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ASSESSING PERFORMANCE THROUGH THE UTILIZATION OF LIGHT WEIGHT DEFLECTOMETER

Prakashkumar Makwana
(Assistant Engineer)
Road and Building Department, Government of Gujarat, India
ORCID ID: https://orcid.org/0009-0007-3511-1113

ABSTRACT

Rapid infrastructure development, particularly in India, has emerged as a prominent global trend. Over the past few decades, it has become apparent that many road projects necessitate early-stage maintenance. To identify the underlying causes, a comprehensive structural evaluation study is imperative to assess the existing material properties of pavements. While Light Weight Deflectometer (LWD) is gaining widespread acceptance and popularity as an in-situ spot-testing device worldwide, in India, only a few researchers have delved into its applications. This study aims to estimate the in-situ layer moduli of flexible pavements using LWD and further utilize these layer moduli for performance analysis. A series of tests were conducted at NH-15 on 52 distressed locations, and samples were systematically collected for subsequent laboratory testing. LWDmod software was employed to calculate the back-calculated modulus for each layer. The results revealed that the Coefficient of Variation (CV) of the back-calculated average modulus on both the Left-Hand Side (LHS) and Right-Hand Side (RHS) ranged from 24% to 30% for the bituminous surface, 33% to 45% for the WMM, 35% to 45% for the GSB, and 40% to 52% for the Sub-grade. It was observed that the CV value was higher for softer materials and subsequently decreased for granular layers. The performance analysis indicated that the existing pavement is structurally distressed.

Keywords: Light Weight Deflectometer (LWD), LWDmod, Layer Moduli, and Coefficient of Variation (CV).

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1. INTRODUCTION

Rapid road infrastructure development is a prominent trend both in India and globally. However, this surge has led to a significant number of roads deteriorating, necessitating a thorough pavement evaluation. This evaluation serves as the basis for formulating effective rehabilitative strategies aimed at ensuring long-term pavement performance and serviceability.

To conduct structural evaluations, the Benkelman Beam Deflection (BBD) and Falling Weight Deflectometer (FWD) are commonly utilized. While BBD is user-friendly, it operates at a slower measurement rate and requires temperature considerations [1]. In contrast, the FWD, a standard tool for structural assessment, particularly on unbound pavement layers, has been in use for over a decade [2].Recognizing the limitations of current methods, there is a need for a new, portable, and cost-effective tool for evaluating flexible pavement structures.

The long-term serviceability and performance of roads are contingent upon the strength parameters of the materials used. There is a global shift towards a mechanistic-empirical approach for pavement design, considering the mechanics of materials in relating inputs to pavement responses [3]. AASHTO's pavement design, based on structural numbers, quantifies the necessary structural strength for specific conditions (Guide for the Design of Pavement Structures) [4]. IRC 37-2012 incorporates a stiffness-based mechanistic-empirical approach for flexible pavements [5].

Traditional quality assurance in roadwork emphasizes density and compaction. Modulus assessment, vital for mechanistic pavement design, is often overlooked [6]. To expedite work, adopting new technologies like the Lightweight Deflectometer (LWD) is recommended. The LWD, which rapidly assesses surface modulus, shows promise for evaluating material properties and optimizing construction methods [2]. This study aims to evaluate surface and sub-grade modulus of flexible pavements using LWD.

This study addresses a critical need in the country's infrastructure. Poor road maintenance costs approximately Rs 35,000 crore annually, leading to the erosion of extensive stretches of rural and secondary roads [7]. This underscores the urgency for effective rehabilitation measures. Current conventional in-situ structural evaluation tests like BBD are time-consuming, labor-intensive, and economically inefficient, with questionable reliability. They fall short in estimating the strength of layers and the remaining lifespan of existing pavement. Swift and reliable in-situ test results are crucial for designing effective rehabilitation measures. Therefore, there is a pressing need for a rapid and cost-effective technique to gauge the structural strength of flexible pavement. With a global shift towards mechanistic-based pavement design, which offers more reliable and specified design methods compared to empirical approaches, accurate input values like elastic/surface modulus are crucial for design and rehabilitation strategies. This study focuses on evaluating stiffness/surface modulus values using LWD. The main objectives are to assess the surface modulus of each layer in flexible pavement using the LWD technique and to evaluate and analyze potential rehabilitation strategies. The study is limited to a 47 km stretch of flexible pavement on the National Highway in Kutch, Gujarat. Surface modulus calculations will be performed using LWDmod software.

2. OVERVIEW OF LWD

The Lightweight Deflectometer (LWD) is utilized for measuring the in situ modulus of material layers. Unlike the Falling Weight Deflectometer (FWD) commonly employed in roadworks, the LWD offers portability, weighing approximately 15 kg to 25 kg, and can be operated by a single person, allowing for tests to be completed within 1 to 2 minutes. The LWD comprises three primary components: (A) a base with a loading mechanism, (B) a falling weight (either 10 kg or 20 kg sliding hammer), and (C) sensors equipped with associated electronics and an upper frame (housing for sensors, rubber buffers, and guidance rod).

The base houses two sensors: a load cell and a geophone (velocity transducer). Both sensors are linked to a PAD that incorporates data acquisition and filtering systems.

2.1. Operational Principle

This method is a plate bearing test. It involves dropping a weight onto a buffer system, which transmits the load through a plate onto the material being tested. The force and velocity time histories are then measured beneath the loading plate's center. Displacement time histories are automatically derived by integrating the recorded velocity within the device. The instrument is connected to a PDA equipped with software for recording, interpreting, and visualizing data. The output provides time histories and peak values of the applied load and resulting deflection, along with an estimated surface modulus (E_0) as defined in Equation :

$$\boldsymbol{E_0} = \frac{\boldsymbol{A * \left(1 - \vartheta^2\right) * a * \sigma_0}}{\boldsymbol{d_0}}$$

Where:

E_0 = Surface modulus (MPa), **σ_0**= Contact Pressure (kPa);**A** = Radius of the loading plate (mm); **d_0**= deflection (µm); **ϑ** = Poisson’s Ratio.,**A** = plate rigidity factor, default = 2 for a flexible plate, π/2 for a rigid plate

3. LITERATURE REVIEW

Various factors influence Lightweight Deflectometer (LWD) results, including dropping weight, drop height, and loading plate diameter. Researchers have extensively studied these factors. Fleming et al. (2007) noted that buffer temperature doesn't significantly impact results. However, non-uniform contact with the material under test can be mitigated by applying a thin layer of uniform-sized sand [2]. Kavussi et al. (2010) discovered that PFWD moduli increased with higher drop weights, but remained consistent regardless of drop height variations. They also highlighted the pronounced effect of contact area on elastic modulus results [8]. Singh et al. (2010) emphasized that the LWD provides valuable information about deeper zones, and stiffness increases with higher soil density [9]. Lin et al. (2006) found that the size of the loading plate significantly affects E_0 modulus, with the 100 mm diameter plate producing higher moduli than the 300 mm diameter plate. Drop height had minimal effects on PFWD moduli[10]. Mooney and Miller (2009) determined that contact stress distributions affect in situ stress at depths ranging from 1.0D to 1.5D, encompassing the entire influence depth of the LWD test [11].

Researchers have extensively investigated the relationship between LWD modulus and various parameters including FWD, DCP determined CBR, degree of compaction, and plate load test. Fleming et al. (2007) conducted comparative studies, finding correlations dependent on site, material, and device specifics [2]. Kavussi et al. (2010) noted a good correlation between CBR and PFWD stiffness moduli within the range of 20% to 80%, emphasizing the difficulty in defining this relationship for low-strength materials [8]. Lin et al. (2006) observed slightly higher DCP-determined CBRs compared to laboratory measurements, with PFWD moduli consistently lower than those from DCP but closer to laboratory-determined modulus through CBR [10]. Gurp et al. (2010) highlighted that a series of LWD drops lead to post-compaction and an increase in foundation surface modulus. They also emphasized that weather conditions have limited impact on LWD test results [6]. Alshibli et al. (2005) obtained strong statistical correlations between E_{LFWD} and elastic moduli obtained from Plate Load Tests [12]. Sulewska M. J. (2004) found a dependency between dynamic modulus of soil deformation and soil degree of compaction, providing valuable insights for compaction control during construction [13].

Siekmeier et al. (2006) conducted a review, concluding that LWD stress depth and modulus are influenced by factors such as drop height and stress applied, particularly relevant for LWD compared to FWD [14].

Fleming et al. (2007) noted that in their review of raw data displaying load-deflection-time relationships, they observed instances of poor contact, characterized by early small peaks in the deflection trace, as well as movement and vibration of the apparatus, indicating irregular contact. They emphasized that the peak deflection encompasses both plastic and elastic components, representing the total deflection under load, not just the recoverable portion. After six passes, the deflection trace exhibited increased uniformity, highlighting the significance of a level surface[2]. The Highways Agency's current design guidelines specify acceptable PFWD equipment, emphasizing factors like load pulse magnitude, duration, plate diameter, and deflection measurement capacity. Steinert et al. (2006) recommended following a protocol of six drops per location, without specifying whether to disregard the first three drops or average all six [15]. Fleming et al. (2002) introduced the Coefficient of Variance (CoV) as a valuable metric for reporting variability in trial sections, noting CoV ranges for FWD and LWD on different sub-grades [16]. Terzaghi K. (1943) discussed theoretical soil mechanics and the distribution of contact stress on various soil types [17]. Edwards & Fleming (2009) provided practical guidelines for LWD use, suggesting adjustments based on material surface modulus, emphasizing the importance of a stable LWD setup, and offering insights on interpreting deflection-time histories [18]. Lambert et al. (2008) developed a system utilizing LWD to assess the environmental stability of materials, considering factors like water content and compaction timing for performance-based design, with implications for field compliance testing of pavement foundations [19].

3.1. Analytic Techniques

The behavior of flexible pavement under wheel load was initially described by Boussinesq (1885), who formulated equations to calculate stress, strain, and displacement in a linear elastic semi-infinite space under a concentrated point load. However, this approach assumes soil elasticity, which doesn't align with the non-linear, permanent deformation properties of sub-grade soils under stationary loads. Given that real-world pavements are multilayered and non-homogeneous, Boussinesq's solutions aren't directly applicable. Odemark introduced the Method of Equivalent Thickness (MET) to transform multilayered systems into an equivalent system with uniformly adjusted layer thicknesses and equal moduli. This transformation relies on layer stiffness, regardless of changes in thickness, modulus, or Poisson's ratio. The equivalent thickness 'h_e' can be calculated using the formula $(h^3*E)/((1-\vartheta^2))$. For layers with equal Poisson's ratio, the formula simplifies to $h_e=h_1*[E_1/E_2]^{(1/3)}$. To refine Odemark's method, a correction factor 'f' is often applied, with 'f' values typically falling between 0.8 and 0.9. IRC 37-2012 and LWDmod program guide suggest a relationship between modular ratio and thickness: $E_1/E_2=0.2*h_1^{0.45}$. When characterizing the behavior of a flexible pavement with known layer moduli, Odemark's method transforms the system into equivalent thickness, enabling the application of Boussinesq's equations. Conversely, in LWD data analysis, this process is reversed to back-calculate the moduli of different layers using surface deflection or deformation under a load. The surface modulus (E_0) is determined using Boussinesq's equation and factors in the non-elastic nature of flexible pavements. Additionally, the sub-grade modulus (E) is stress-dependent and can be described by the equation $E=C*(\sigma/\sigma')^n$, where C is the modulus at a reference stress level and n accounts for non-linearity. The study employs the LWDmod software, which utilizes the Boussinesq-Odemark method, to determine surface and sub-grade moduli through back-calculation iterations.

The Back-Calculation process involves assuming initial seed values and structural data, such as modulus, thickness, Poisson ratio, C, and n, based on the current pavement condition and experience. Utilizing Boussinesq's-Odemark's method, deflection values are then forward calculated. These calculated deflections are compared with those obtained from LWD measurements using the Gradient Search algorithm, which acts as an inverse solver. Validation is based on the Root Mean Square (RMS) value of deflections, following an objective function proposed by Senseney et al. (2012) [20]. The Gradient Search Algorithm iterates until the objective function is minimized. The finalized moduli values, yielding the least RMS, are considered as the final results.

3.2. LWDmod TOOL

The LWDmod tool, developed by Dynatest specifically for LWD analysis, allows for analysis of up to three layers. It employs the Odemark-Boussinesq Method, an iterative analysis approach. LWDmod can import two types of raw data files: the *.kdb file generated on the PDA during testing, or raw data from Excel files in the format of the Excel export from the previous Keros Toolbox program. Before analysis, data quality and structure are crucial. This involves accurate field testing, error correction from poor or erroneous data, logical naming of points and files, elimination of unsuitable test results, and selection of drops for analysis. Careful drop selection is advised, avoiding seating drops and those with abnormal deflection readings. It's recommended to include drops with various load levels and plate sizes for non-linearity and layer thickness calculation. The layer thickness in multi-layer systems should be preferably known from measurements or construction data; otherwise, it may be based on the best estimate. Seed values, the initial values in the iteration process, greatly influence results, so entering realistic values is essential. Results should be studied for quality evaluation, with attention to any drops with notably high root mean square (RMS) values. It's worth considering re-running the analysis without these drops. Comparing results with other information about the structure validates their reasonableness. Experimenting with input values for iterations in terms of width, steps, and alternate might improve results. Finally, when analyzing data, start by selecting a single point, adjusting settings in File Settings, entering pavement structure and seed values, and then conducting the analysis. Once satisfied with the single point analysis, similar input values and settings can be applied to calculate all points in the project. The calculated sub-grade modulus (EM) at the top of the sub-grade and surface deflection modulus (E_o) on the construction's top surface, along with deflection and RMS values, are obtained for each point. The finalized modulus values with the least RMS are considered the final results. The entire process is illustrated in Figure 1.

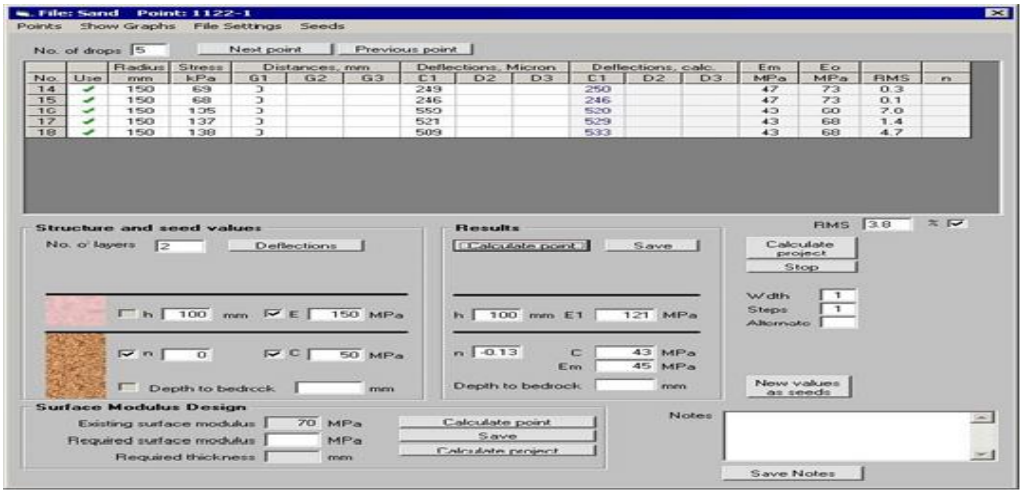

Figure 1 Single point calculation of modulus

4. SITE INTRODUCTION

In this study, a site encompassing four lanes in section Kutch, Gujarat state, along NH-15 road, was chosen for conducting LWD tests at 52 distressed locations, with test pits on both sides. The testing spanned from Chainage 198+000 to 245+000 km, covering an approximate distance of 48 km. During the site visit, several observations were made: the section predominantly traverses plain and marshy terrain, drainage conditions were found to be adequate, instances of rain-induced erosion were noted on the embankment beyond the paved shoulder, and a total of 52 test locations were identified as distressed, with 31 on the left-hand side (LHS) and 21 on the right-hand side (RHS). These trial pit locations were carefully selected to encompass both distressed and non-distressed portions. LWD testing was subsequently conducted on 31 test pits on the LHS (Chainage: 198+772 to 244+252) and 21 test pits on the RHS (Chainage: 218+670 to Chainage: 235+333). Measurements were taken at four layers: Bituminous Surface (BS), WMM, GSB, and Sub-grade, and corresponding points were assessed for field density using the Sand replacement method (WMM, GSB) and core cutter method (Sub-grade).

5. PAVEMENT INVESTIGATIONS

Sub-grade soil, GSB, and WMM investigations are crucial for assessing sub-grade strength and designing flexible pavements. The field studies aim to identify the strength, physical, and mechanical properties of these layers. The investigations are divided into field and laboratory categories. Field investigations are paramount for assessing in-situ pavement strength and material properties. These included trial pits, in-situ density and moisture content assessments, and LWD measurements. Trial pits were dug at 52 predefined locations, providing valuable information on pavement composition. For each pit, data on composition, layer thickness, and field densities were recorded. The LWD test, conducted in accordance with ASTM E2583-07 (2011) standards [21], was performed at 52 locations on distressed areas of NH-15. The generated impact force ranged from 7.0-9.0 KN. The stress distribution factor and Poisson’s Ratio were set as per IRC 37-2012[5]. At each point, field density was also determined using appropriate methods.

Sand replacement and core cutter tests were conducted for density measurements. These comprehensive investigations provided essential data for pavement assessment and design.

5.1. On-Site and Laboratory Assessments of In-Situ Density, Moisture Content, and California Bearing Ratio (CBR)

The in-situ density of the sub-grade, crucial for assessing compaction in the field, was evaluated using the sand replacement method in accordance with IS 2720-Part-28 standards [22]. Simultaneously, in-situ moisture content was also assessed along the project corridor section and vividly represented for detailed variation analysis. The sand replacement method was employed for the WMM and GSB layers, while the core cutter method was used for the Sub-grade. On average, for the LHS, the field dry density of WMM was 2.02 gm/cc, GSB was 1.80 gm/cc, and Sub-grade was 1.75 gm/cc (as detailed in Table: I). Meanwhile, for the RHS, the average field dry density of WMM was 1.87 gm/cc, GSB was 1.64 gm/cc, and Sub-grade was 1.74 gm/cc (detailed in Table: II). Moisture content for the LHS and RHS followed similar patterns, with average values of 9.61%, 14.06%, and 17.48% for WMM, GSB, and Sub-grade, respectively, on the LHS (as presented in Table: I), and 9.19%, 13.90%, and 23.09% on the RHS (as detailed in Table: II). The laboratory California Bearing Ratio (CBR) is assessed following the procedure outlined in IS 2720 (Part – 16), a crucial factor in pavement design. The variation in CBR values along the chainage is a key parameter for determining the required crust thickness. On average, the CBR at FDD is 6% on the LHS and 5.95% on the RHS. For detailed results, refer to Table: I & Table: II

SR. NO	LHS		WMM		GSB		Sub-grade		
			w	FDD	w	FDD	w	FDD	CBR at FDD
	Chainage		%	gm/cc	%	gm/cc	%	gm/cc	%
1	198+772	SL/OWP	13.00	2.01	30.00	1.75	11.00	1.70	5.80
2	200+000	SL/OWP	11.00	2.06	13.00	1.73	10.00	1.05	3.70
3	202+710	SL/OWP	9.00	2.06	12.00	1.91	25.00	1.76	6.00
4	203+160	SL/OWP	9.00	1.94	13.00	1.90	7.00	1.79	6.30
5	203+670	SL/IWP	9.00	2.08	12.00	2.12	13.00	1.79	6.20
6	204+180	SL/IWP	10.00	1.93	30.00	1.73	10.00	1.85	6.40
7	204+910	SL/OWP	9.00	2.17	12.00	1.92	13.00	1.71	6.00
8	205+565	SL/OWP	13.00	1.90	12.00	1.85	29.00	1.61	5.50
9	205+848	SL/IWP	9.00	1.97	13.00	1.84	22.00	1.78	6.10
10	214+725	SL/OWP	10.00	1.92	13.00	1.83	19.00	1.73	6.00
11	215+330	SL/IWP	11.00	2.04	12.00	1.84	20.00	1.76	6.10
12	215+480	SL/IWP	11.00	2.08	12.00	1.88	21.00	1.84	6.30
13	217+170	SL/IWP	5.00	2.07	10.00	1.83	30.00	1.50	5.10
14	229+910	SL/IWP	12.00	2.05	22.00	1.88	30.00	1.57	5.30
15	234+600	SL/IWP	11.00	2.07	17.00	2.00	12.00	1.90	6.55
16	235+655	SL/IWP	8.00	2.12	20.00	1.76	17.00	1.95	6.70
17	236+082	FL/OWP	10.00	2.08	12.00	1.80	14.00	1.85	6.30
18	236+505	FL/OWP	10.00	2.05	10.00	1.79	23.00	1.74	6.00
19	236+775	FL/IWP	10.00	2.02	13.00	1.95	24.00	1.62	5.60
20	239+825	SL/IWP	10.00	1.91	14.00	1.86	33.00	1.54	5.20
21	240+025	FL/OWP	9.00	2.03	17.00	1.74	17.00	1.77	6.10
22	240+400	SL/OWP	8.00	2.03	11.00	1.59	18.00	1.64	5.60
23	241+005	FL/IWP	11.00	1.99	9.00	1.63	16.00	1.79	6.10
24	241+103	FL/OWP	10.00	1.95	11.00	1.79	17.00	1.85	6.40
25	241+301	FL/OWP	8.00	2.11	11.00	1.72	9.00	1.97	6.80
26	241+520	FL/OWP	6.00	2.11	16.00	1.76	22.00	1.73	6.00
27	241+305	SL/IWP	8.00	1.99	10.00	1.85	10.00	1.93	6.70
28	242+615	SL/IWP	7.00	2.07	9.00	1.96	12.00	1.93	6.60
29	243+850	SL/OWP	10.00	1.90	12.00	1.74	11.00	1.83	6.30
30	243+910	FL/OWP	8.00	1.96	10.00	1.50	12.00	1.83	6.30
31	244+252	SL/OWP	13.00	1.84	18.00	1.42	15.00	1.97	7.00
Average			**9.61**	**2.02**	**14.06**	**1.80**	**17.48**	**1.75**	**6.00**

Table: I LHS: Chainage wise w(%) FDD gm/cc and CBR (%) of GSB Layer, WMM Layer and subgrade

SR. NO	RHS		WMM		GSB		Sub-grade		
			w	FDD	w	FDD	w	FDD	CBR at FDD
	Chainage		%	gm/cc	%	gm/cc	%	gm/cc	%
32	218+670	SL/IWP	9.00	1.84	12.00	1.62	11.00	1.89	6.50
33	219+975	FL/ON CRACK	9.00	1.73	12.00	1.54	24.00	1.79	6.20
34	221+575	SL/OWP	9.00	1.74	13.00	1.16	25.00	1.77	6.00
35	222+310	SL/OWP	6.00	1.84	10.00	1.66	20.00	1.95	6.80
36	223+400	SIDE SH	7.00	1.73	10.00	1.66	20.00	1.76	6.00
37	223+520	SL/OWP	9.00	1.78	18.00	1.70	26.00	1.71	5.80
38	224+305	FL/OWP	7.00	1.85	14.00	1.78	27.00	1.69	5.50
39	224+870	SL/OWP	9.00	1.90	14.00	1.55	45.00	1.40	4.80
40	225+950	FL/CENTRE	9.00	1.87	12.00	1.76	21.00	1.83	6.20
41	226+528	CENTRE/	10.00	1.93	15.00	1.72	14.00	1.77	6.10
42	227+600	SL/CENTRE	9.00	1.89	12.00	1.64	17.00	1.85	6.40
43	227+760	SL/OWP	10.00	1.91	12.00	1.55	15.00	1.91	6.50
44	228+402	SL/OWP	13.00	1.77	17.00	1.49	15.00	1.88	6.40
45	228+620	FL/IWP	8.00	2.03	11.00	1.78	33.00	1.61	5.50
46	229+728	SL/OWP	9.00	1.95	21.00	1.39	45.00	1.48	5.00
47	231+848	FL/OWP	10.00	1.90	19.00	1.77	21.00	1.78	6.00
48	232+330	SL/IWP	7.00	1.86	9.00	1.74	28.00	1.64	5.60
49	232+553	SL/CENTRE	8.00	1.92	16.00	1.75	38.00	1.52	5.00
50	234+320	SL/IWP	9.00	1.91	13.00	1.83	13.00	1.78	6.20
51	235+240	SL/CENTRE	11.00	1.98	11.00	1.69	25.00	1.73	6.00
52	235+333	SL/CENTRE	15.00	1.98	21.00	1.61	13.00	1.88	6.50
Average			9.19	**1.87**	13.09	**1.64**	23.09	**1.74**	**5.95**

Table: II RHS: Chainage wise w(%) FDD gm/cc and CBR (%) of GSB Layer, WMM Layer and subgrade .

5.2. RESULTS AND LWD: DATA ANALYSIS

The data analysis was conducted using the LWDmod back calculation program developed by Dynatest, specifically designed for LWD analysis. Seed values and structural information for both the left-hand side (LHS) and right-hand side (RHS) were configured based on raw data obtained from the LWD tests, along with thickness data from trial pits. Poisson ratios were set in accordance with IRC 37-2012 and LWDmod program guidelines, while 'n' was assigned a value of 0 to assume sub-grade material linearity.

The results for LHS and RHS of various layers (BS, WMM, GSB, and sub-grade) were obtained using LWDmod, and outliers were removed for increased reliability. Outliers were identified based on the time histories of deflection and load. Notably, irregular pulse shapes were observed, indicating that the deflection-time pulse did not return to its initial level, suggesting poor contact between the loading plate and material layer. These points were excluded for more dependable results.

Despite the study focusing on distressed locations, it was observed that some test points exhibited significantly higher strength compared to others, indicating a variation in distress severity. Therefore, these points were also considered as outliers to ensure accuracy in the analysis. For instance, on the RHS, the WMM test point at Chainage 228+620 displayed a surface modulus of 253 MPa and a field dry density of 2.03 gm/cc, significantly higher than the average surface modulus of 119.81 MPa and field dry density of 1.87 gm/cc.

5.2.1. Surface Modulus (E_o) and Sub-grade Modulus (E_m) Results Utilizing Bituminous Surface Layer Input in LWDmod Software

On the left-hand side (LHS), the average surface modulus (E_o) for the Bituminous Surface layer was initially observed at 635.38 MPa with a coefficient of variation (COV) of 66.78, while the sub-grade modulus (E_m) was 335.13 MPa with a COV of 146.81. After removing outliers (Chainage points: 203+670, 204+910, 240+025, and 242+305), E_o decreased to 499.08 MPa with a COV of 30.61, and E_m decreased to 170.88 MPa with a COV of 40.35, The corresponding results for the right-hand side (RHS) showed similar trends. On the RHS, the average E_o for the Bituminous Surface layer was initially 587.62 MPa with a COV of 36.09, and the E_m was 227.86 MPa with a COV of 53.02. After removing outliers (Chainage points: 227+760, 218+670, and 232+320), E_o reduced to 519.11 MPa with a COV of 24.90, and E_m decreased to 187.39 MPa with a COV of 33.47, The corresponding results for the Bituminous Surface layer on both sides are presented in Tables III & IV.

5.2.2. Surface Modulus (E_o) and Sub-grade Modulus (E_m) Results Utilizing GSB Layer Input in LWDmod Software

On the left-hand side (LHS), the GSB layer exhibits an average Surface Modulus (E_o) of 117.74 MPa with a coefficient of variation (COV) of 48.06, and a Sub-grade Modulus (E_m) of 98.84 MPa with a COV of 75.03. After excluding outlier points at chainages 242+305 and 243+850, the adjusted E_o becomes 107.10 MPa with a COV of 36.08, and E_m is 82.93 MPa with a COV of 44.20. The LWDmods outcomes for the GSB layer on the left-hand side are detailed in Table -III. On the right-hand side (RHS), the GSB layer demonstrates an average E_o of 98.25 MPa with a COV of 40.69, while E_m measures 84 MPa with a COV of 50.34. Following the removal of outlier points at chainages 223+400, 225+950, and 228+260, the adjusted E_o is 96.86 MPa with a COV of 43.30, and E_m is 76.5 MPa with a COV of 48.9, The LWDmods results for the GSB layer on the right-hand side can be found in Table-IV.

5.2.3. Surface Modulus (E_o) and Sub-grade Modulus (E_m) Results Utilizing WMM Layer Input in LWDmod Software

On the left-hand side (LHS), the WMM layer demonstrates an average Surface Modulus (E_o) of 148.52 MPa with a coefficient of variation (COV) of 60.28, and a Sub-grade Modulus (E_m) of 114.42 MPa with a COV of 81.36. After identifying outlier points at chainages 236+082, 242+305, and 243+850, the adjusted E_o becomes 122.41 MPa with a COV of 45.80, while E_m is 85 MPa with a COV of 45.78, The LWDmods results for the WMM layer on the left-hand side are detailed in Table-III. On the right-hand side (RHS), the WMM layer shows an average E_o of 119.81 MPa with a COV of 39.93, and E_m is 102 MPa with a COV of 49.83. After isolating the outlier point at chainage 228+620, the adjusted E_o becomes 113.15 MPa with a COV of 33.41, and E_m is 93.1 MPa with a COV of 33.42, The LWDmods outcomes for the WMM layer on the right-hand side can be found in Table-IV.

5.2.4. Surface Modulus (E_o) and Sub-grade Modulus (E_m) Results Utilizing Subgrade Input in LWDmod Software

On the left-hand side (LHS), the Sub-grade layer exhibits an average Surface Modulus (E_o) of 117.14 MPa with a coefficient of variation (COV) of 69.39, while the Sub-grade Modulus (E_m) is 99.52 MPa with a COV of 58.03. After identifying chainage point 235+655 as an outlier and excluding it from the analysis, the adjusted E_o becomes 105.89 MPa with a COV of 52.14, and E_m is 92.36 MPa with a COV of 47.40, The LWDmods results for the Sub-grade layer on the left-hand side are detailed in Table -III. On the right-hand side (RHS), the Sub-grade layer shows an average E_o of 102.90 MPa with a COV of 39.58, and E_m is 90.33 MPa with a COV of 39.40, which falls within an acceptable range. The LWDmods outcomes for the Sub-grade layer on the right-hand side are presented in Table -IV.

Sr.No	LHS		Utilizing Bituminous Surface		Utilizing GSB		Utilizing WMM		Utilizing Subgrade	
			Em	Eo	Em	Eo	Em	Eo	Em	Eo
	Chainage	Location	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
1	198+772	SL/OWP	193	486	12	33	57	109	52	55
2	200+000	SL/OWP	209	380	96	131	88	146	106	111
3	202+710	SL/OWP	189	524	80	90	62	111	89	89
4	203+160	SL/OWP	94	371	111	89	66	112	68	70
5	203+670	SL/IWP	***1139***	***1761***	53	170	423	434	98	144
6	204+180	SL/IWP	312	632	38	52	106	246	102	112
7	204+910	SL/OWP	***755***	***1177***	67	87	122	250	213	269
8	205+565	SL/OWP	134	473	57	92	81	103	61	67
9	205+848	SL/IWP	204	531	62	115	65	140	158	167
10	214+725	SL/OWP	183	622	111	145	56	89	18	21
11	215+330	SL/IWP	149	600	146	180	149	188	111	122
12	215+480	SL/IWP	119	394	90	118	130	192	125	198
13	217+170	SL/IWP	81	259	50	85	142	177	30	30
14	229+910	SL/IWP	60	223	72	98	105	122	69	75
15	234+600	SL/IWP	113	430	147	136	95	108		
16	235+655	SL/IWP	227	754	23	32	47	81	***300***	***432***
17	236+082	FL/OWP	206	740	88	123	**392**	**284**	78	134
18	236+505	FL/OWP	124	620	123	129	159	168	65	71
19	236+775	FL/IWP	163	450	138	127	16	21	65	75
20	239+825	SL/IWP	145	411	63	111	57	70	109	118
21	240+025	FL/OWP	***1252***	***942***	87	118	23	50	59	61
22	240+400	SL/OWP	186	560	32	37	103	109	50	50
23	241+005	FL/IWP	192	520	78	75	138	165	89	92
24	241+103	FL/OWP	221	552	118	146	29	40	96	106
25	241+301	FL/OWP	119	362	56	65	71	86	83	84
26	241+520	FL/OWP	98	283	74	108	95	94	50	50
27	242+305	SL	***2465***	***2219***	***412***	***313***	***178***	***282***		
28	242+615	SL/IWP	286	639	133	128	53	78	146	146
29	243+850	SL/OWP			***247***	***231***	***259***	***299***	181	181
30	243+910	FL/OWP	330	809	120	146	110	131	107	159
31	244+252	SL/OWP	106	351	80	140	70	119	108	108
	Average		**335.13**	**635.83**	**98.84**	**117.74**	**114.42**	**148.52**	**99.52**	**117.14**
	S.D		**492.00**	**424.62**	**74.16**	**56.58**	**93.09**	**89.52**	**57.75**	**81.28**
	COV		**146.81**	**66.78**	**75.03**	**48.06**	**81.36**	**60.28**	**58.03**	**69.39**
*** Result after removing outliers**										
	Average		**170.88**	**499.08**	**82.93**	**107.10**	**85.00**	**122.41**	**92.36**	**105.89**
	S.D		**68.96**	**152.78**	**36.65**	**38.64**	**38.91**	**56.06**	**43.78**	**55.21**
	COV		**40.35**	**30.61**	**44.20**	**36.08**	**45.78**	**45.80**	**47.40**	**52.14**

Table: III LHS: Chainage wise E_m & E_0 Utilizing Bituminous Surface, GSB, WMM & Subgrade inputs in LWDmod Software

Sr.No	RHS		Utilizing Bituminous Surface		Utilizing GSB		Utilizing WMM		Utilizing Subgrade	
			Em	Eo	Em	Eo	Em	Eo	Em	Eo
	Chainage	Location	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
32	218+670	SL/IWP	***482***	***744***			91	118	64	120
33	219+975	FL/ON CRACK	76	375	57	107	119	88	50	52
34	221+575	SL/OWP	218	466	18	38	80	128	70	88
35	222+310	SL/OWP	101	472	72	73	59	72	107	150
36	223+400	SIDE SH	318	430	*157*	*105*	112	91	98	101
37	223+520	SL/OWP	230	589	60	101	50	69	110	121
38	224+305	FL/OWP	192	546	31	75	78	110	77	78
39	224+870	SL/OWP	126	280	59	73	111	137	38	39
40	225+950	FL/CENTRE	162	389	*146*	*122*	81	111	95	103
41	226+528	CENTRE	160	480	85	94	37	50	69	69
42	227+600	SL/CENTRE	174	488	44	62	94	87	90	90
43	227+760	SL/OWP	***561***	***823***	38	60	116	138	148	166
44	228+402	SL/OWP	219	539	91	121	57	150	104	137
45	228+620	FL/IWP	216	760	***118***	***174***	***280***	***253***	86	129
46	229+728	SL/OWP	257	807	84	119	142	160	78	87
47	231+848	FL/OWP	148	471	114	100	63	93	57	57
48	232+330	SL/IWP	***369***	***1240***	56	48	122	157	41	41
49	232+553	SL/CENTRE	184	616	124	98	138	97	66	69
50	234+320	SL/IWP	291	638	154	185	140	208	151	166
51	235+240	SL/CENTRE	142	492	121	153	91	119	142	142
52	235+333	SL/CENTRE	159	506	51	57	81	80	156	156
	Average		**227.86**	**578.62**	**84.00**	**98.25**	**102.00**	**119.81**	**90.33**	**102.90**
	S.D		**120.80**	**208.84**	**42.29**	**39.98**	**50.82**	**47.84**	**35.59**	**40.72**
	COV		**53.02**	**36.09**	**50.34**	**40.69**	**49.83**	**39.93**	**39.40**	**39.58**
*** Result after removing outliers**										
	Average		**187.39**	**519.11**	**76.50**	**96.56**	**93.10**	**113.15**		
	S.D		**62.72**	**129.25**	**37.41**	**41.81**	**31.11**	**37.80**		
	COV		**33.47**	**24.90**	**48.90**	**43.30**	**33.42**	**33.41**		

Table: IV RHS: Chainage wise E_m & E_0 Utilizing Bituminous Surface, GSB, WMM & Subgrade inputs in LWDmod Software

5.3. Comparison Between Measured (LWD Test) and Back-Calculated Modulus

The comparison between actual modulus values obtained from the LWD test and the back-calculated modulus obtained from the LWDmod software reveals some variation. The LWD tests were conducted on various layers including BS, WMM, GSB, and Sub-grade, with different layer conditions and seed values used as inputs in the LWDmod software. This led to diverse modulus values based on the specific layer conditions. Specifically:

-A- For Sub-grade, there are four modulus values; one from the LWD test on Sub-grade considered as the actual modulus, and three back-calculated Sub-grade moduli. The first is based on GSB, the second on WMM, and the third on BS.

- B- For GSB, three modulus values exist; one from the LWD test on GSB considered as the actual modulus, and two back-calculated GSB moduli. The first is based on WMM, and the second on BS.

- C- For WMM, there are two modulus values; one from the LWD test on WMM considered as the actual modulus, and one back-calculated GSB modulus based on BS.

Hence, the selection of which modulus values to use for further work is of significant importance. The left-hand side (LHS) and right-hand side (RHS) chainage-wise comparisons of actual modulus with LWDmod software back-calculated modulus are described in the section below.

A-SUB-GRADE

For the left-hand side (LHS), the average Sub-grade Modulus based on the LWD test is 94.61 MPa with a coefficient of variation (COV) of 46.67. Comparatively, using the LWDmod software for back calculation, the values are (A) 84.35 MPa with a COV of 42.81 based on GSB, (B) 87.30 MPa with a COV of 44.02 based on WMM, and (C) 169.43 MPa with a COV of 41.94 based on BS. Similarly, for the right-hand side (RHS), the average Sub-grade Modulus from the LWD test is 100.07 MPa with a COV of 41.60. Using the LWDmod software, the back-calculated values are (A) 77.69 MPa with a COV of 48.84 based on GSB, (B) 89.33 MPa with a COV of 38.21 based on WMM, and (C) 178.47 MPa with a COV of 32.52 based on BS.

B-GSB

For the left-hand side (LHS), the average GSB Modulus based on the LWD test is 104.32 MPa with a coefficient of variation (COV) of 37.58. When using the LWDmod software for back calculation, the values are (A) 115.44 MPa with a COV of 47.64 based on WMM, and (B) 244.96 MPa with a COV of 30.95 based on BS. Similarly, for the right-hand side (RHS), the average GSB Modulus from the LWD test is 97.07 MPa with a COV of 38.96. Using the LWDmod software, the back-calculated values are (A) 111.53 MPa with a COV of 42.97 based on WMM, and (B) 223.93 MPa with a COV of 19.52 based on BS.

C-WMM

For the left-hand side (LHS), the average WMM Modulus based on the LWD test is 121.83 MPa with a coefficient of variation (COV) of 41.38. Using the LWDmod software for back calculation based on BS, the value is 240.29 MPa with a COV of 30.67, Similarly, for the right-hand side (RHS), the average WMM Modulus from the LWD test is 116.83 MPa with a COV of 43.50. Utilizing the LWDmod software for back calculation based on BS, the value is 218.28 MPa with a COV of 21.47.

Table-V presents a comparison between sub-grade modulus (E_m) obtained from LWD tests on sub-grade and back-calculated modulus values from different layers, along with finalized averaged sub-grade modulus and their coefficients of variation (COV). The surface modulus (E**o**) and IRC recommended MR values are also included. It is evident that the sub-grade modulus obtained from the BS layer is significantly higher compared to the other layers, leading to its exclusion from further consideration. The remaining layers exhibit E_m values ranging from 80 to 90 MPa with COVs ranging from 33 to 47. The surface and sub-grade modulus values for individual layers are notably lower than the IRC 37-2012 recommended values. To address this, the 90th percentile modulus values are introduced in Table-VI for more accurate results. A sub-grade modulus of 51 MPa (E_m) is selected for further analysis.

It is noteworthy that both surface and sub-grade modulus values for individual layers remain considerably lower than the IRC 37-2012 recommended modulus values.

MODULUS (MPa)	**SURFACE MODULUS (E_o)**				**IRC RECOMMENDED VALUE**	**SUB-GRADE MODULUS (E_m)**			
	LHS	**COV**	**RHS**	**COV**		**LHS**	**COV**	**RHS**	**COV**
BS	500	*30.61*	519	*24.9*	**1700 or 3000***	170.88	*40.35*	187.39	*33.47*
WMM	122	*45.8*	113	*33.41*	**450**	85	*45.78*	93.1	*33.42*
GSB	107	*36.08*	96	*43.3*	**300**	82.93	*181.7067*	**201.5217**	221.33667
Sub-grade	105	*52.14*	102	*39.58*		92.36	*145.14*		197.92
*** At 35^{0}C 1700 for VG30 and 3000 for VG40.**									

Table: V Averaged Modulus with IRC Recommended values

MODULUS (MPA)	SURFACE MODULUS (Eo)		IRC RECOMMENDED VALUE	SUB-GRADE MODULUS (Em)	
	LHS	**RHS**		**LHS**	**RHS**
BS	320	382	**1700 or 3000***	98	120
WMM	68	72	**450**	42	56
GSB	52	56	**300**	38	36
Sub-grade	50	52		51	51
* At 35^0C 1700 for VG30 and 3000 for VG40.					

Table: VI 90^{th} Percentile Modulus with IRC Recommended Values

5.4. Comparison of Sub-grade Modulus with CBR-derived Sub-grade Modulus.

Comparison between sub-grade moduli obtained from LWD and CBR values, following the IRC 37-2012 guidelines. Chainage-wise, on the left-hand side (LHS), the average sub-grade modulus from CBR is 57.7 MPa with a coefficient of variation (COV) of 8.52, while the sub-grade modulus obtained from LWD is 78.67 MPa with a COV of 35.22, Similarly, on the right-hand side (RHS), the average sub-grade modulus from CBR is 55.07 MPa with a COV of 5.94, whereas the sub-grade modulus obtained from LWD is 90.33 MPa with a COV of 39.40.

6. DISCUSSION AND CONCLUSION

In this study, a site in the Kutch region of Gujarat was carefully selected for investigation. Site visits were conducted, and 52 distressed locations were identified. One-meter by one-meter trial pits were excavated, and a series of tests was performed. The LWD test was applied to the bituminous surface, WMM, GSB, and sub-grade layers. Concurrently, field densities were measured at the same locations, and samples were collected for CBR testing, yielding CBR values ranging from 5% to 6%.

The LWDmod software was employed for back-calculation. The results revealed that the average back-calculated surface modulus on both the left-hand side (LHS) and right-hand side (RHS) for the bitumen surface fell within the range of 500 MPa to 520 MPa, with coefficients of variation (COV) ranging from 24% to 30%. For the WMM layer, the range was 110 MPa to 125 MPa with COVs from 33% to 45%. Similarly, the GSB layer exhibited a range of 95 MPa to 110 MPa with COVs of 35% to 45%, and for the sub-grade, the range was 100 MPa to 105 MPa with COVs from 40% to 52%.

Furthermore, it was observed that the back-calculated surface modulus for the bituminous surface was notably higher compared to the other layers. Subsequently, the surface modulus for other layers decreased; WMM had higher values compared to GSB and sub-grade but was lower than the bituminous surface. GSB showed higher values compared to sub-grade but lower than WMM and bituminous surface, which held true for sub-grade as well. Additionally, it was noted that COV was higher for softer materials like the sub-grade, and decreased for granular layers and the bituminous surface.

Interestingly, the observed back-calculated surface modulus values were considerably lower compared to the modulus values prescribed in IRC 37-2012. Moreover, the back-calculated sub-grade modulus obtained from the bituminous surface layer ranged from 170 MPa to 95 MPa. Therefore, for the bituminous surface, the back-calculated sub-grade modulus was higher compared to the other layers, whereas for other layers, it ranged from 76 MPa to 95 MPa. The WMM and GSB layers exhibited lower variations.

It was noted that the depth of influence of the LWD, which used a 300 mm plate diameter in this study, typically ranged from 450 mm to 600 mm. However, the existing pavement composition thickness was notably greater, ranging from 740 mm to 770 mm. This resulted in higher variation for the sub-grade modulus obtained from the bituminous surface.

LWD has emerged as an indispensable tool for assessing the in-situ strength of pavement materials [23],[24],[25] & [26]. It showcases impressive efficiency, requiring a mere 5 to 10 minutes for operation and data recording per point. While demanding a skilled workforce, its sensitivity means that the workforce can be kept to a minimum. This method substantially reduces inspection time, costs, and minimizes exposure of inspection personnel to traffic, distinguishing itself from Nuclear Density Gauges (NDGs) which require safety training or certification [27]. The incorporation of a sand pad made from uniformly grained sand enhances surface contact, resulting in improved measurement accuracy. Overall, this tool presents a swift and highly recommended means of evaluating the in-situ strength of pavement materials, making it an excellent choice for road maintenance and rehabilitation projects.

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