	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.103	0.274489	77	NA	NA	62.0	382.9532	72.002	15.5[illegible]437	0.000368	0.000129	3.62E-05	0.000135	300	301
	23	208.80	0.00	0.00	64.96	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.274034	82	NA	NA	65.0	552.1267	53.344	11.6[illegible]762	0.000256	8.94E-05	2.51E-05	9.48E-05	209	209
	24	141.80	0.00	0.00	42.5	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.103	0.274123	79	NA	NA	63.0	811.848	34.856	7.5[illegible]128	0.000174	6.07E-05	1.71E-05	6.4E-05	142	142
B	25	321.60	0.00	0.00	86.76	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.103	0.274523	71	NA	NA	57.0	359.3943	71.141	15.4[illegible]037	0.000393	0.000138	3.86E-05	0.000144	321	322
	26	241.00	0.00	0.00	65	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.273889	71	NA	NA	56.0	478.6471	53.439	11.6[illegible]169	0.000296	0.000103	2.9E-05	0.00011	242	241
	27	159.60	0.00	0.00	41.6	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.103	0.27448	69	NA	NA	55.0	724.1483	34.118	7.40[illegible]461	0.000195	6.83E-05	1.91E-05	7.18E-05	159	160
	28	272.00	0.00	0.00	87.3	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.273877	84	NA	NA	67.0	422.9396	71.674	15.5[illegible]871	0.000334	0.000117	3.28E-05	0.000124	273	272
	29	218.40	0.00	0.00	89.6	0.15	0.3	0.6	0.15	0.15	1	0.9	0.8	0.35	0.102	0.273658	108	NA	NA	85.0	526.7446	73.656	16.0[illegible]611	0.000268	9.37E-05	2.63E-05	0.0001	220	218

LAYER 5

Location	Test No	d(1)	d(2)	d(3)	Load σ_o	α	r_1	r_2	t_1	t_2	f_1	f_2	f_3	μ	Z_{equi2} @ t_{SM}	Z_{equi1} @ t_{SM1}	SM1	SM2	SM3	RM_{top}	R	σ_r	σ_r/σ_r	ε_c	Def 3rd	Com 2nd	Com top	Σ Def	Act d
		Deflections (microns)			kpa	m	m	m	m	m					m	m													
A	30	232.80	57.80	25.20	86.38	0.15	0.3	0.6	0.3	0.15	1	0.9	0.8	0.35	0.219	0.400607	98	98	113	95.0	1041.37	37.858	1.46[illegible]186	0.00016	7.25E-05	1.6E-05	0.000144	232	233
	31	215.25	57.25	24.25	98.93	0.15	0.3	0.6	0.3	0.15	1	0.9	0.8	0.35	0.225	0.407139	121	114	134	120.0	1107.813	41.915	1.4[illegible]506	0.000153	7.03E-05	1.53E-05	0.000131	216	215
	32	318.40	69.80	29.40	148.16	0.15	0.3	0.6	0.3	0.15	1	0.9	0.8	0.35	0.220	0.40118	122	140	166	120.0	764.4391	64.743	2.48[illegible]146	0.000219	9.91E-05	2.18E-05	0.000196	316	318
	33	474.20	103.40	22.00	148.08	0.15	0.3	0.6	0.3	0.15	1	0.9	0.8	0.35	0.219	0.400827	82	94	221	80.0	512.1389	64.967	2.5[illegible]411	0.000326	0.000148	3.24E-05	0.000283	473	474

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Appendix J

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Numerical model

The numerical model used for this exercise is Excel based and is primarily based on the application of the Bussinesq's equations using a process of back calculating deflections values in order to match with measured values. Before describing the model elements it is important to examine three important concepts on which the model is based. The concepts are

1. Back analysis
2. Equivalent thickness
3. Surface modulus

Back analysis

The back analysis refers to an iterative procedure whereby the elastic Modulus of the constituent layers of the pavement model is adjusted until the computed deflections under a given load agree with the corresponding field values of deflection. It utilizes the Boussinesq's equations. The equations for a load distributed over a circular area of radius α and of applied stress σ_0 at a depth z below the surface are:

$$\sigma_z = \sigma_0 * \{1-1/[1+(a/z)2]3/2\}$$

$$\sigma_r = \sigma_t = \sigma_0 \{(1+2n)/2 - (1+n)/[1+(a/z)2]1/2 + 1/2/[1+(a/z)2]3/2$$

$$\varepsilon_z = (1+n)\ \sigma_0 / E * \{(z/a)/[1+(z/a)2]3/2 - (1-2n)\{(z/a)/[1+(z/a)2]1/2-1\}\}$$

$$\varepsilon_r = e_t = [(1-n)/2n * \{\sigma_z - E*\varepsilon_z\} - n*\sigma_z] / E$$

$$d_z = (1+n)\ \sigma_0\ a / E*\{1/[1+(z/a)2]1/2 + (1-2n)\{[1+(z/a)2]1/2 - z/a\}\}$$

Boussinesq's equations are only applicable to a homogeneous layer. In practice, most pavement structures are not homogeneous but are layered system of different materials. A system called the method of equivalent thickness is employed to transform the layered system into a homogenous one in order for the Boussinesq's equations to be used.

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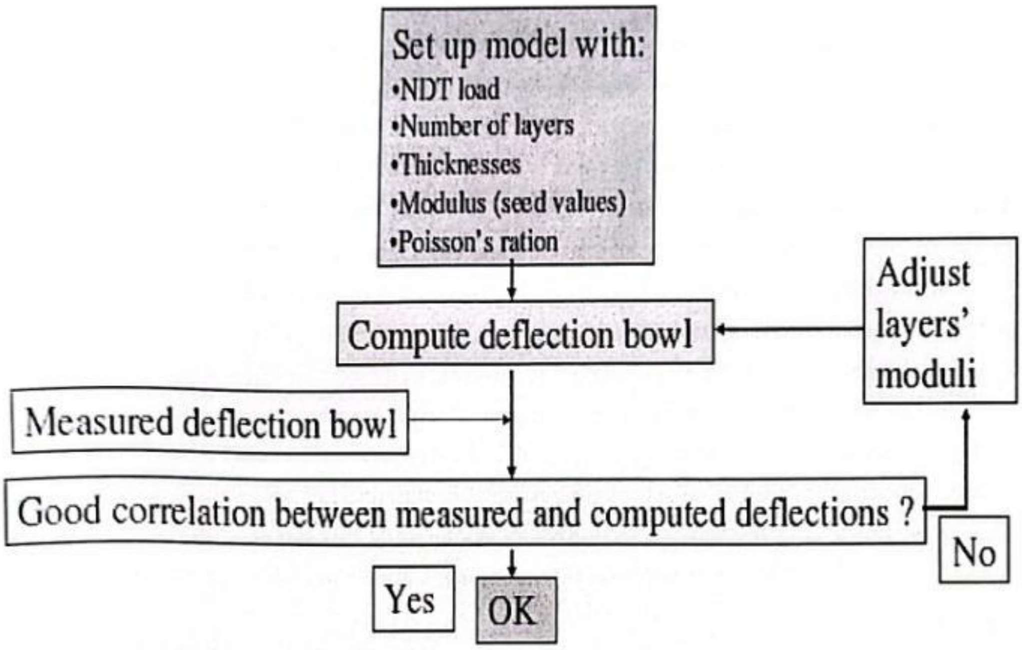

Fig.2.2 Back analysis sequence

As represented in figure 2.2, the basic sequence for back analysis is as follows.

- Define the input parameters of the pavement system including: thickness of each layer, Poisson's ratio, etc.
- Assume moduli seed values for the pavement system. Seed moduli values can be assumed based on experience or based on typical moduli values.
- Calculate the pavement deflections, using the forward program, at the FWD geophone locations (along the surface).
- Compare calculated deflections with the measured deflections. If the difference between the calculated and measured deflections is acceptable, then the assumed layer moduli are the actual moduli. Otherwise, the assumed layer moduli are not the actual moduli and the assumed moduli should be refined.

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- Repeate steps 2 through 4 if necessary.

Equivalent thickness method.

Odemark developed an approximate method to transform a system consisting of layers with different moduli into an equivalent system where the thicknesses of the layers are altered but all layers have the same modulus. This is known as the Method of Equivalent Thickness. The transformation assumes that the stiffness of the layer remains the same, i.e. I x E / (1 – μ2) remains constant where I = moment of inertia; E = layer modulus; and μ = Poisson ratio. Since I is a function of the cube of the layer thickness, the equivalent thickness transformation for a layer with thickness = h1, modulus = E1, and Poisson ratio μ1 into a layer with equivalent thickness = he, modulus E2, and Poisson ration μ2 may be expressed as follows: h13 x E1 / (1 – μ12) = he3 x E2 / (1 – μ22); or he = h1 x [E1 / E2 x(1 – μ22) / (1 – μ12)] 1/3. Since this is an approximate method, an adjustment factor 'f' is applied to the right hand side of the above equation to obtain a better agreement with elastic theory. The value of 'f' depends on the layer thicknesses, modular ratios, Poisson ratios and the number of layers in the pavement structure. Furthermore, the Poisson ratio for all pavement materials can be assumed to be the same, usually equal to 0.35. The equivalent thickness equation can therefore be expressed as:

$$h_{e.n} = f \sum_{i-1}^{n-1}\{h_i[E_i/E_n]^{\left(\frac{1}{3}\right)}\}$$

Surface Modulus

The surface modulus is the weighted mean modulus of the semi-infinite space calculated from the surface deflection using Boussinesq's equations. The surface modulus at a distance 'r' roughly reflects the surface modulus at the same equivalent depth z = r. If the sub grade is a linear elastic semi-infinite space, the surface modulus should be the same at varying distances. If a stiff layer is present, the surface modulus at some distance should become very large. According to Boussinesq's theory, the elastic modulus of a homogeneous half space can be calculated from the deflection measured at a given distance following:

$$E_0 = 2\,\sigma_0.\alpha.\,(1 - \mu 2) / d0$$

$$E_r = (1 - \mu 2).\,\sigma_0.\alpha / dr\,.\,r$$

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Where: E = elastic modulus,

α = radius of loading plate,

μ = Poisson's ratio,

σ0 = contact pressure under loading plate.

Model architecture
The model simply provides for the presentation of the following parameters

- Chainage

This is the chainage point at which deflection measurement is obtained.

- Deflection (measured)

Deflection measurements in microns obtained from the PDA as deflection recorded by each attached geophone. Therefore the number of deflection data is equal to the number of geophones.

- Layer thickness

Thickness of the constituent layers obtained by physical measurement or from the result of other tests like Cone penetration test.

- Equivalent thickness

Calculated from the expression. $h_{e.n} = f\sum_{i-1}^{n-1}\{h_i[E_i/E_n]^{\left(\frac{1}{3}\right)}\}$

- Loading plate radius (α)

This the radius of the loading plate as supplied by the LWD manufacturers.

- Applied stress (**σo**)

This is a measure of the applied stress delivered through a loading plate of a given area and it is measured directly from the LFWD display unit.

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- Radius of curvature **(R)**

This is the radius of curvature of the deflection bowl and it is given by

$R = E*\alpha / [(1-\nu^2)*\sigma_0] / \{ 1+[1+3 / 2 / (1-\nu)] * (z/\alpha)^2 \} *[1+(z/\alpha)^2]^{(5/2)}$

and then to calculate the strain from

$\varepsilon_r = z/2/R$

- Stress at any depth z **(σz)**

This is calculated from $\sigma z = \sigma 0 * \{1-1/[1+ (a/z)2]3/2\}$

- Strain at depth z **(εz)**

$\varepsilon z = (1+n)\ \sigma 0 / E * \{ (z/a) / [1+(z/a)2]3/2 - (1-2n)\ \{(z/a)/[1+(z/a)2]1/2-1\} \}$

- Moduli of Granular and Sub grade layers

The least value of surface modulus obtained from a point is taken as the Modulus of the sub grade. Then with modular ratio concept, the modulus of the granular layer was computed. The modular ratio estimates the modulus of granular layer to be 2.5 times that of the sub grade.

- **Compression at top layer and second layer**

$$dz = \frac{(1+v)\sigma_0\alpha}{E} * \left\{ \frac{1}{\sqrt{\left[1+\left(\frac{z}{\alpha}\right)^2\right]}} + (1-2v) * \{\left[1+\left(\frac{z}{\alpha}\right)^2\right]^{1/2} - z/\alpha\} \right\}$$

- **Deflection at semi finite layer**

First the stress at the top of the sub grade is obtained using

$$\sigma_z = \sigma_0 * \{1 - 1/\left[1+\left(\frac{z}{\alpha}\right)^2\right]^{3/2}\}$$

Then the compression is obtained using