Transportation Infrastructure Geotechnology (2024) 11:2023–2045
https://doi.org/10.1007/s40515-023-00359-2

TECHNICAL PAPER

In-Situ Assessment of Dynamic Deformation Modulus of Pavement Layers using Light Weight Deflectometer

Sidhu Ramulu Duddu[1] · Vamsi Kommanamanchi[1] · Hariprasad Chennarapu[1] · Prabodh Kumar Mahopatra[1]

Accepted: 23 November 2023 / Published online: 22 December 2023

Abstract

The light-weight deflectometer (LWD) device provides a quick, consistent, direct measurement of dynamic deformation modulus (E_{LWD}) and an integrated way to characterize the layered pavement section. This study encompasses an intensive 453 data points obtained from six test pad cases constructed with different materials to evaluate: (i) compaction quality control parameters in terms of E_{LWD} for four different types of subgrade soils, soling, base and surface layers; (ii) effect of rigidity of underneath layer on E_{LWD} of the base layer; (iii) effect of number of compaction roller passes on the E_{LWD} of the base layer; and (iv) spatial variability of E_{LWD} to check the uniformity of compaction. The results show that the E_{LWD} depends on the type of material, number of compaction roller passes and the rigidity of underneath layer. It is easy to perform quality control tests frequently, and a range of E_{LWD} were found by using LWD devices that ensure proper monitoring of various materials owing to compaction. However, this study was carried out using LWD device to evaluate E_{LWD}, which resulted in an overall improvement in the quality of compacted pavement layers to enhance their long-term performance and thus reduce maintenance costs. In order to set the desired modulus of various materials for proper compaction in the field, field compaction verification tests are necessary.

Keywords Light-weight deflectometer (LWD) · Dynamic deformation modulus (E_{LWD}) · Quality control (QC) · Coefficient of variation (*COV*) · and Spatial variance (*SV*)

1 Background

Flexible and rigid pavements are the most representative types of pavements globally. These pavement sections consist of granular bases (GSB and WMM) and a surface layer (DBM), which are constructed on an existing or compacted subgrade soils

✉ Hariprasad Chennarapu
hari.chennarapu@mahindrauniversity.edu.in

Extended author information available on the last page of the article

of various site-specific conditions. A significant problem may arise during the design, construction and compaction processes of the proposed pavement projects due to extrinsic factors. These include allowable wheel loads, alterations in pavement classification, analysis of materials physical and mechanical characteristics for design purposes, feasibility of implementation and the evaluation of quality control parameters related to compaction. This necessitates the adoption of a novel strategy based on a flexible approach in terms of design, execution and compaction quality control parameters of materials. Compaction is one of the most important parameters for any earthwork or layered pavement section. Some of the pavement sections fail due to poor compaction of layered materials. (Rajagopal et al. 2014). Typically, there are various destructive testing (DT) methods (viz., core cutter, sand cone, density gauges and dynamic cone penetrometer) for assessing the quality of compacted layered pavement sections in terms of targeted density and relative compaction (Duddu and Chennarapu 2022). To evaluate QC parameters quickly in terms of modulus, several non-destructive testing (NDT) devices are available, such as Benkelman beam deflectometer (BBM), Lacroix deflectograph (LD), static plate load test (PLT) and falling weight deflectometer (FWD) (Tayabji and Lukanen 2000; Newcomb and Birgisson 1999). However, these test methods are uneconomical to perform in the field owing to their initial cost and maintenance. Enforcing their usage abruptly increases the project costs and duration, especially when testing needs to be conducted frequently at multiple locations. Moreover, it is a challenging task to transport and operate these devices in remote or inaccessible locations, which further increases the cost and logistic complications of field testing (Dwivedi and Suman 2023; Liu et al. 2020; Newcomb and Bjorn 1999).

To address the drawbacks of the abovementioned conventional DT and NDT methods, several portable NDT devices were introduced which help in quality control of compaction in terms of modulus. Extensive research work has been carried out for several years to develop light and portable devices that can provide a quick assessment of the bearing capacity of pavement layers (Mahamid 2013), such as TRL foundation tester (TFT) (Rogers et al. 1995), natural vibration device, loadman device (Fleming and Rogers 1995), soil stiffness gauge (Fleming et al. 2002) and dynamic plate device (known as light-weight deflectometer) (TP BF-StB Part B 8.3-1997 (R1) 2012). The aforementioned devices are categorized by intensity and rate of maximum load pulse (Fleming and Rogers 1995), while all portable devices have their own advantages and disadvantages. Despite many alternative devices, the in-situ quality control in terms of dynamic deformation modulus was assessed, and monitored using LWD device for layered structures like pavements, embankments and sports amenities (e.g., tennis and basketball courts) (Michael 2021; Cesar et al. 2017; Sunny et al. 2016; Senseney and Mooney 2016). Now-a-days, a light-weight deflectometer device is emerging as the most acceptable tool for quality control of pavement layers. The LWD device has the advantage of precisely resembling the loading rate and contact area of a single moving wheel, using the same transducer technology as the falling weight deflectometer (FWD) (Fleming et al. 2007). Furthermore, over the past couple of decades, many research studies have explored the use of LWD devices in examining the mechanistic characterization of subgrade soils, aggregate bases and unbound material (Senseney and Mooney 2016; Hossain and Apeagyei 2007).

A light-weight deflectometer (LWD) device was first used in India for pavement assessment in the early twenty-first century. Despite, there is a lack of knowledge regarding the effectiveness and reliability of LWD devices for evaluating pavements in Indian conditions. Furthermore, the usage of LWD devices for different kinds of pavement materials and subgrade conditions is limited. Previous studies have used LWD device to assess the surface layer of flexible pavement, but its use has been limited to certain subgrade circumstances. (Lee et al. 2021; Kumar et al. 2021; George and Anil 2017; Umashankar et al. 2016; Senseney and Mooney 2016; Elhakim et al. 2014; Ebrahimi and Edil 2013; Vennapusa and White 2009; Mooney and Miller 2009; Rahman et al. 2008; Fleming et al. 2007; Alshibli et al. 2005).

Most of the literature studies reveal that the LWD device was used for quality control (QC) evaluation of compacted homogeneous materials, whereas only a few research studies present QC in the field of composite layered pavement sections. In addition, most of the previous studies have mainly concentrated on finding the compaction characteristics using conventional devices and the deformation modulus using plate load tests. There are several shortcomings, such as limited sampling area (< 1%), which may cause test bias (Nie 2011), damages to the compacted layer, longer testing time and heavy equipment's loading that cause significant interference to the subsequent construction process (Hua et al. 2020). Lately, sensor-based NDT technology has been emerging progressively as a reliable way to measure critical in-situ performance (Xiaochao et al. 2013; Timm et al. 2013), check structural health and monitor the response of pavement sections (Lajnef et al. 2011). In view of this, it is necessary to assess the effectiveness and reliability of NDT devices like LWD for pavement layers in an Indian scenario.

The overall structural quality of a pavement is defined by its weakest layer, which can be located anywhere in the layered pavement section. As a result, the dynamic deformation modulus of pavement sections will be computed by considering the subgrade soil properties, base and surface layers. A similar rule applies when designing and strengthening an existing road (Petri et al. 2010; Zubeck and Doré 2009). Moreover, extensive research was carried out earlier in evaluating the dynamic deformation modulus of sand, subgrade soils, bases (wet mix macadam - WMM), bitumen (dense bitumen macadam - DBM), reclaimed asphalt pavement (RAP), crushed limestone, cement stabilized clayey soil and fly ash by various researchers (Deshmukh et al. 2022; Duddu et al. 2023; Lee et al. 2021; Sunny et al. 2016; Senseney and Mooney 2016; Elhakim et al. 2014; Ebrahimi and Edil 2013; White et al. 2010; Mooney and Miller 2009; Rahman et al. 2008; Fleming et al. 2007; George et al. 2004). A few field investigations have been mentioned in the published literature, with an emphasis on measuring the dynamic deformation modulus of specific layers within composite layered pavement sections (Umashankar et al. 2016; Livneh and Goldberg 2001). The current study is the first of its kind to discuss the variation in dynamic deformation modulus for six test pad cases of composite layered pavement sections. In addition, assessed the effect of compaction passes as well as the rigidity of underneath layers on the WMM layer.

2 Configurations of Six Test Pad Cases

In this study, test pad cases of various composite layered pavement sections were discriminated to determine the dynamic deformation modulus, as indicated in Table 1 and Fig. 1(a–f). The phenomenon observed is the extensive construction of highways, low-volume and unpaved roads stretching thousands of kilometres with various configurations. One such scenario may arise for different site-specific conditions, primarily in the expansion of metropolitan cities (i.e., for such scenarios, the configurations of six test pad cases were discriminated). The composite pavement layers of six test pad cases were considered in accordance with Indian codal provisions (IRC 37 2018; MoRTH 2013) and identified as case-1, case-2, case-3, case-4, case-5 and case-6. These test pad cases were located at Mahindra University, Hyderabad, Telangana, India. The detailed test configurations, such as layer thickness (H), materials used and number of test points (N), are provided in Table 1. Figs. 1(a–f) show a schematic 3D view of six test pad cases of finite thickness and their testing points. Case-1 is solely constructed with subgrade soil (refer to Table 1 and Fig. 1a), while cases 2, 3 and 4 consist of a surface layer (DBM of VG 30) laid on a WMM layer and subgrade soils (soil-2 and -3), which resemble the flexible pavement. While, in cases 5 and 6, the surface layer was proposed to be constructed with reinforced cement concrete

Table 1 Details of test configurations, materials used, thickness of layers (H) and number of test points (N)

S. no.	Test pad cases	Materials used	H (m)	N
1	Case-1	Subgrade soil: prepared soil-1	0.50	24
2	Case-2	Surface layer: DBM (VG 30)	0.05	28
		Base layer: WMM	0.15	84
		Subgrade soil: existing soil-2	0.50	28
3	Case-3	Surface layer: DBM (VG 30)	0.05	28
		Base layer: WMM	0.15	56
		Subbase layer: existing RCC bed	0.15	-
		Subgrade soil: existing soil-2	0.50	28
4	Case-4	Surface layer: DBM (VG 30)	0.05	28
		Base layer: WMM	0.15	56
		Subgrade soil: prepared soil-3	0.50	28
5	Case-5	Base layer: WMM	0.15	10
		Milled bitumen	0.05	10
6	Case-6	Base layer: WMM	0.15	15
		Soling (boulders)	0.15	15
		Subgrade soil: prepared soil-4	0.50	15
			Total number of test points, $N = 453$	

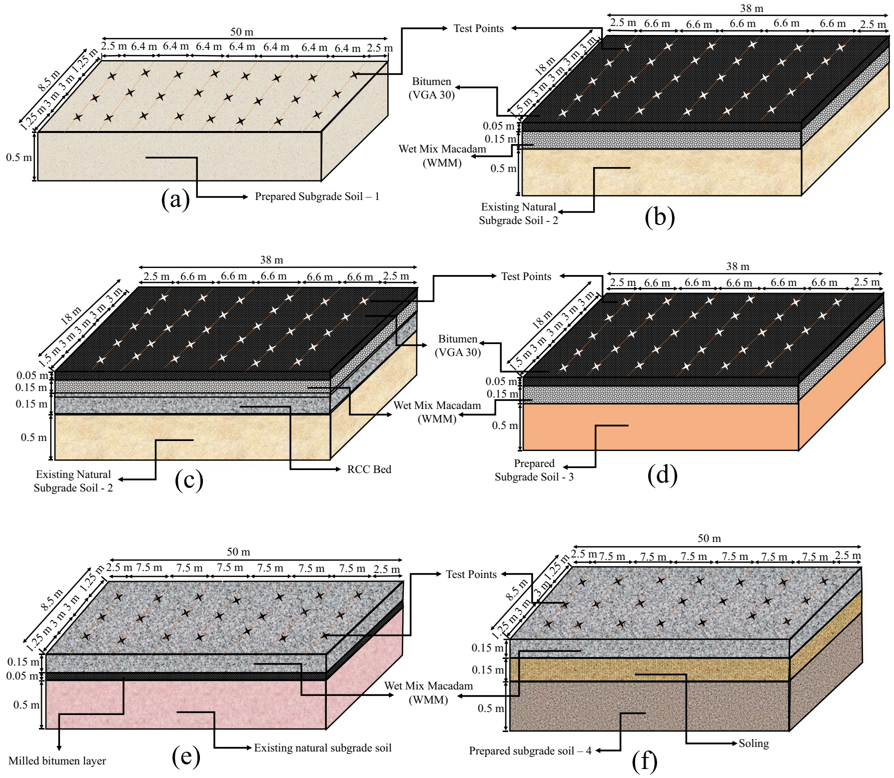

Fig. 1 Schematic 3D view of field test configurations of six test pad cases with dimensions and test locations; **a** case-1, **b** case-2, **c** case-3, **d** case-4, **e** case-5, and **f** case-6

(RCC) on a WMM layer, which lies on milled bitumen and soling, respectively, which resemble the rigid pavement. The testing on RCC layer was not encompassed in the present study. In view of this, the LWD tests were performed on the WMM layer. For cases 2 to 6, a minimum thickness of 0.15 m for the WMM layer was provided as per codal provision (IRC 37 2018). However, cases 3, 5 and 6 were special composite cases in which a WMM layer was laid on an existing RCC bed, milled bitumen and soling layers, respectively, to assess their effect on the dynamic deformation modulus of a WMM layer. While the subgrade soil is consistent in cases 2 and 3, it differs in cases 1, 4 and 5.

Several test points were selected to study the uniformity of compaction and to generate numerous sets of data points to analyse the dynamic deformation modulus of various layers of pavement sections. For instance, a 38 m × 18 m test area was divided into test intervals of 6.6 m × 3 m, as shown in Fig. 1(a–d). Similarly, for the test pads shown in Figs. 1(e, f), a number of test points (*N*) for each layer is chosen accordingly (refer to Table 1).

3 Materials and Construction Process

3.1 DBM

Dense bituminous macadam (DBM) of viscosity grade (VG 30) was chosen because the considered test pad cases were constructed for low-volume traffic roads in accordance with standard specifications (IRC 37 2018; MoRTH 2013) for the surface layer to prevent rutting failures. Table 2 illustrates the physical properties of DBM in accordance with standards (AASHTO M 226-80 2021; BIS 73 2013; ASTM D2937 2004).

3.2 Base Layer and Subgrade Soil

Base layers were constructed with well-graded crushed aggregate mix collected from a local quarry. The mix was screened and utilized as wet mix macadam (WMM) for the considered test pads, as shown in Fig. 1(b–f) and Table 1. Figure 2a presents the gradation curve of base layer and subgrade materials (ASTM D2487 2017; MoRTH 2013). Figure 2b presents the compaction characteristics of various subgrade soils (soils: 1–4) and WMM material. Table 3 presents the physical properties of subgrade soils, determined in accordance with the specifications of ASTM standards.

3.3 Construction Process of Test Pads

After the characterization of selected materials, subgrade soil was prepared by spreading and levelling the surface using a dozer. The compaction process was performed by using

Table 2 Physical properties of surface layer (DBM of VG 30)

S. no.	Characteristics	Viscosity grade (VG 30)*
1	Bitumen density, g/cm^3	1.01
2	Absolute minimum viscosity 60 °C, N-s/m^2	240
3	Absolute maximum viscosity 60 °C, N-s/m^2	360
4	Kinematic viscosity, 135 °C, cm^2/s	3.50
5	Flash point, C, min	220
6	Solubility in trichloroethylene, %/m	99.0
7	Penetration value of VG 30, at 25 °C	50 - 70
8	Softening point, °C, min	47.0
Tests on residue from rolling thin film oven test (RTFOT)		
9	Viscosity ratio at 60 °C, Max	4.0
10	Ductility at 25 °C, cm/min, after thin film over test	40.0
11	Specific gravity at 25 °C	1.01

*Provided by the local bitumen manufacturer

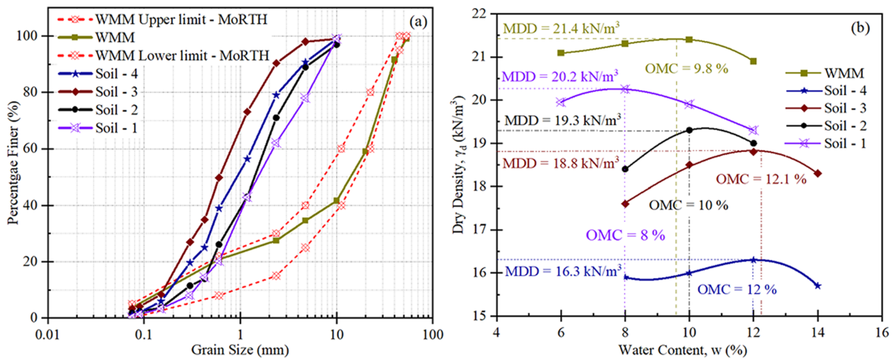

Fig. 2 **a** Grain-size distribution curve and **b** compaction characteristics of the materials

Table 3 Physical properties of subgrade soils as per ASTM standards

S. no.	Properties	Soil — 1	Soil — 2	Soil — 3	Soil — 4	Standards
1	Specific gravity, G_s	2.73	2.67	2.76	2.71	(ASTM D854-02 2014)
2	Grain size distribution (*GSD*)					(ASTM D2487 2017)
	Gravel, *G* (%)	22.00	11.0	2.0	9.25	
	Sand, *S* (%)	76.25	84.80	93.6	87.72	
	Fines, (%)	1.75	4.20	4.40	3.03	
	Effective size, D_{10} (mm)	0.34	0.26	0.16	0.19	
	D_{30} (mm)	0.80	0.68	0.34	0.50	
	D_{60} (mm)	2.2	1.84	0.80	1.35	
	Coefficient of uniformity, Cu	6.47	7.08	5.16	7.11	
	Coefficient of curvature, Cc	0.86	0.97	0.93	0.97	
3	Soil classification					(ASTM D2487 2017)
	As per AASHTO	A-1-a	A-1-b	A-1-b	A-1-a	
	As per USCS and IS	SP	SP	SP	SP	
4	Maximum dry density, γ_{dmax} (kN/m^3)	20.2	19.3	18.8	16.3	(AASHTO T180-93 2020; ASTM D1557-02 2007)
	Optimum moisture content, OMC (%)	8.0	10.0	12.10	12.0	

a 10-ton steel drum vibratory roller (refer to Fig. 3) after sprinkling the water on surface in accordance with codal provisions (IRC SP 97 2013). The calibration studies were performed to determine the number of roller passes required to achieve the targeted relative compaction of greater than 95%. It was observed that a vibratory roller of 8 passes was required to achieve the targeted relative compaction of 95%.

The base layer (WMM) material was laid, and dozer was used to spread uniformly and compacted with the specified number of roller passes to obtain a uniform thickness

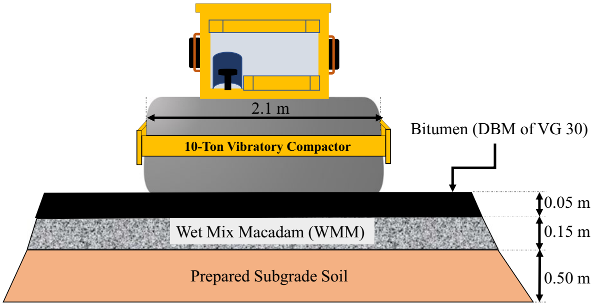

Fig. 3 Schematic view of steel drum vibratory roller on a typical test pad

of 0.15 m for test pad cases 2 to 6. The surface layer for cases 2, 3 and 4 comprising a 0.05-m thickness of DBM course was prepared on the compacted WMM layer and compacted to eight roller passes on the surface layer. However, in case 5, the existing bitumen top layer was milled to a specified thickness without affecting the underneath existing base layer. Case-5 was undertaken to enhance the pavement thickness by laying the WMM layer and proposed RCC layer to align with the top surface level of the rigid pavement in case-6. Subgrade soil, milled bitumen and soling were prepared to establish a strong and stable base for the WMM layer.

The soling stones were initially positioned along the entire stretch to ensure a uniform thickness of 0.15 m, with a maximum allowable deviation of ± 20 mm. Subsequently, the entire stretch was filled with soling stones. If any voids were left in between the soling stones, they were filled with a thin layer of stone chips. A thin layer of stone chips was spread uniformly throughout the soling surface and sprinkled with water, allowing the chips to fill any residual voids. After filling the voids, the irregularities of the stones were knocked off by using hammers to maintain a levelled top surface, and a vibratory compactor roller was used to compact the soling for the proposed case-6 test pad, as shown in Table 1 and Fig. 1f. LWD tests were conducted for the proposed number of test points (refer to Table 3) on subgrade soils (cases-1 to 4 and 6), milled bitumen (case-5), soling (case-6), base layer (WMM for cases 2 to 6) and surface layer (DBM for cases 2 to 4), respectively (refer to Fig. 4).

4 Methodology

A light weight deflectometer is a non-destructive testing (LWD) device that was used to perform a series of tests on six test pad cases (i.e., cases 1 to 6) mentioned in Table 1 and shown in Fig. 1. The LWD device used in this study consists of a 15-kg-standard weight with a drop height of 0.72 m. The impact energy induced by the drop weight is cushioned by elastomeric buffers, resulting in a pulse load of 10.6 kN. An accelerometer sensor is positioned in the middle of the circular loading plate with a diameter of 0.3 m to detect the accelerations of the tested layer. LWD measurements were communicated with a handheld personal digital assistant (PDA) device (refer to Fig. 5). The PDA device generates the reaction of tested layer with a time history for the applied dynamic load in terms of

Fig. 4 Pictorial representation of LWD testing on **a** subgrade soil, **b**–**c** base layer (WMM), and **d** surface layer (DBM)

deformation (w) from the loading plate. Initially, at every selected test point, three seating drops were established to ensure proper contact between the loading plate and surface of the respective testing layer. Furthermore, for three consecutive drops, the corresponding deformations were recorded as per standard (ASTM E2835 – 11 2020). The mean value of the surface deformations from these three consecutive drops was employed in Eq. (1) to evaluate the dynamic deformation modulus (E_{LWD}) of the tested layer by using Boussinesq's Eq. (1) (Vennapusa and White 2009; Fleming et al. 2007).

$$E_{\mathrm{LWD}} = \frac{qr\left(1 - v^2\right)fr}{\overline{w}} \quad (1)$$

where E_{LWD} = dynamic deformation modulus (MPa); q = maximum contact pressure (0.15 MPa); r = radius of loading plate (150 mm); ν = Poisson's ratio; f_r = stress distribution factor (1.57); and $\overline{w}$ = mean deformation of the loading plate measured at its centre (mm).

5 Results and Discussions

A series of LWD tests resulted in an intensive 453 field data points (for all 6 cases), which were represented using a radar chart. Radar charts show multivariate data in the form of quantitative variables of dynamic deformation modulus (E_{LWD}), mapped on the Y-axis originating from the centre of the radar chart (2-D). It represents a spider's web, with a central axis that has at least three spokes, called radii. Dynamic deformation modulus (E_{LWD}) values were mapped on the spokes. It is intended to highlight the resemblances, differences, outliers and symmetry in the distribution of variation in E_{LWD} values rather than specific values among observations. Also, it is a quick visual way of viewing variation in E_{LWD} data for various layers at a glance for the six test pad cases.

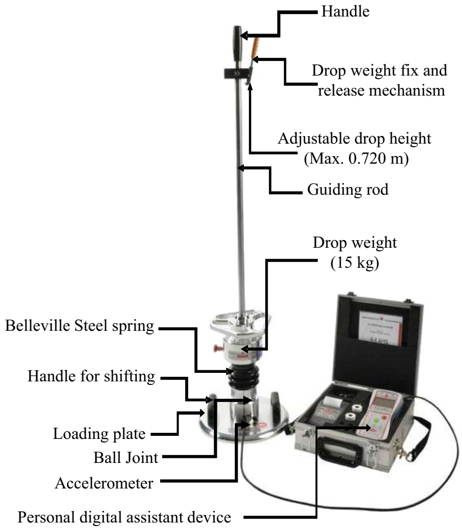

Fig. 5 Pictorial view of light weight deflectometer device and its components

In LWD testing, deformations of each test point were recorded for three consecutive testing drops, and dynamic deformation modulus (E_{LWD}) was calculated using Eq. (1). The statistical parameters such as mean ($\mu_{E_{\mathrm{LWD}}}$), standard deviation ($\sigma_{E_{\mathrm{LWD}}}$), coefficient of variation ($COV_{E_{\mathrm{LWD}}}$) and spatial variance ($SV_{E_{\mathrm{LWD}}}$) of the dynamic deformation modulus were calculated by using Eqs. (2)-(5) and represented in Table 4 for all the considered test pad cases.

$$Mean, \mu_{E_{\mathrm{LWD}}} = \frac{1}{N}\sum_{i=1}^{N}\left(E_{\mathrm{LWD}_i}\right) \tag{2}$$

$$\text{Standard deviation}, \sigma_{E_{\mathrm{LWD}}} = \sqrt{\frac{\sum_{i=1}^{N}\left(E_{\mathrm{LWD}_i} - \mu_{E_{\mathrm{LWD}}}\right)^2}{N-1}} \tag{3}$$

$$\text{Coefficient of variation}, COV_{E_{\mathrm{LWD}}} = \frac{\sigma_{E_{\mathrm{LWD}}}}{\mu_{E_{\mathrm{LWD}}}} \tag{4}$$

$$\text{Spatial variance}, SV_{E_{\mathrm{LWD}}} = \frac{1}{2N}\sum\left(E_{\mathrm{LWD}_{i+1}} - E_{\mathrm{LWD}_i}\right)^2 \tag{5}$$

where N = number of E_{LWD} data points; $i = E_{\mathrm{LWD}}$ value at each data point; and $i + 1 = E_{\mathrm{LWD}}$ value at $i + 1$ data point.

5.1 Dynamic Deformation Modulus of Subgrade Soil-1 (Case-1)

Case-1 was designed particularly to measure the dynamic deformation modulus of subgrade soil of a thickness equal to 0.50 m (refer to Fig. 1a). A series of LWD

Table 4 Comparison of multivariate and spatial statistics of deformation modulus (E_{LWD}) for six test pad cases

Test pad cases	Materials	Statistical parameters of E_{LWD}			
		Mean, μ (MPa)	Standard deviation, σ	Coefficient of variation, *COV*	Spatial variance, *SV*
Case-1	Soil-1	33.5	6.0	17.5	2.7
Case-2	Soil-2	19.1	2.8	14.7	1.2
	WMM (before passes)	27.0	3.9	14.3	2.0
	WMM (4 passes before watering)	29.7	4.3	14.4	3.9
	WMM (4 passes after watering)	39.1	5.0	12.7	8.2
	DBM (VG 30)	65.2	8.4	13.0	17.0
Case-3	Soil-2 (after 8 passes)	21.1	3.1	15.0	1.0
	WMM (4 passes before watering)	81.8	4.3	5.3	4.0
	WMM (4 passes after watering)	90.2	6.1	6.8	10.7
	DBM (VG 30)	103.7	9.1	8.8	15.3
Case-4	Soil-3 (after 8 passes)	47.8	7.0	14.4	17.3
	WMM (before passes)	48.8	6.5	13.4	10.1
	WMM (after 8 passes)	60.0	8.1	13.5	14.1
	DBM (VG 30)	75.8	5.8	7.7	8.1
Case-5	Milled bitumen	143.1	20.0	14.0	39.1
	WMM (after 8 passes)	73.2	5.7	7.8	8.3
Case-6	Soil-4 (after 8 passes)	26.1	5.0	19.0	1.6
	Soling (after 8 passes)	35.6	6.8	19.1	7.7
	WMM (after 8 passes)	49.3	6.8	13.7	9.4

tests were carried out for 24 test points, as shown in Table 3. Figure 6 represents the dynamic deformation modulus (E_{LWD}) values of the prepared subgrade soil-1, which were estimated using Eq. (1). The mean dynamic deformation modulus ($\mu_{E_{LWD}}$) of 33.5 MPa was reported for the prepared subgrade (case-1) obtained from Eq. (2). A coefficient of variation ($COV_{E_{LWD}}$) and spatial variance ($SV_{E_{LWD}}$) values were observed as 17.5% and 2.7, respectively (refer to Table 4). The reported *COV* and *SV* values of dynamic deformation modulus evaluated from LWD test results were based on the type of materials tested and their state (i.e., moisture content, lift thickness and relative compaction). The results indicate that the utmost care should be employed in the field work while constructing the subgrade layers to ensure consistency in test results. However, for the typical highway test pad sections in the field, a coefficient of variation (*COV*) of less than 20% was considerable. As per the study carried out by Maji and Das (2008) on all the test sections, it was observed that 90% of the test sections showed *COV* values of less than 25%, which can be considered a practical value. Hence, in this case, the observed *COV* value of 17.5% was practically in the considerable range.

5.2 Dynamic Deformation Modulus (E_{LWD}) of Pavement Layers Resting on Subgrade Soil-2 (Case-2)

Figure 7 illustrates the variation of the dynamic deformation modulus for a relative compaction value of 95% for each layer (refer to Fig. 1b). Dynamic deformation modulus (E_{LWD}) follows a comparable trend across all layers. The mean dynamic deformation modulus ($\mu_{E_{LWD}}$) values were evaluated by using Eq. (2) of existing subgrade soil (soil-2), base layer (WMM) and surface layer (DBM) and were found to be 19.1 MPa, 39.1 MPa and 65.2 MPa, respectively.

The number of compaction roller passes plays a crucial role in determining the mechanical properties of a material. Effective compaction passes enhance interparticle bonding and densification, resulting in a stiffer and more resistant material. The dynamic deformation modulus (E_{LWD}) of the WMM layer was increased after application of water and compaction passes. For instance, the mean dynamic deformation modulus ($\mu_{E_{LWD}}$) value increased from 29.7 to 39.1 MPa as the number of roller passes increased from 4 to 8, respectively. However, the optimal range of compaction roller passes should be carefully considered to avoid issues such as material fracture and reduced durability.

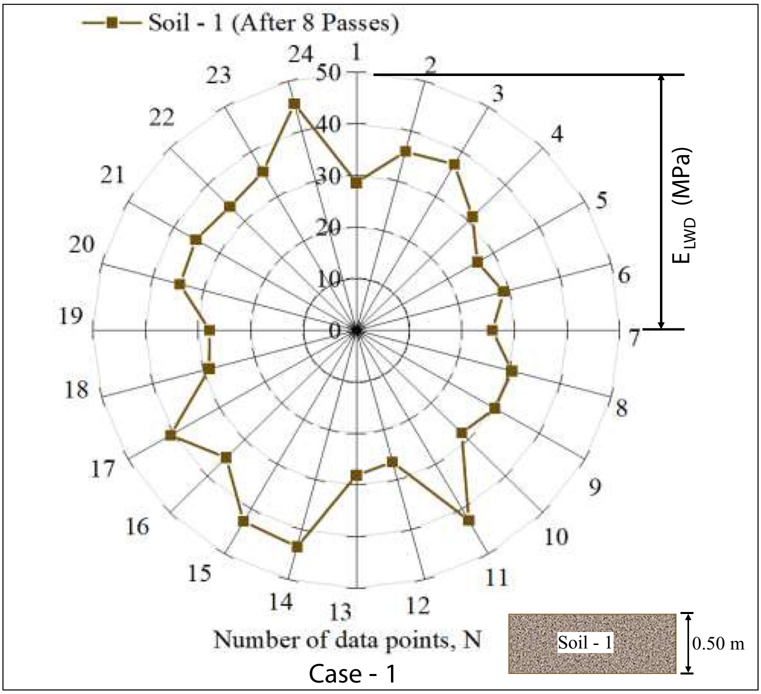

Fig. 6 Radar chart of dynamic deformation modulus (E_{LWD}) for case-1

The mean value of dynamic deformation modulus ($\mu_{E_{\mathrm{LWD}}}$) for a DBM layer with a thickness of 50 mm was reported as 65.2 MPa. According to Umashankar et al. (2016) and Fleming et al. (2007), the range of dynamic deformation modulus was 105–120 MPa for dense bitumen macadam (DBM) of thickness equal to 130 mm. However, the coefficient of variation (*COV*) of the dynamic deformation modulus (E_{LWD}) was calculated using Eq. (4) and reported as 14.7%, 12.7% and 13.0%, respectively (refer to Table 4). These values were observed to be within the acceptable range. However, for typical highway test pad sections in the field, a coefficient of variation (*COV*) value of less than 20% was practically considerable Maji and Das (2008). The spatial variance values were calculated using Eq. (5) and observed in the range of 1.2 to 17.0.

5.3 Effect of Rigid Base (RCC Layer Existing on Subgrade Soil-2) on Dynamic Deformation Modulus of WMM and DBM Layers (Case-3)

Figure 8 represents the variation of dynamic deformation modulus (E_{LWD}) for the composite layered pavement section of case-3 test pad, which comprises a WMM layer laid on an existing RCC layer (as shown in Fig. 1c). The impact of an existing rigid base (RCC bed) on the dynamic deformation modulus of WMM and DBM layers was evaluated by constructing a specific test pad (case-3). The mean E_{LWD} values were calculated using Eq. (2) of the existing subgrade (soil-2), base layer (WMM) and surface layer (DBM), which were reported as 21.1 MPa, 90.2 MPa and 103.7 MPa, respectively. The *COV* of dynamic deformation modulus ($COV_{E_{\mathrm{LWD}}}$) values were calculated by using Eq. (4) and reported as 15.0%, 6.8% and 8.8% respectively. The spatial variance values ($SV_{E_{\mathrm{LWD}}}$) were calculated using Eq. (5), which are in the range of 1.0 to 15.3 (refer to Table 4). In comparison with case-2, due to the rigid base (existing RCC bed), the effect of rigidity of the underneath layer results

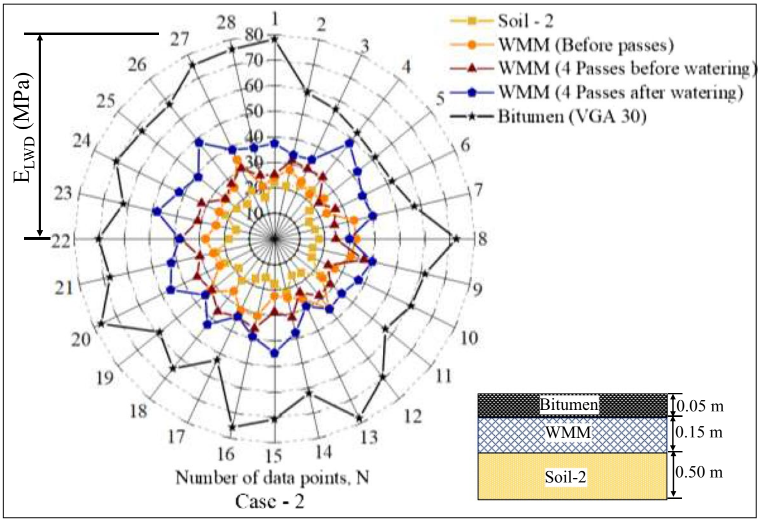

Fig. 7 Radar chart of dynamic deformation modulus (E_{LWD}) of case-2

in a significant improvement in mean E_{LWD} value. The improved mean dynamic deformation modulus $\left(\mu_{E_{\mathrm{LWD}}}\right)$ values were reported as 51.1 MPa for WMM layer and 38.5 MPa for the DBM layer when it was laid on the same subgrade soil (soil-2). Maji and Das (2008) reported that the *COV* of dynamic deformation modulus for the granular base layer (WMM) and bituminous surface layer (DBM) was in the range of 10–30% and 10–20%, respectively, for the field studies. Therefore, the uniform rigidity of an existing RCC bed plays a critical role in determining the E_{LWD} values of WMM and DBM layers. The radar chart indicates a huge variation in E_{LWD} between WMM layer when laid on the subgrade soil-2 and on an existing RCC bed, respectively (refer to Figs. 7 and 8). This indicates the rigidity of the bottom layer has a significant effect on the immediate layer (WMM and DBM) of the composite layered pavement section. In this study, a mean E_{LWD} value of 103.7 MPa was reported for a DBM layer of 50-mm thickness when it was laid on a WMM layer resting on an existing RCC bed. The results were in close agreement with an average modulus value of 110 MPa of an asphalt surface placed in two layers of 65-mm thickness reported by Fleming et al. (2007). In the case of WMM layer, the mean dynamic deformation value was increased from 81.8 MPa to 90.2 MPa for an increase in the number of passes from 4 to 8. This indicates the effect of compaction roller passes on the compacted pavement layers.

5.4 Dynamic Deformation Modulus of Pavement Layers Resting on Subgrade Soil-3 (Case-4)

Figure 9 represents the variation of dynamic deformation modulus (E_{LWD}) of various layers resting on subgrade soil-3 of the case-4 test pad (refer to Fig. 1d). The LWD readings on each layer follow a similar trend of increment and are consistent

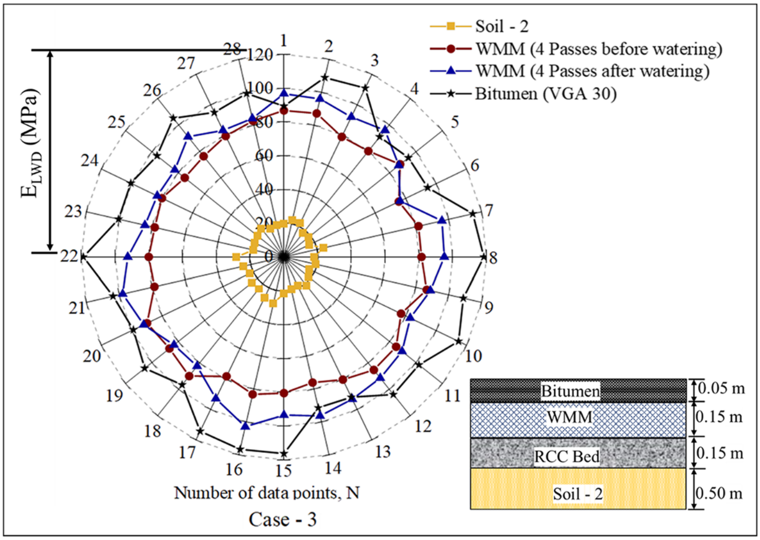

Fig. 8 Radar char of dynamic deformation modulus (E_{LWD}) of case-3

in comparison with the other layers. The mean of dynamic deformation modulus ($\mu_{E_{\mathrm{LWD}}}$) values of the existing subgrade soil (soil-3), base layer (WMM) and surface layer (DBM) were determined by using Eq. (2) and were found to be 47.8 MPa, 60 MPa and 75.8 MPa, respectively. The corresponding *COV* values ($COV_{E_{\mathrm{LWD}}}$) were reported as 14.4%, 13.5% and 7.7%, with a spatial variation of 8.1 to 17.3 (refer to Table 4) and were evaluated by using Eqs. (4)–(5) respectively. The mean dynamic deformation modulus ($\mu_{E_{\mathrm{LWD}}}$) values for the surface layer (DBM) of test pad cases 2 and 4 show good consistency, with a minimal percentage difference of 15%. However, there is a significant difference in percentage for the subgrade soil and WMM layer, with values of 85.8% and 42.2%, respectively. This is due to the different types of subgrade soils (i.e., soils 2 and 3) and their stiffness, despite the similar type of WMM material being laid. This indicates that a significant influence on the mean E_{LWD} of the WMM layer was observed. In the case of WMM layer, the mean dynamic deformation modulus ($\mu_{E_{\mathrm{LWD}}}$) values were increased from 48.8 MPa to 60.0 MPa for the number of passes from 4 to 8.

5.5 Effect of Milled Bitumen on Dynamic Deformation Modulus of WMM Layer (Case-5)

In this case, the WMM layer was placed on a milled bitumen layer as a part of the overlay design (refer to Fig. 1e). The presence of a milled bitumen layer influenced the LWD test results. Figure 10 illustrates the variation of dynamic deformation modulus (E_{LWD}) obtained from 10 test points using the LWD device. The mean dynamic

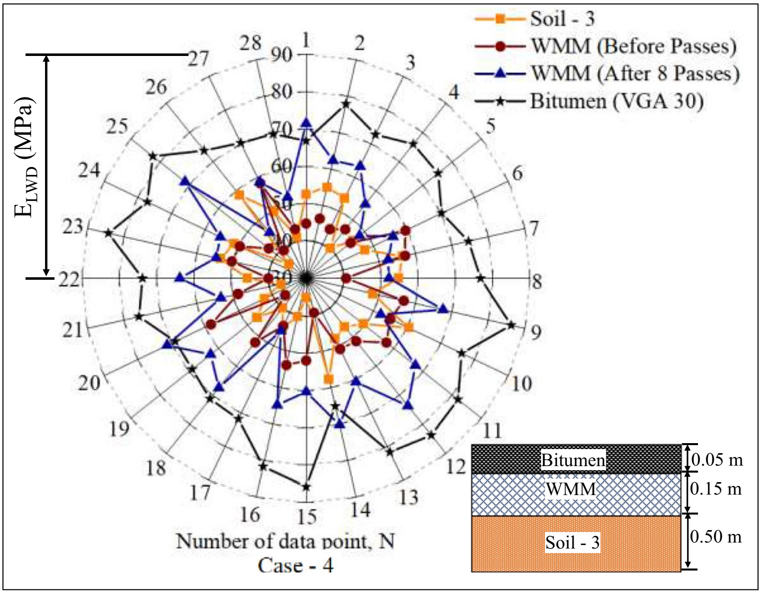

Fig. 9 Radar chart of dynamic deformation modulus (E_{LWD}) of case-4

deformation modulus ($\mu_{E_{\mathrm{LWD}}}$) was calculated by using Eq. (2) and reported as 143.1 MPa and 73.2 MPa for milled bitumen and WMM layers, respectively. This indicates that there is a significant influence of milled bitumen on the mean E_{LWD} value of the WMM layer, with an improvement of 34.1 MPa when compared with the WMM layer laid on subgrade soil-2. Whereas a reduction of 17 MPa was observed when the WMM layer was laid on an existing RCC layer, owing to which the overlay of 0.15-m thickness of WMM layer was laid similar to the other considered test pad cases. The reason beyond this is the leftover thin layer of milled bitumen on an existing base layer (WMM) which has minimal influence on the constructed WMM layer. The reported *COV* value of 14% for milled bitumen can be due to the variability in milled thin layers and uneven levelling. *COV* and *SV* of the WMM layer were calculated using Eqs. (4) and (5) and reported as 7.8% and 8.3%, respectively. Most care should be taken in pavement rehabilitation works, such as milling, pre-levelling and cleaning to place WMM layers, to ensure consistency in *COV* results, which should be within an acceptable range (i.e., 10–20%), as reported by Maji and Das (2008).

5.6 Effect of Soling (Resting on Subgrade Soil-4) on Dynamic Deformation Modulus of WMM Layer (Case-6)

Soling is a technique for creating a stable base for the pavement layer by placing a layer of uniform-sized boulders on subgrade soil. Its purpose is to distribute the low-volume traffic load evenly and avoid subsidence in the subgrade soil. Soling is frequently employed in regions with unfavourable subgrade soil conditions, for

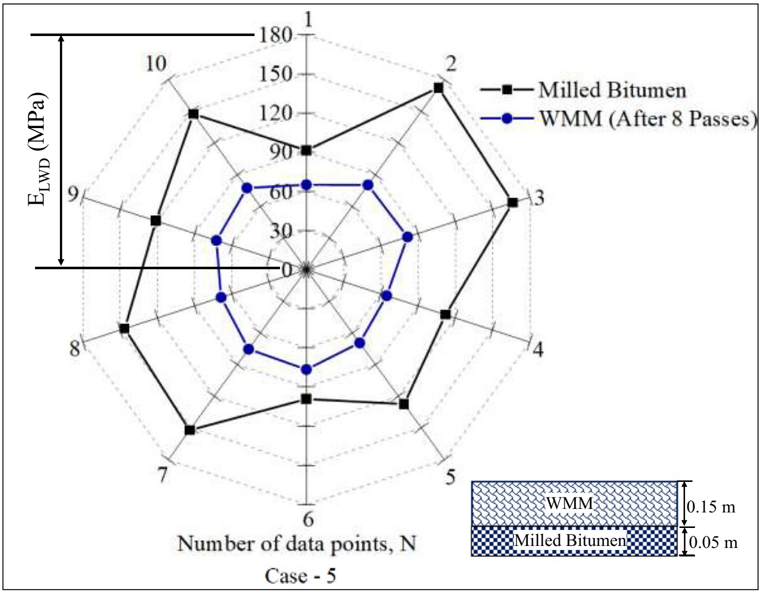

Fig. 10 Radar chart of dynamic deformation modulus (E_{LWD}) of case-5

instance, with high water tables and is considered a challenge by constructing the case-6 test pad (refer to Fig. 1f) to protect the pavement layers from the impact of the nearby water body.

Figure 11 represents the variation of dynamic deformation modulus (E_{LWD}) obtained from 15 test points. The mean dynamic deformation modulus ($\mu_{E_{\mathrm{LWD}}}$) values of the existing subgrade (soil-4), soling and base layer (WMM) were found to be 26.1 MPa, 35.6 MPa and 49.3 MPa, respectively. The corresponding $COV_{E_{\mathrm{LWD}}}$ was reported as 19%, 19.1% and 13.7%, respectively, and was evaluated using Eq. (4) (refer to Table 4). The reported *SV* values of 1.6, 7.7 and 9.4 were determined by using Eq. (5) for soil-4, soling and WMM layer, respectively. There is minimal influence of soling on the mean E_{LWD} of WMM layer (improvement of 10.2 MPa) when compared with the mean E_{LWD} of WMM layer when it was laid on subgrade soils (soil-2 and -3) for cases 2 and 4, respectively. This variation is a result of filling the voids with stone chips, and a thin layer of stone chips was spread all over the soling surface, which behaves similarly to the granular sub-base layer. The reported *COV* value of 19% for soil-4 and soling was due to the variability of unfavourable soil conditions under testing and their state (i.e., moisture content and compacted density). However, for typical highway test pad sections in the field, a coefficient of variation (*COV*) value of less than 20% was practically considerable as reported by Yoder and Witczak (1975).

5.7 Statistical Analysis (Mean, Standard Deviation, Coefficient of Variation and Spatial Variance) of Dynamic Deformation Modulus for Six Test Pad Cases

The present study focused on evaluating the dynamic deformation modulus values for various materials in composite pavement systems. Experiments were performed and resulted in 453 data points. Statistical analysis was performed by using Eqs. (2)–(5) to calculate the mean, standard deviation, coefficient of variation of E_{LWD} and spatial variance, respectively. Table 4 represents a summary of all test pad cases considered in this study. The estimated *COV* using Eq. (4) for soil-1, -2, -3, -4, milled bitumen and soling was reported as 17.5%, 15%, 14.5%, 19%, 14% and 19.1%, respectively. The LWD results tend to be in the acceptable range, as reported by Yoder and Witczak (1975). However, *COV* values were reported within the limits for stiff layers such as WMM and surface layers (i.e., 6.8%–13.7% and 7.7%–13%, respectively). The *COV* is influenced by several factors, such as non-uniform compaction around the test pad sections (edges and corners), variations in material properties, density, moisture content and lift thickness. Consequently, these factors lead to disparities in the effective measurements of dynamic deformation modulus (E_{LWD}) from LWD NDT devices and their reliability. In addition, this study highlighted the importance of proper compaction of subgrade soil and the WMM layer in pavement performance by summarizing the statistical analysis as tabulated in Table 4.

The overall results from the six test pad cases showed that the dynamic deformation modulus (E_{LWD}) values varied significantly depending on the composite-layered pavement sections. This study highlights the importance of effective

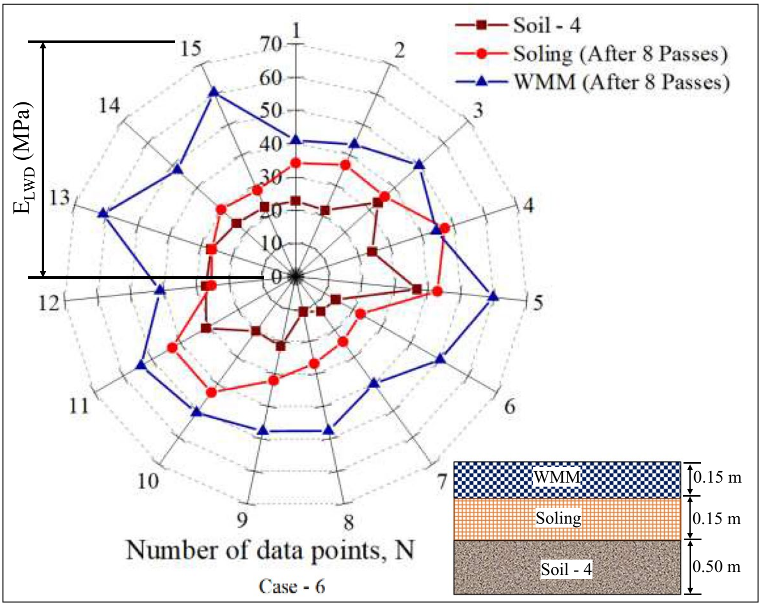

Fig. 11 Radar chart of dynamic deformation modulus (E_{LWD}) of case-6

measurements of E_{LWD} using LWD devices in designing and optimizing composite-layered pavement sections of various materials, which ultimately leads to increased performance and durability while reducing maintenance cost of the project. The practical implications of these findings extend to the construction and maintenance of composite layered pavement sections in various contexts.

5.8 Limitations and Future Scope

The current study is focused on the measurement of dynamic deformation modulus (E_{LWD}) of composite-layered pavement sections and proposes the range of dynamic deformation modulus for the six test pad cases. In addition, studied the influence of underneath layers on the dynamic deformation modulus of composite layered pavement sections. However, this study has a few limitations, such as that the effect of variation in moisture content, bitumen (DBM) temperature, climatic temperature and influence depth of the LWD device on DBM was not considered. Further research can be expanded to compare the effects of abovementioned limitations on the dynamic deformation modulus (E_{LWD}). In addition, the data obtained from LWD device can be compared with other kinds of NDT devices, such as dynamic cone penetrometer, soil stiffness gauge, falling weight deflectometer and Benkelman beam deflectometer devices.

6 Conclusions

The results of this study were presented to evaluate the potential use of LWD devices in determination of the in-situ dynamic deformation modulus (E_{LWD}) of layered composite pavement sections (six test pad cases). Based on the results obtained from the LWD device for six test pad cases, the following conclusions were drawn:

1. The field test results indicate that the repeatability of the LWD tests and their results depend on the compacted material being tested and the composition of the layers that are being evaluated. The repeatability of the LWD tests was found to be in good agreement for the subgrade soil-2 of cases 2 and 3. For instance, mean dynamic deformation modulus ($\mu_{E_{LWD}}$) values of 19.1 and 21.1 MPa were obtained for cases 2 and 3, respectively.
2. The dynamic deformation modulus (E_{LWD}) of the WMM layer was different for various cases based on the subgrade soil. For instance, when the WMM layer was laid on existing subgrade soil-2 (i.e., case-2), the mean E_{LWD} of WMM was reported as 39.1 MPa with a *COV* of 12.7%. Whereas for case-4, the mean E_{LWD} of WMM layer was reported as 60 MPa, with a *COV* of 13.5% when the WMM layer was laid on prepared subgrade soil-3.
3. The rigidity of the underneath layer also influences the dynamic deformation values (E_{LWD}) of the WMM layer. For instance, where a WMM layer was laid on an existing RCC bed (i.e., in case 3), the mean E_{LWD} of WMM layer was found to be 90.2 MPa. Whereas for cases 5 and 6, the mean E_{LWD} of WMM layer was reported as 73.2 MPa, and 49.3 MPa when the WMM layer was laid on milled bitumen and soling, respectively. In comparison, a higher E_{LWD} value was observed in case-3 due to the RCC bed underneath the WMM layer.
4. The number of roller passes played a major role in increasing the dynamic deformation modulus values. For instance, as the number of passes increased from 4 to 8, the mean E_{LWD} values of WMM layers increased from 29.7 MPa to 39.1 MPa, 81.8 MPa to 90.2 MPa and 81.8 MPa to 90.2 MPa for test pad cases 2, 3 and 4, respectively.
5. In the case of surface layer (i.e., cases 2–4), where a DBM material was laid on the WMM layer, the mean E_{LWD} values of the DBM layer of 50-mm thickness were found to be 65.2 MPa, 103.7 MPa and 75.8 MPa for cases 2, 3 and 4, respectively. However, the *COV* and *SV* values were obtained in the range of 5.81% to 13% and 8.1 to 17, respectively.

LWD tests were carried out to determine the dynamic deformation modulus (E_{LWD}) of the layered composite pavement section to ensure optimal compaction and prevent failures. This makes the LWD device a strong tool for evaluating the compaction quality control of various materials used in the construction of infrastructure projects, improving durability and reducing maintenance costs. It allows optimization of the compaction process and ensures the construction of high-quality and long-lasting infrastructure projects.

Notations/Symbols *COV*: coefficient of variation, (%); ($COV_{E_{\mathrm{LWD}}}$): coefficient of variation of dynamic deformation modulus (MPa); *DBM*: dense bituminous macadam; *DT*: destructive testing; E_{LWD}: dynamic deformation modulus, (MPa); *FWD*: falling weight deflectometer; i : $\mathrm{E}_{\mathrm{LWD}}$ value at each data point (i^{th} point); *LWD*: light weight deflectometer; *NDT*: non-destructive testing; *N*: number of E_{LWD} test data points; SV_{ELWD}: spatial variance of dynamic deformation modulus (MPa); VG: viscosity grade; w: deformation, (mm); WMM: wet mix macadam; $\overline{w}$: mean deformation, (mm); $\mu_{E_{\mathrm{LWD}}}$: mean of dynamic deformation modulus (MPa); $\sigma_{E_{\mathrm{LWD}}}$: standard deviation of dynamic deformation modulus (MPa)

Author Contribution Sidhu Ramulu Duddu: collection of material from nearby source, preparation of pavement layers, field experimental testing for all case studies, acquisition of LWD data and its analysis, plotting, images, drafting of manuscript and provided the revised article content. Vamsi Kommanamanchi: collection of material from nearby source, preparation of pavement layers, field experimental testing for all case studies, acquisition of LWD data and its analysis, plotting, images, drafting of the manuscript and provided the revised article content. Hariprasad Chennarapu: provided the concept of broad area of case studies, acquisition of LWD data and its analysis part, drafting of the manuscript and provided the revised article content and final approval of the manuscript to be submitted. Prabodh Kumar Mahopatra: field experimental work using LWD device, plotting and proof reading of the manuscript to be submitted.

Data Availability Some or all the data that support the findings of this study are available from the corresponding author upon reasonable request.

Code Availability Not applicable (NA).

Declarations

Ethics Approval Not applicable (NA).

Consent to Participate For this type of study, formal consent is not required.

Consent for Publication We, the undersigned, consent to the publication of identifiable details, which may include photograph(s) and/or details within the text to be published in the "Transportation Infrastructure Geotechnology", Springer.

Conflict of Interest The authors declare no competing interests.

References

AASHTO M226-80: Standard specification for asphalt-rubber binder. In: American Association of State Highway and Transp. Officials (AASHTO), Washington, DC, USA (2021)

AASHTO T 180-93: Standard method of test for moisture-density relations of soils using a 4.54-kg (10-lb) rammer and a 457-mm (18-in.) drop. In: American Association of State Highway and Transp. Officials (AASHTO), Washington, DC, USA (2020)

Alshibli, K., Abu-Farsakh, M., Seyman, E.: Laboratory evaluation of the geogauge and light falling weight deflectometer as construction control tools. J. Mater. Civ. Eng. **17**(5), 560–569 (2005). https://doi.org/10.1061/(ASCE)0899-1561(2005)17:5(560)

ASTM D1557-02: Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lb/ft3 (2,700 kN-m/m3)). ASTM International, West Conshohocken, PA, USA (2007)

ASTM D2487: Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA, USA (2017)

ASTM D2937: Standard test method for density of soil in place by the drive cylinder method. ASTM International, West Conshohocken, PA, USA (2004). https://doi.org/10.1520/D2937-17E02

ASTM D854-02: Standard test methods for specific gravity of soil solids by water pycnometer. ASTM International, West Conshohocken, PA, USA (2014)
ASTM E2835–11: Standard test method for measuring deflections using a portable impulse plate load test device. ASTM International, West Conshohocken, PA, USA (2020)
BIS 73: Paving Bitumen—Specification. In: 3rd Revision. Bureau of Indian Standards (BIS), Manak Bhavan, New Delhi, India (2013)
Cesar, T., Gamez-Rios, K.Y., Fathi, A., Mazari, M., Nazarian, S.: Simulation of lightweight deflectometer measurements considering nonlinear behavior of geomaterials. Transp. Res. Board. **2641**, 58–65 (2017). https://doi.org/10.3141/2641-08
Deshmukh, R., Patel, S., Shahu, J.T.: Full-scale field performance of geocell reinforced-fly ash in the subbase course of flexible pavement. Int. J. Geosynth. Ground Eng. **8**(3), 36 (2022). https://doi.org/10.1007/s40891-022-00383-1
Duddu, S.R., Chennarapu, H.: Quality control of compaction with lightweight deflectometer (LWD) device: a state-of-art. Int. J. Geo-Eng. **13**(6),(2022). https://doi.org/10.1186/s40703-021-00171-2
Duddu, S.R., Vamsi, K., Hariprasad, C., Umashankar, B.: Evaluating improved moduli of geogrid-stabilized sandy soil with a deflectometer. Proc. Inst. Civ. Eng. – Ground Improv. 1–34 (2023). https://doi.org/10.1680/jgrim.22.00075
Dwivedi, S., Suman, S.K.: A comprehensive review on non-destructive testing using LWD and Geogauge for quick QC/QA of pavement layers. Innov. Infrastruct. Solut. **8**, 101 (2023). https://doi.org/10.1007/s41062-023-01061-5
Ebrahimi, A., Edil, T.B.: Light-weight deflectometer for mechanistic quality control of base layer materials. Proc. Inst. Civ. Eng. – Geotech. Eng. **166**(5), 441–450 (2013). https://doi.org/10.1680/geng.11.00011
Elhakim, E.F., Elbaz, K., Amer, M.I.: The use of light weight deflectometer for in situ evaluation of sand degree of compaction. Hous. Build. Res. Cent. J. **10**(3), 298–307 (2014). https://doi.org/10.1016/j.hbrcj.2013.12.003
Fleming, P.R., Frost, M.W., Lambert, J.P.: Review of lightweight deflectometer for routine in situ assessment of pavement material stiffness. Transp. Res. Board. **2007**(1), 80–87 (2007). https://doi.org/10.3141/2004-09
Fleming, P.R., Lambert, J.P., Frost, M.W., Rogers, C.D.F.: In-situ assessment of stiffness modulus for highway foundations during construction. In: 9th Int. Conf. on Asphalt Pavements, Copenhagen, Denmark (2002)
Fleming, P.R., Rogers, C.D.F.: Assessment of pavement foundations during construction. Proc. Inst. Civ. Eng. – Transp. **111**(2), 105–115 (1995)
George, K.P., Bajracharya, M., Stubstad, R.: Subgrade characterization employing the falling weight deflectometer. Transp. Res. Rec.: J. Transp. Res. Board. **1869**, 73–79 (2004). https://doi.org/10.3141/1869-09
George, V., Anil, K.: Effect of soil parameters on modulus of resilience based on portable falling weight deflectometer tests on lateritic subgrade soils. Int. J. Geotech. Eng. **1-7**, (2017). https://doi.org/10.1080/19386362.2017.1403075
Hossain, M.S., Apeagyei, A.K.: Evaluation of the light weight deflectometer for in situ determination of pavement layers moduli. FHWA/VTRC 10-R6, Virginia Transp. Res. Counc, Charlottesville, VA (2007)
Hua, T., Yang, Z.J., Yang, X., Huang, H., Yao, Q., Wu, G., Li, H.: Assessment of geomaterial compaction using the pressure-wave fundamental frequency. Transp. Geotech. **22**, 100318 (2020). https://doi.org/10.1016/j.trgeo.2020.100318
IRC 37: Guidelines for the design of flexible pavements. In: Publication No. 37. Indian Road Congress (IRC), R.K. Puram, New Delhi, India (2018)
IRC SP 97: Guidelines on compaction equipment for road works. Indian Road Congress (IRC), R.K. Puram, New Delhi, India (2013)
Kumar, R., Kumar, V.A., Guzzarlapudi, S.D.: Stiffness-based quality control evaluation of modified subgrade soil using Light weight deflectometer. J. Mater. Civ. Eng. **299**, 1–9 (2021). https://doi.org/10.1061/ASCEMT.1943-5533.0001958
Lajnef, N., Rhimi, M., Chatti, K., Mhamdi, L.: Toward an integrated smart sensing system and data interpretation techniques for pavement fatigue monitoring. Computer-Aided Civ. and Infrastruct. Eng. **26**(7), 513–523 (2011). https://doi.org/10.1111/j.1467-8667.2010.00712.x
Lee, J.S., Tutumluer, E., Hong, W.T.: Stiffness evaluation of compacted geo-materials using cross hole-type dynamic cone penetrometer (DCP), RPLT, and LFWD. Construct. Build Mater **303**, 124015 (2021). https://doi.org/10.1016/j.conbuildmat.2021.124015

Liu, D., Wang, Y., Chen, J., Zhang, Y.: Intelligent compaction practice and development: a bibliometric analysis. Eng. Constr. and Archit. Manag **27**(5), 1213–1232 (2020). https://doi.org/10.1108/ecam-05-2019-0252

Livneh, M., Goldberg, Y.: Quality assessment during road formation and foundation construction: use of falling-weight deflectometer and light drop weight. Transp. Res. Rec.: J. Transp. Res. Board. **1755**, 69–77 (2001). https://doi.org/10.3141/1755-08

Mahamid, I.: Effects of project's physical characteristics on cost deviation in road construction. J. King Saud. Univ. Eng. Sci. **25**(1), 81–88 (2013). https://doi.org/10.1016/j.jksues.2012.04.001

Maji, A., Das, A.: Reliability considerations of bituminous pavement design by mechanistic-empirical approach. Int. J. Pavement Eng. **9**(1), 19–31 (2008). https://doi.org/10.1080/10298430600997240

Michael, G.: LWD Correlation Trail. Transport Scotland, Project No. 70061041. Ref. No. 70061041 – 101. WSP, 7 Lochside View, Edinburgh Park, Edinburgh, Midlothian, EH12 9DH. (2021)

Mooney, M.A., Miller, P.K.: Analysis of lightweight deflectometer test based on in situ stress and strain response. J. Geotech. Geoenviron. Eng **135**(2), 199–208 (2009). https://doi.org/10.1061/(ASCE)1090-0241(2009)135:2(199)

MoRTH: Specifications for Road and Bridge Works. 5th Revision. Ministry of Road, Transp. and Highways (MORTH), Sector 6, Kama Koti Marg, New Delhi (2013)

Newcomb, D., Birgisson, B.: Methods for measuring in situ subgrade mechanical properties of pavement subgrade soils. NCHRP Synthesis 278, pp. 24–42. Transp. Res. Board (1999)

Newcomb, E., Bjorn, B.: Condition survey and evaluation of inaccessible pavements. J. Transp. Eng. **125**(6), 535–542 (1999)

Nie, Z.H.: Comparison experimental study on subgrade compaction quality test methods. Appl. Mech. Mater. **71–78**, 4679–4684 (2011). https://doi.org/10.4028/www.scientific.net/AMM.71-78.4679

Petri, V., Timo, S., Pauli, K., Esa, J.: The ROADEX Pavement Stress and Strain. Roadex Publications. The Roadex IV Project, EU Northern Peripher (2010)

Rahman, F., Hossain, M., Hunt, M.M., Romanoschi, S.A.: Soil stiffness evaluation for compaction control of cohesionless embankments. Geotech. Test. J. **31**(5), 1–13 (2008). https://doi.org/10.1520/GTJ100971

Rajagopal, K., Chandramouli, S., Parayil, A., Iniyan, K.: Studies on geosynthetic-reinforced road pavement structures. Int. J. Geotech. Eng. **8**(3), 287–298 (2014). https://doi.org/10.1179/1939787914Y.0000000042

Rogers, C.D.F., Brown, A.J., Fleming, P.R.: Elastic stiffness measurement of pavement foundation layers. In: Proc. 4th Int. Symp. of Unbound Aggregate in Roads (UNBAR4), Nottingham Univ, pp. 271–280, UK (1995)

Senseney, C.T., Mooney, M.A.: Characterization of two-layer soil system using a lightweight deflectometer with radial sensors. Transp. Res. Board. **2186**(1), 21–28 (2016). https://doi.org/10.3141/2186-03

Sunny, D.G., Vinod, K.A., Rakesh, K.: Comparative studies of lightweight deflectometer and Benkelman beam deflectometer in low volume roads. J. Traffic. and Transp. Eng. **3**(5), 438–447 (2016). https://doi.org/10.1016/j.jtte.2016.09.005

Tayabji, S.D., Lukanen, E.O.: Non-destructive testing of pavements and back-calculation of moduli. ASTM STP1375-EB. **3**(548), (2000). https://doi.org/10.1520/STP1375-EB

Timm, D.H., Priest, A.L., McEwen, T.V.: Design and instrumentation of the structural pavement experiment at the NCAT test track. Natl. Cen. Asph. Technol., NCAT Report 04-01, Auburn, AL, USA (2013)

TP BF-StB Part B 8.3-1997 (R1): Dynamic Plate Load Testing with the Light Drop Weight Tester. In: Technical Testing Regulations for Soil and Rock in Road Construction. Forschungsgesellschaft für Straßen- und Verkehrswesen e.V, Cologne (2012)

Umashankar, B., Hariprasad, C., Kumar, G.T.: Compaction quality control of pavement layers using LWD. J. Mater. Civ. Eng. **27**(7), (2016). https://doi.org/10.1061/(ASCE)MT.1943-5533.0001379

Vennapusa, P.K.R., White, D.J.: Comparison of light weight deflectometer measurements for pavement foundation materials. Geotech. Test. J. **32**(3), 239–251 (2009)

White, D.J., Gieselman, H.H., Douglas, C., Zhang, J., Vennapusa, P.: In-situ compaction measurements for geosynthetic stabilized subbase: Weirton, West Virginia. Iowa State Univ. Inst. of Trans.: Earthwork Eng. Res. Cen. (2010)

Xiaochao, T., Shelley, M.S., Angelica, M.P.: Evaluation of pavement layer moduli using instrumentation. Int. J. Pavement Res. Technol. **6**(6), 755–764 (2013). https://doi.org/10.6135/ijprt.org.tw/2013.6(6).755

Yoder, E.J., Witczak, M.W.: Principles of Pavement Design, 2nd edn, pp. 204–222. John Wiley & Sons Inc., New York (1975)

Zubeck, H.K., Doré, G.: Cold Regions Pavement Engineering, p. 432. McGraw Hill, ASCE Press, New York, USA (2009)

Declaration of Self-citations The authors declare that they have three numbers of citations in this research article, which is less than 5 as per journal guidelines.

Authors and Affiliations

Sidhu Ramulu Duddu[1] · Vamsi Kommanamanchi[1] · Hariprasad Chennarapu[1] · Prabodh Kumar Mahopatra[1]

Sidhu Ramulu Duddu
sidhuramulu20pcie005@mahindrauniversity.edu.in

Vamsi Kommanamanchi
vamsi21pcie003@mahindrauniversity.edu.in

Prabodh Kumar Mahopatra
prabodh22pcie003@mahindrauniversity.edu.in

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