Duddu and Chennarapu
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TECHNICAL NOTE

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Quality control of compaction with lightweight deflectometer (LWD) device: a state-of-art

Sidhu Ramulu Duddu[1] and Hariprasad Chennarapu[2*]

*Correspondence: hari.chennarapu@mahindrauniversity.edu.in
[2] Ecole Centrale School of Engineering, Mahindra University, Bahadurpally, Jeedimetla, Hyderabad, Telangana 500043, India
Full list of author information is available at the end of the article

Abstract

The infrastructure plays a vital role in stimulating economic growth. Any infra project requires proper planning, design, construction, quality control (QC), and quality assessment (QA). It is important to comply with QC and QA to avoid failure and enhance the long-term pavement performance in order to provide a safe and solid system of transportation. Researchers were replacing laborious and time-consuming density-based methods (sand cone and/or core cutter) with advanced stiffness or modulus-based NDT devices for the QC of compacted geomaterials. The lightweight deflectometer (LWD) is such a highly advanced and sophisticated device that was developed to evaluate the deformation modulus (E_{LWD}) of compacted geomaterials as an alternative of density test. This device is portable, light-weight, user-friendly, and it is ideally suitable for all constructional geomaterials. This study is intended to provide a state-of-the-art on the LWD device as well as presented the ranges of deformation modulus for various geomaterials from several studies. For instance, in the case of soils, aggregates, and asphalt materials deformation modulus values were found to be in the range of 35–60 MPa, 80–120 MPa, and 120–170 MPa respectively. In addition, several studies have been compiled to completely comprehend the relationship between LWD and various devices.

Keywords: Quality control (QC), Compacted geomaterials, Lightweight deflectometer (LWD), Deformation modulus (E_{LWD})

Introduction

Road networks are one of the key components for the economic growth of any developed nation. The Ministry of Road Transport and Highways [1] proposes to develop various mega projects by connecting expressways/access-controlled/strategic, coastal and port connectivity highways, economic corridors, and border roads. Quality control and Quality Assurance (QC and QA) are the important criteria in order to ensure quality of construction, minimal maintenance, and long-term performance of pavements. The required degree of compaction needs to be achieved by controlling the process of geomaterials compaction in the field. Typically, this process involves the use of periodic in-situ monitoring of density and moisture, generally obtained by using destructive tests such as sand cone test, core cutter test and rubber balloon test as well as non-destructive tests (NDT) such as Moisture Density Indicator (MDI) and Electrical Density Gauge (EDG) which are tedious, time-consuming, laborious and sometimes not feasible to perform in accordance with the specifications, whereas Nuclear Density Gauge (NDG) releases gamma radiation, which causes a potential hazard to the user and frequency response of the Soil Density Gauge (SDG) will be influenced by the soil gradation (refer Table 1). Hence, the importance and usage of non-destructive test (NDT) devices based on stiffness/modulus has been increased and the success rate is in the range of 64–86%, compared to the density-based devices [2].

The Stiffness/modulus-based NDT devices are Briaud Compaction Device (BCD), Clegg Hammer (CH), Dynamic Cone Penetrometer (DCP), and Soil Stiffness Geo-Gauge (SSGG). In addition, various deflectometer devices are available for measuring the deformation modulus of the compacted geomaterials. Those are, dropping weight deflectometer (DWD), Heavyweight deflectometer (HWD), Falling weight deflectometer (FWD), Rolling weight deflectometer (RWD), and Lightweight deflectometer (LWD). According to Ebrahimi and Edil [3], the usage of lightweight deflectometer (LWD) has been increased to evaluate the quality of any compacted geomaterial for its ease of use, portability, without interrupting the construction activities and suitable for all types of geomaterials.

In 1981, a portable dropping weight deflectometer (DWD) was first invented and developed by the Federal Highway Research Institute (FHRI) and Headquarters of Magdeburger Prufgeratebau (HMP) Company [4]. However, research within European countries has been focused on demonstrating the usefulness and reliability through field trials. The LWD currently uses technology that is similar to trailer mounted-FWD equipment, with the reduced load pulse duration and reduced maximum applied force being the first compromise in the development of the LWD device to convert into portability. An extensive study has been carried out using the LWD device on pavement structures for QC for the past three decades. The utilization of LWD device is more reliable as it provides consistent correlation and measurements [5]. A general comparison of conventional in-situ density-based devices and stiffness/modulus-based devices are listed in Tables 1 and 2 respectively. A detailed description of the LWD operating principles, strengths and limitations, has been reported in the literature [6–9]. The main focus of this study is to present the various research works carried out by using the LWD device.

Description of LWD device and operating procedure

Figure 1 shows the schematic view of LWD device with the components. The major components of the LWD device are drop weight, loading plate, and accelerometer. Initially, place the loading plate on top of the compacted geomaterials, release the drop weight along the guide rod by ensuring a standard drop height. The drop weight is allowed to drop on buffers made of either rubber pads or steel springs and deformation of the loading plate is measured with the help of an accelerometer. The first three drops are allowed for seating to enhance the intact contact between the loading plate and compacted geomaterials. The next three consecutive drops are used to evaluate the average deformation. Finally, the deformation modulus (E_{LWD}) can be calculated

Table 1 Comparison of in-situ density-based devices

Function	SCT	CCT	RBT	NDG	MDI	EDG	SDG
Mode of measurement	Physically	Physically	Physically	Gamma radiation	Electro-magnetic wave	High radio frequency	Electro-magnetic impedance spectroscopy
Standards	ASTM D1556	Not applicable	ASTM D2167	ASTM D6938	ASTM D6780	ASTM D7698	ASTM D7830
Final output	γ_d	γ_d	γ_d	γ_d and W	γ_d and W	γ_d and W	γ_d and W
Calibration	Not applicable	Not applicable	Not applicable	Required	Lab test in Proctor Mould	Field calibration required	Field calibration required
Portability	No	No	No	Yes	No	No	Yes
Durability	Good	Medium	Medium	Good	Good	Good	Good
Operator skill and training	Moderate and not required	Moderate and not required	Moderate and required	Extensive and licensed	Moderate and required	Moderate and required	Extensive and required
Operating	Easy	Easy	Easy	Difficult	Difficult	Difficult	Difficult
Destructive	Yes	Yes	Yes	No	No	No	No
Storing data	No	No	No	Yes	Yes	Yes	Yes
GPS	No	No	No	Yes	No	Yes	Yes
Man power	2	2	1	1	2	2	1
Merits	Easy to operate	Easy to operate	Accurate and reliable	Relatively speed to perform	Operator dependency	Does not require any special license to operate	Accurate and repeatable
	Long history of acceptancy	Long history of acceptancy	Long history of acceptancy	Accurate and repeatable		Safer compare to NDG	
	Low cost	Low cost	Low cost	Able to vary depth of measurement			
De-Merits	Tedious and Time-consuming	Tedious and Time-consuming	Tedious and Time-consuming	Gamma radiation may represent potential hazard	Complex and time-consuming	Complex and time-consuming	Necessary corrections need to apply
	Pause operation	Pause operation	Balloon membranes can puncture during testing	Safety concerns require monitoring of personnel by dosimeter badges	Cumbersome in operating	Cumbersome in operating	Results are not reliable, because soil gradation affects the frequency response
	Excavated material needs to be recovered carefully	Excavated material needs to be recovered carefully	Excavated material needs to be recovered carefully	–	Cannot be used to test frozen soils	Difficult to drive probes into stiff soils	–

SCT sand cone test, *CCT* core cutter test, *RBT* rubber balloon test, *NDG* nuclear density gauge, *MDI* moisture density indicator, *EDG* electrical density gauge, *SDG* soil density gauge

Table 2 Comparison of in-situ stiffness/modulus-based devices

Function	BCD	CH	DCP	SGG	LWD
Mode of measurement	Strain gauges	Accelerometer	Physically	Velocity (small dynamic force-frequency)	Geophone or accelerometer
Standards	None	ASTM D5874	ASTM D6951	ASTM D6758	ASTM E 2583
Final output	Modulus	CIV	DPI	Modulus	Deformation modulus
Moisture reading	No	Yes	No	No	No
Calibration of device	BCD test on rubber blocks	Lab test in proctor mould	None	Calibration plate	Required
Portability	Yes	Yes	Yes	Yes	Yes
Durability	NA	Good	Good	Good	Good
Operator skill and training	Low and moderate	Low and moderate	Low and moderate	Moderate and high	Low and Moderate
Operating	Easy	Moderate	Easy	Easy	Easy
Destructive	No	No	Low	No	No
Storing data	Yes	Yes	No	Yes	Yes
GPS	No	Yes	No	Yes	Yes
Man power	1	2	2	1	1
Merits	Quick	Quick	Assess up to 1.2 m thick layer	Quick and non-intrusive	Very quick
		Strong correlations with CBR	Strong correlation with CBR and M_R		Suitable for all materials
De-merits	Not suitable for very stiff or soft soil	Boundary effects during calibration	Maximum allowed particle size is 50 mm	Extremely sensitive to seating conditions	High variability in weak soft soils
		Different CIV for CH models	Slow test	Inconsistencies in testing data	Shallow Influence depth

BCD briaud compaction device, *CH* clegg hammer, *DCP* dynamic cone penetration, *SSGG* soil stiffness geo-gauge, *LWD* lightweight deflectometer, *CIV* clegg impact value, *DPI* dynamic cone penetration index, *CBR* California bearing ratio, E_{LWD} deformation modulus, M_R resilient modulus

by using the well-known Boussinesq's elastic solution (Eq. 1) for the case of a rigid or flexible base resting on an elastic half-space. Table 3 presents various LWD devices and specifications which were manufactured by various agencies.

$$\mathrm{E_{LWD}} = \frac{qr(1-\upsilon^2)f_r}{w} \tag{1}$$

where $\mathrm{E_{LWD}}$ = Deformation modulus of compacted geomaterial (MPa), r = Radius of loading plate (mm), υ = Poisson's ratio of the compacted geomaterial, f_r = Plate rigidity factor (Fig. 3), w = Deformation of the loading plate measured at its center (mm), and q = Maximum contact pressure (MPa);

where;

$$\mathrm{q} = \frac{\mathrm{AppliedForce(F)}}{\mathrm{Areaofloadingplate(a)}} \tag{2}$$

F = Applied force (N) and a = area of loading plate (mm^2).

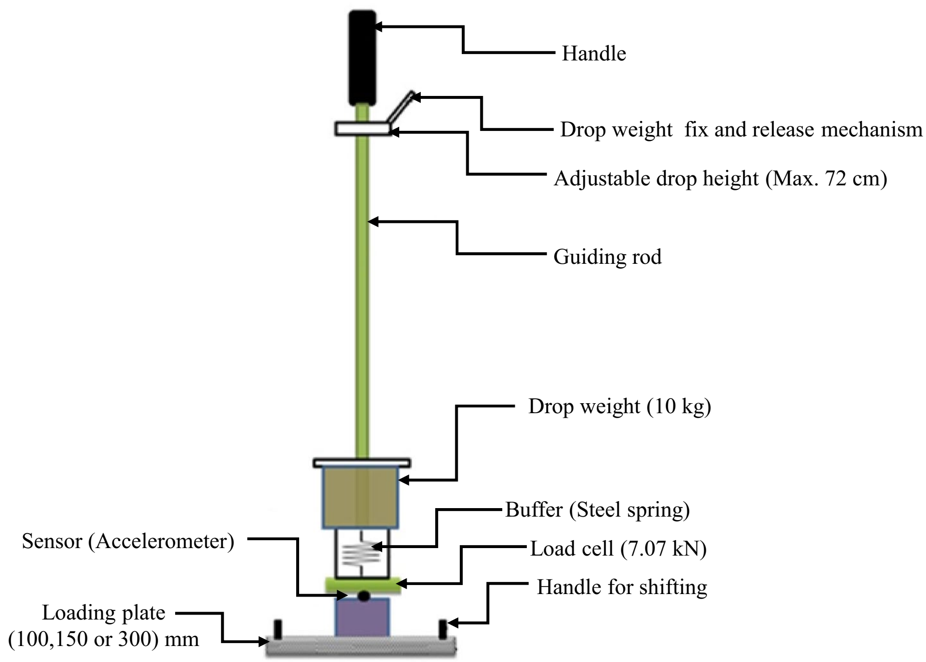

Fig. 1 Schematic view of Lightweight Deflectometer (LWD)

Table 3 Summary of specifications of the LWD devices. (Modified after [9])

Description/devices	Zorn	Keros	Dynatest	Prima	Loadman	ELE	TFT	CSM
Plate type	Solid	Annulus	Annulus	Annulus	Solid	Solid	Annulus	Solid
Plate diameter (mm)	100, 150, 200, 300	150, 200, 300	100, 150, 200, 300	100, 200, 300	110, 130, 200, 300	300	200, 300	200, 300
Plate thickness (mm)	45, 28, 20	20	20	20	Not reported	Not reported	Not reported	Not reported
Plate mass (kg)	15[a]	Not reported	Not reported	12[a]	6[a]	Not reported	Variable	6.8, 8.3
Drop mass (kg)	10, 15	10, 15, 20	10, 15, 20	10, 15, 20	10	10	10, 15, 20	10
Drop height (mm)	720	Variable	Variable	Variable	800	Variable	Variable	Variable
Buffer type	Steel springs	Rubber (conical)	Rubber (flat)	Rubber (conical)	Rubber	Not reported	Rubber	Urethane
Force display	No	Yes	Yes	Yes	Yes	Not reported	Yes	Yes
Transducer type	Accelerometer	Geophone	Geophone	Geophone	Accelerometer	Geophone	Geophone	Geophone
Transducer location	Plate	Ground	Ground	Ground	Plate	Plate	Ground	Plate
Impulse time (ms)	18 ± 2	15–30	15–30	15–20	25–30	Not reported	15–25	15–25
Max load(kN)	7.07	15.0[b]	15.0[b]	15.0[b]	20[b]	10[b]	15[b]	8.8[b]
Plate rigidity	Uniform	Rigid/flexible	Rigid/flexible	User defined	Rigid/flexible	User defined	User defined	User defined

[a] May varies based on plate thickness

[b] May varies based on drop height

Theoretically, the applied force on a surface cannot be constant, because it clearly depends on the stiffness of the buffer material on which the load is applied (Eq. 3):

$$F = \sqrt{2mghc} \tag{3}$$

where; F = Applied force (N), m = mass of falling weight (kg), g = acceleration due to gravity, 9.81 (m/s^2), h = drop height (m), and c = material stiffness constant (N/m).

Factors influencing the deformation modulus

Various parameters that influence the deformation modulus of compacted geomaterials are diameter of loading plate, plate rigidity, plate contact stress, loading rate, buffer type, location, and type of deformation transducer [7, 9]. Further details on the various factors influencing the deformation modulus (E_{LWD}) are discussed in the following sections.

Diameter of loading plate

The diameter of loading plate is in the range of 100–300 mm (refer Table 3). Researchers (Deng-Fong Lin et al., Chaddock and Brown [6, 10]) concluded that the selection of the diameter of loading plate is a significant factor that influences deformation modulus due to the reason of depth of influence. Generally, the depth of influence is equal to 1.0–1.5 times the diameter of the loading plate. In the literature, it is reported that the decrease in diameter of the loading plate leads to an increase in the deformation modulus, due to the reason of increase in contact stresses of loading plate. Chaddock and Brown [10] conducted tests on crushed rock base and subbase materials over compacted clay materials. The deformation modulus for the 200 mm diameter loading plate was found to be 1.3–1.5 times that of a 300 mm diameter loading plate. Deng-Fong Lin et al. [6], performed field studies using the LWD device on a natural sand soil deposit and found that the estimated E_{LWD} from a 100 mm diameter loading plate was found to be 1.5–1.6 times that of a 300 mm diameter loading plate. Vennapusa and White [9] recommended 300 mm, 200 mm, and 100 mm diameter of loading plates, for the range of $E_{LWD} < 125$ MPa, E_{LWD} between 125 and 170 MPa, and $E_{LWD} > 170$ MPa respectively.

Plate rigidity

The plate rigidity factor depends on the rigidity of loading plate and type of compacted geomaterials as shown in Fig. 2. Mooney and Miller [8] reported that it might be the tendency of a soil to attain a failure where the stress distribution is uniform. Das [14] stated that it may imply some consequences of the plate rigidity, but theoretically, a flexible plate shows uniform stress distribution for a loaded clayey subgrade and a true rigid plate should not deform under a load. Various thickness of plates (refer Table 3) and their materials, which cause variations in their rigidity. Plate rigidity factors (f_r) under the loading plate vary with the stiffness of the plate and compacted geomaterials. Borowicka [11] proposed an analytical solution to evaluate the relative rigidity of the plate (Eq. 4).

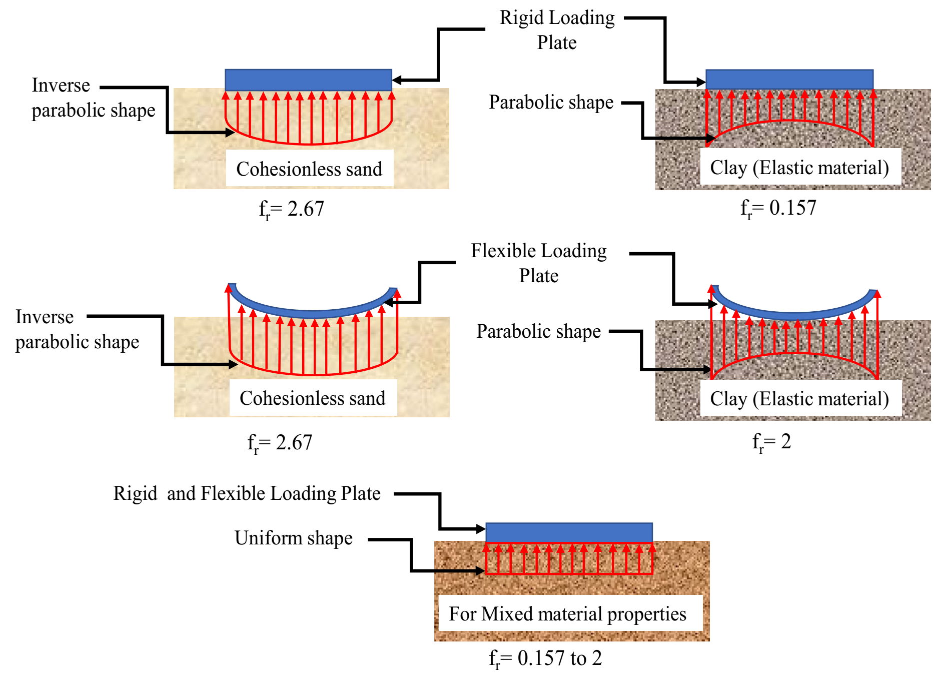

Fig. 2 Schematic view of Plate Rigidity (shape) factors (f_r) [12–14]

$$K = \frac{E_p\left(1-\upsilon_p{}^2\right)}{6E_s\left(1-\upsilon_s{}^2\right)}\left(\frac{t_p}{r}\right)^3 \tag{4}$$

where; K = Relative rigidity of the loading plate, E_p and E_s = Modulus of elasticity of the loading plate and compacted geomaterial respectively (MPa), υ_p and υ_s = Poisson's ratio of the loading plate and compacted geomaterial respectively, t_p = Thickness of the loading plate (m) and r = Radius of the loading plate (m).

For $K = 0$, the contact stress distribution under the loading plate is uniform and it is considered as a flexible plate, $K > 0$, the contact stress distribution at the edges increases to infinity and varies at the center of loading plate, and $K = \infty$, the contact stress at the center of the loading plate is half of the applied stress and it is considered as a perfectly rigid plate.

Plate contact stress

The contact stress between the loading plate and the compacted geomaterials is assumed to be uniform or that of a parabolic and inverse parabolic for a rigid plate on an elastic half-space (as shown in Fig. 2). The applicability of linear elastic half-space theory to the LWD device, as well as the nature of the contact stress between the loading plate and the compacted geomaterials, must be assessed. The impact force and diameter of the loading plate are designed to deliver a peak contact stress in the range of 100–200 kPa, simulating the approximate stress pulse on a typical sub-grade or base layer caused by traffic loading on top of a finished pavement [9, 15, 17]; Nazzal et al. [16].

Most of the studies indicated that the measured deformation modulus increases with higher applied contact stress and it depends on the type of compacted geomaterials. For dense and compacted granular materials, E_{LWD} increases with higher applied contact stress and for the materials with cementitious properties and soft subgrade soils are not influenced by change in the contact stress stated by Vennapusa and White [9]. Fleming et al. [18] found that the measured E_{LWD} with a 300 mm diameter loading plate was increased by 1.15 times by increasing the plate contact stress from 35 to 120 kPa. Similar studies on very stiff crushed aggregate and stabilized aggregate materials shown no significant difference in the plate contact stress from 140 to 200 kPa [19].

The contact stress for the 100 mm diameter loading plate was 8–9 times that of a 300 mm diameter loading plate [6]. Bilodeau and Dore [20] conducted an experiment with both 100 mm and 300 mm diameter loading plate on Ultra High Molecular Weight Polyethylene (UHMWP) plastic material (properties similar to granular soils). The higher stresses were recorded with the 100 mm diameter loading plate. However, the contact stress distribution for the 100 mm loading plate shows flattening and/or increasing stresses near the plate edge. The assessment of contact stress under the LWD loading plate was found to be affected by the diameter of the loading plate. Hence, the contact area has a significant impact on the E_{LWD}.

Loading rate and buffer type

The rate of loading can be regulated by changing the spring rigidity of the buffer between the drop weight and the contact loading plate and thus can affect the measured deformation modulus. Lenngren and Lukanen [21] reported that by using stiffer buffer for the case of asphalt concrete pavements, the load pulse time history was shortened and the resulting E_{LWD} is increased by 10–20%. Lenngren and Lukanen [21] also indicated that the shape of the load pulse, its peak, and time history affects the magnitude of the measured deformations to some extent. Fleming [18] reported that a comparatively lower stiffness buffer provides more efficient load transfer and better simulates static plate loading conditions. Deng-Fong Lin et al. [6] also evaluated the effect of drop heights, concluding there was a very low impact of different drop heights on stiffness buffers.

The effect of buffer temperature and loading pulse was evaluated by Adam and Kopf [22]. E_{LWD} was measured on the rigid laboratory floor for a fixed drop weight and height at different temperatures. Data for 10 repetitive loading has been recorded with two buffers. The applied impulse load varied approximately 30% with a change in the buffer temperature from 0 to 30 °C because the rubber buffers are slightly softened when heated due to repetitive loading because of the impact of load on the loading plate is independent of the surrounding and equipment temperature. However, it remains constant for a steel-spring buffer. Hence, the researchers recommend to using the steel spring buffers (Larsen BW et al. 2008) [23].

Location and type of deformation transducer

The various LWD manufacturers provide various transducers and their built-in position. For instance, the spring-loaded geophone is used in direct contact with the compacted geomaterial through a hole in the center of the loading plate to measure the velocity of the compacted geomaterial in Keros, Dynatest, Prima, and TFT devices as shown in Fig. 3a. Whereas, the Zorn device has an accelerometer built into the loading plate (Vennapusa and White 2009) [9] from which the readings are twice integrated to calculate

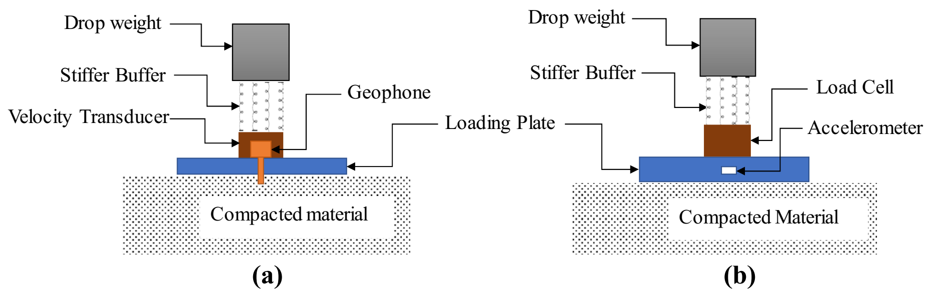

Fig. 3 Schematic sketch of the location and type of transducer: **a** Geophone measures velocity and is located on the compacted material, **b** Accelerometer measures vibrations and is located in the plate

Table 4 Correlations between LWD and other devices for various compacted geomaterials

Tested material	Empirical/regression correlations	R^2	References
Sandy soil	$CBR_{(us)} = 0.0009\ E_{LWD}^2 - 0.064\ E_{LWD} + 6.904$	0.807	Dwivedi and Suman [25]
	$CBR_{(s)} = 0.0001\ E_{LWD}^2 - 0.0015\ E_{LWD} + 1.184$	0.805	
	$\gamma_d = 1 \times 10^{-5}\ E_{LWD}^2 + 0.002\ E_{LWD} + 1.098$	0.77	
Lime stabilized subgrade soil	$UCS = 4.9\ E_{LWD}$	0.99	Bisht et al. [26]
	$CBR = 0.15\ E_{LWD}$	0.93	
Lateritic subgrade	$CBR = -2.754 + 0.2867E_{LWD}$	0.90	Rao et. al [27]
Soil classification[a]	$E_{V1} = 0.91\ E_{LWD\text{-}P3} - 1.81$	0.84	Alshibli et al. [28][a]
GC, GC, GW, GP, SP, CL-ML, CL	$E_{V2} = 25.25\ e^{0.006ELWD-P3}$	0.90	
Cohesive soils	$E_{V1} = 0.833 \times E_{LWD\text{-}Z3}$	–	Adam and Kopf [22][a]
Non-cohesive soils	$E_{V1} = 150\ \ln\ [180/(180 - E_{LWD\text{-}Z3})]$ or $E_{V1} = 1.25 \times E_{LWD\text{-}Z3} - 12.5$ ($E_{LWD\text{-}Z3}$ ranging between 10 and 90 MPa)	–	
Crushed limestone	$CBR = -14 + 0.66\ E_{LWD}$	0.83	Nazzal [16]
Sandy soils	$E_{V2} = (600 - 300)/(300 - E_{LWD\text{-}Z3})$	–	Livneh and Goldberg [15]

$CBR_{(us)}$ unsoaked California bearing ratio, $CBR_{(s)}$ soaked California bearing ratio, E_{LWD} deformation modulus measured by a lightweight deflectometer (LWD) device, γ_d dry density of the compacted material, *UCS* unconfined compressive strength

[a] Materials classified as per the Unified Soil Classification System (USCS); Ev_1 = Static modulus of layer 1; Ev_2 = Static modulus of layer 2; $E_{LWD\text{-}P3}$ and $E_{LWD\text{-}Z3}$ = Modulus of deformation measured by Prima 100 and Zorn LWD device with 300 mm diameter plate

deformation of the loading plate as shown in Fig. 3b. These differences seem to contribute to differences in the evaluation of loading plate deformation. The contact area of the geophone is very disturbed due to the narrow foot of the geophone, and has a relatively stiff spring buffer inside the housing to maintain contact between the geophone and the compacted geomaterials, which results in disturbance (Fleming et al. 2007) [18]. This disturbance is common on softer subgrades and some granular compacted geomaterials. However, it is not clear about the quantifying of recorded permanent deformation during the impact and effect of disturbance on E_{LWD}. The contact area of the accelerometer loading plate has not reported any such disturbances under it, as it is built into the loading plate.

Correlations and ranges of deformation modulus (E_{LWD})

Since LWD tests are easy and rapid to conduct, the testing period can be significantly shortened [24]. Hence, researchers proposed the correlations (refer Table 4) between measured E_{LWD} and other parameters like density, unconfined compressive strength, California bearing ratio, etc. The deformation of modulus range varies based on the type of LWD device used and type of material. Based on available data, the typical deformation modulus reported for various types of subgrades, subbase, base layers, granular layers, and backfilling materials are listed in Table 5.

Application of lightweight deflectometer

The LWD device is a new evolution through the use of its best practice and simple operating principle, moreover internationally recognized and widely accepted for infrastructural applications in recent years after being used over 34 years in European countries (i.e., Germany, United Kingdom, United States, Australia and New Zealand on a performance design basis). The several advantages of the methods are likely to benefit the

Table 5 Typical range of deformation modulus (E_{LWD}) for various compacted geomaterials

Type of material	E_{LWD} (MPa)	References
High binder Reclaimed asphalt pavement (100%)	203	Akmaz et al. [29]
Virgin aggregate (100%)	129	
Aggregate base layer post-construction with and without geogrid and geotextile	79	Jason et al. [30]
Well and gap graded gravel sand	35–60	Choi et al. [31]
Coarse-grained sand	69–132	Dwivedi and Suman [25]
Cohesive soil	5	Barounis [32]
Very soft clayey silt	8–14	
Loose to medium dense silt	17–27	
Dense to very dense compacted gravel (moist–dry)	40–64	
Lime stabilized subgrade	94	Bisht et al. [26]
Compacted Base	45–60	Umashankar et al. [33]
Surface layers	105–120	
Cement modified crushed stone	63.5	Matthew et al. [34]
Lime modified crushed stone	68.5	
Non-modified crushed stone	37	
Bituminous surface layer	170–190	Prakash and Rakesh [35]
Calcareous Sand ($D_r = 20–80\%$)	8–35	Elhakim et al. [4]
Siliceous Sand ($D_r = 20–80\%$)	12–43	
Soft clay subgrade	48	
Silty sand	13.5–63.5	Kim et al. [36]
	31–105	
Asphalt	110–140	
Poorly compacted sub base	5–81	
Granular sub base	100	
Natural subgrade	67–78	Deng-Fong Lin et al. [6]
Clayey soil (Optimal), dry and wet	31, 50 and 28.5	Khalid et al. [27]
Crushed limestone	74–131	
Recycled Asphalt Pavement (RAP)	138	
Granular sub base	50	

sectors, such as monitoring of compaction activities of earthworks, pavements, runways, embankments, retaining walls, mechanically stabilized earth walls (MSE), landfills, compressibility of waste or contaminated land, marine works, treated and untreated soil, canal construction. In addition, a new testing procedure has been implemented to obtain direct measurements of resilient modulus (M_R) of a compacted geomaterials using a simple technique and it was designed for both laboratory and in-situ testing [37]. Recent studies have been carried out based on the forward and back-calculation solutions, which are formulated as an inverse problem to match the predicted deformations to the observed deformations by using most existing techniques such as static back-calculations use regression equations that are fitted to a database of deformations by using artificial neural network system (ANNS) [38] and by employing gradient search or genetic algorithm iterative methods to minimize an objective function of any set of independent variables (i.e., thicknesses and layer moduli) [39].

The instant results of the compacted geomaterials obtained from LWD makes it an effective device and an ideal replacement, saving time and minimizing the cost. The deformation modulus value depends on various factors such as the diameter of the loading plate, drop height, contact stress, and flexural rigidity. Hence, researchers recommend that the range of deformation modulus values need to be exercised for a selected geomaterials by constructing a test pad before proceeding to the actual construction.

Conclusions

The lightweight deflectometer (LWD) device is an internationally recognized and widely used technique in infrastructural applications. The long-term performance of any project depends on the characteristics of the compacted geomaterials. This study provides a state-of-the-art resource for contractors and engineers by focusing on evaluation of deformation modulus by using various LWD devices and discussed the influence of various factors on deformation modulus. Several correlations between deformation modulus and other engineering properties of geomaterials like dry density, UCS, and CBR. Range of deformation modulus values were presented for various geomaterials. Infield, it is necessary to construct a test pad for evaluating the range of deformation modulus values for the corresponding geomaterials. It is concluded that the lightweight deflectometer (LWD) is a valuable and very effective device for monitoring the quality of construction as it is versatile, portable, can reduce duration, running cost of major projects, and it is suitable for all construction geomaterials. The LWD has to be deploy in India and other developing countries by the consultants, geomaterial specifiers, contractors, and clients to play a major role in QC/QA in ensuring the safe and solid system of transportation and long-term pavement performance along major road network corridors.

Abbreviations

QC: Quality control; LW: Lightweight deflectometer; E_{LWD}: Deformation modulus; MoRTH: Ministry of Road Transport & Highways; SCT: Sand cone test; CCT: Core cutter test; RBT: Rubber balloon test; NDT: Non-destructive tests; MDI: Moisture density indicator; EDG: Electrical density gauge; NDG: Nuclear density gauge; SDG: Soil density gauge; BCD: Briaud compaction device; CH: Clegg hammer; DCP: Dynamic cone penetrometer; SSGG: Soil stiffness geo-gauge; FHRI: Federal Highway Research Institute; HMP: Headquarters of Magdeburger Prufgeratebau; FWD: Falling weight deflectometer; CIV: Clegg impact value; DPI: Dynamic cone penetration index; CBR: California bearing ratio; M_R: Resilient modulus; ASTM: American Society of Test Method; UHMWP: Ultra high molecular weight polyethylene; GC: Clayey gravel; GW: Well graded gravel; GP: Poorly graded gravel; SP: Poorly graded sand; CL-ML: Clayey silt of low plasticity; CL: Lean clay; RAP: Recycled asphalt pavement; ANNS: Artificial neural network system.

List of symbols

γ_d: Dry density of the compacted geomaterial (kN/m^3); W: Water content (%); r: Radius of loading plate (mm); υ and υ_s: Poisson's ratio of the compacted geomaterial; f_r: Plate rigidity factor; w: Deformation of the loading plate measured at its center (mm); q: Maximum contact pressure (MPa); a: Area of loading plate (mm^2); F: Applied force (N); m: Mass of falling weight (kg); g: Acceleration due to gravity, 9.81 (m/s^2); h: Drop height (m); c: Material stiffness constant (N/m); K: Relative rigidity of the loading plate; E_p: Modulus of elasticity of the loading plate (MPa); E_s: Modulus of elasticity of the compacted geomaterial (MPa); υ_p: Poisson's ratio of the loading plate; t_p: Thickness of the loading plate (mm); $CBR_{(us)}$: Unsoaked California bearing ratio (%); $CBR_{(s)}$: Soaked California bearing ratio (%); UCS: Unconfined compressive strength (kN/m^2); Ev_1: Static modulus of layer 1 (MPa); Ev_2: Static modulus of layer 2 (MPa); $E_{LWD\text{-}P3}$: Modulus of deformation measured by Prima LWD device with a 300 mm diameter plate; $E_{LWD\text{-}Z3}$: Modulus of deformation measured by Zorn LWD device with a 300 mm diameter plate; D_r: Relative density (%).

Authors' contributions

DSR: acquisition of data, images, drafting of manuscript and provided the revised article content. HC: provided the area of study, acquisition of data, images, drafting of manuscript, provided the revised article content and final approval of the version to be submitted. Both authors read and approved the final manuscript.

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Author details

[1]Deptartment of Civil Engineering, Ecole Centrale School of Engineering, Mahindra University, Bahadurpally, Jeedimetla, Hyderabad, Telangana 500043, India. [2]Ecole Centrale School of Engineering, Mahindra University, Bahadurpally, Jeedimetla, Hyderabad, Telangana 500043, India.

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