International Research Journal of Engineering and Technology (IRJET) **e-ISSN: 2395-0056**
Volume: 10 Issue: 10 | Oct 2023 **www.irjet.net** **p-ISSN: 2395-0072**

Assessment of Flexible Pavement Using the Falling Weight Deflectometer: A Comprehensive Review

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Abstract - Rapid development of road networks have become a global trend, particularly in India. Over the past couple of decades, it has been observed that numerous highways are undergoing a phase of deterioration. Identifying the reasons for this deterioration necessitates a pavement evaluation study. Many performance studies have been conducted, focusing on flexible pavements. The widely accepted Falling Weight Deflectometer (FWD) is utilized as a non-destructive test (NDT) and considered a standard for structural assessment.

The primary objective of this study is to review the FWD instrument and explore empirically derived methods, along with a back-calculation process for computing layer moduli and understanding the factors influencing them. Additionally, the crucial need for correction factors to obtain reliable layer moduli is discussed. Furthermore, the study delves into the advancements in low-cost indigenous FWD models.

Key Words: *Falling weight deflectometre (FWD), Back calculation process, Correction factor, Surface deflection.*

Nomenclature:

E_S = *Subgrade Modulus.*
P = *Applied Load.*
μ= *Poisson Ratio.*
a= *Plate Rigidity Factor.*
E_{BASE} = *Modulus of Base Layer.*
E_{AC} = *Modulus of Bituminous Layer.*
r, dr, D_3, D_{72}, d_2, d, W_7, D_1, D_2, D_4. D_5, D_7 = *Measured Deflection at corresponding radial distances.*
$D_X/12$, $D_X/36$, $D_X/60$, $D_X/200$ = *Measured Deflection at corresponding radial distance in lateral Direction.*
$D_y/0$, $D_y/305$, $D_X/36$ = *Measured Deflection at corresponding radial distance in longitudinal direction.*
E_{T1}, E_{T2} = *Modulus @ Temp.* T_1 *and* T_2.
D_{68}, E_{68} = *Deflection and Modulus @ Temp. 68* F^0
D_T, E_T = *Deflection and Modulus @ Temp. T.*
E_{TC}, E_{TW} = *Modulus @ Temp.* T_C *and* T_W.
E_{To}, E_T = *Modulus @ Temp.* T_o *and T.*
λ_E, α = *Correction Factor for Temp.*
E_{gran_Mon} = *Modulus for Granular layer in Monsoon.*
E_{gran_Sum} = *Modulus for Granular layer in Summer.*
E_{gran_Win} = *Modulus for Granular layer in Winter.*
E_{sub_Mon} = *Modulus for Subgrade layer in Monsoon.*
E_{sub_Sum} = *Modulus for Subgrade layer in Summer.*
E_{sub_Win} = *Modulus for Subgrade layer in Winter.*

1. INTRODUCTION

Rapid road infrastructure development has become a global trend, particularly in India. Over the past few decades, it has become evident that many road projects require maintenance at an early stage. To identify the causes of this, a structural evaluation study is essential to assess the properties of the existing pavement layers. Numerous performance studies have been conducted, primarily focusing on flexible pavements, utilizing widely accepted non-destructive testing (NDT) methods.

In NDT, in-situ tests are carried out on in-service pavements without disturbing or breaking the pavement layers. NDT tools for evaluating the material layer properties of in-service pavements are extensively used worldwide. Two approaches, the wave propagation technique and the deflection-based approach, have gained popularity in pavement engineering. In wave propagation techniques, a vibration source is placed on the pavement's surface, and the velocities and wavelengths of surface waves emitted from the vibration source and transmitted through pavement layers are measured. This approach requires highly advanced computer programming for reliable results interpretation and is not widely used.

Since the early 1970s, the surface deflection approach has been extensively used to assess pavement materials due to its reliability, speed of operation, and ease of use. Surface deflection represents the overall response (in terms of deflections) of the full depth of pavements under predefined standard loads. Surface deflection is measured using non-destructive deflection tests, and back-calculation analysis is performed to determine the structural properties of distinct layers or estimate the modulus values of these layers. These computed modulus values are further used for pavement analysis, estimating remaining pavement life, and conducting overlay requirement analysis.

Structural evaluation studies employ various tools such as the Benkelman beam deflection (BBD), lightweight deflectometer (LWD), and Falling Weight Deflectometer (FWD). Among these, FWD is extensively utilized and considered a benchmark test for pavement evaluation because it closely simulates the loading conditions of actual moving loads. The FWD has been used for pavement assessment for numerous years, including on unbound asphalt layers. It is a trusted apparatus and is regarded by many researchers as a standard in comparison to other NDT methods. [31][32][33].

The primary objective of this study is to review the FWD instrument and study empirically derived methods, as well as the back-calculation process for computing layer moduli and the factors that influence them. Additionally, the study discusses the essential need for correction factors to obtain reliable layer moduli and investigates the advancement of low-cost indigenous FWD models.

The FWD test involves allowing mass to fall from a predefined height onto the pavement surface, and surface deflections or deflection basins are measured using velocity transducers (geophones) or deflection sensors equipped with the FWD. It is observed that the amplitude of deflection at distinct radial points occurs at different time moments, which do not closely simulate the actual transient deflection conditions of moving wheel loads. Therefore, measured deflections are further evaluated through back-calculation analysis. Moreover, a detailed explanation of the operating principle and deflection basin is discussed in subsequent sections.

2. COMMERCIALLY AVAILABLE FWDS

In this section, various types of commercially available FWDs are briefly discussed. An international overview of FWDs is presented in Table 1, but it is not discussed in this study. Instead, only indigenous FWDs are the focus of discussion.

Table 1 International overview of FWD

Manufacturer Model	Peak load (KN)	Weight and height of falling mass	Load durations (ms)	Deflections Sensors	Loading plate diameter (mm)	Remarks
Dynatest Model 8000	7 to 120	50 to 300 kg 20 to 380 mm	25 to 30	7 velocity transducers Spacing 2.25 mm apart	300	Denmark and UK
Dynatest Model 8081	30 to 240	--	25 to 30	7 velocity transducers Spacing 2.25 mm apart	--	
Phonix FWD Model ML-10000	10.2 to 102.3	30 to 150kg 50 to 400 mm	--	6 velocity transducers Spacing 2.4 mm apart	--	Europe and US
KUAB 2M- FWD Model 8333	14 to 150	--	--	5 velocity transducers	300 and 450	(Sweden) 2 – Mass system. a falling weight dropped on second buffer weight
KUAB 2M- FWD Model 8714	7 to 65	--	--	5 velocity transducers	300 d 450	

2.1 IITKGP FWD MODEL -I

The first Indian FWD model, developed by the Transportation Engineering section of the Department of Civil Engineering at the Indian Institute of Technology, Kharagpur, India, is discussed in this section [5]. This model is trailer-mounted and towed with the assistance of a jeep. It has loading capabilities ranging from 20 kN to 65 kN, with a loading time between 20-30 milliseconds. A rubber pad is used as a buffer (spring) system to achieve the desired load duration, which closely simulates a moving vehicle speed of 50-60 kmph. Surface deflections can be measured at offset distances of 300 mm apart up to 1500 mm distance using six geophones. A string and pulley arrangement is employed for raising and lowering the weight, while a clamp arrangement supports the stack at any desired height. A single load cell and six geophones are used to measure the magnitudes of load and deflections, respectively. The load and deflection readings are recorded on a computer with the aid of a data acquisition system.

Numerous field investigations were conducted using this equipment, demonstrating good repeatability of deflections [5]. This low-cost equipment proves to be quite suitable for developing countries like India. However, it does have some drawbacks, such as the need for laborious operations like pulling a chain for lifting the mass, placing the geophones on the pavement surface, and releasing the mass. Additionally, tests are performed manually, which takes more time. Furthermore, maneuvering the equipment on in-service highways in India was found to be challenging and awkward.

To address these mentioned drawbacks of the IITKGP Model-I, a second model was developed in 2001 by IIT, Kharagpur, India, with sponsorship from MORT&H.

2.2 IITKGP FWD MODEL –II

The IITKGP FWD Model –II is a fully automated, vehicle-mounted instrument. All processes are computerized, and surface deflection data is collected through a data acquisition system. An additional geophone has been incorporated to enhance the accuracy of surface deflection measurements. The instrument provides an impulse loading range from 20 kN to 100 kN, achieved by adjusting the dropping mass and heights which range from 100 kg to 225 kg and 100 mm to 600 mm respectively on a 300 mm loading plate diameter. This configuration ensures a uniform distribution of stresses on the pavement. With the assistance of seven geophones, surface deflections are measured, and the observed load duration typically varies from 20 to 30 milliseconds.

2.3 GEOTRAN FWD

The GEOTRAN FWD is a fully automated, vehicle-mounted instrument designed for measuring surface deflection. It requires only one operator to handle all its functions. All operations are overseen from a PC or laptop through the DS4000S data acquisition system. This system is highly precise and operates at high speeds, capturing essential data from the geophone, load cell, and temperature sensors. The GEOTRAN FWD is capable of generating impulse loads of up to 100 kN on existing pavement by dropping a weight from a predetermined height. It then assesses surface deflections using its seven built-in geophones. Additionally, it features two temperature sensors for measuring air and road surface temperatures. The loading plate boasts a diameter of 300 mm and is reinforced with a rubber plate for added durability.

3. PRINCIPLE OF OPERATION FOR FALLING WEIGHT DEFLECTOMETERS (FWDS)

The operational principle is consistent across all FWD models. A mass is released from a pre-determined height, creating an impulse load on the pavement surface. This load is transmitted through a buffer system composed of springs with a minimum thickness of 5 mm, mimicking the load duration of actual moving traffic. Deflection sensors, as illustrated in Figure 1, capture the corresponding peak load and vertical surface deflections at various radial positions (DO, D1, etc.). This data is then recorded in the data acquisition system.

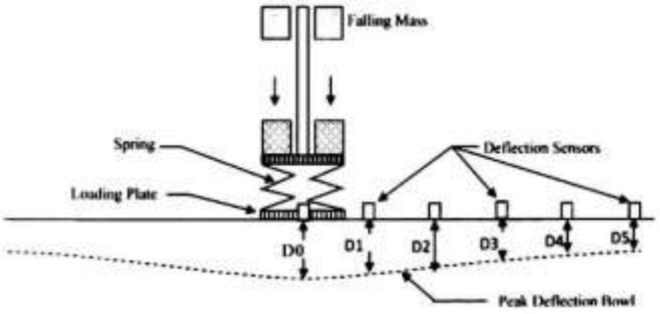

Figure 1 Working Principle of Falling Weight Deflectometer with deflection bowl

3.1 DEFLECTION BASIN ANALYSIS

The reliability and effectiveness of Falling Weight Deflectometers (FWDs) hinge on their ability to closely simulate actual loading conditions. This encompasses factors like traffic loads and stresses induced by environmental and weather conditions. When a moving wheel load traverses the pavement, it creates load pulses. These pulses result in both vertical and horizontal normal stresses at a specific location on the pavement, with their magnitude increasing from zero to a peak value as the wheel load approaches that location. The duration taken for the stress pulse to transition from zero to peak value is termed the 'rise time of the pulse'. As the wheel moves away from the location, the stress magnitude decreases from its peak value back to zero. The period over which the stress pulse transitions from 'zero-to-peak-to-zero' is known as the pulse duration.

The size and shape of the deflection basin enable a thorough structural assessment of the pavement. Essentially, the outer deflections reveal the modulus characteristics of the sub-grade, while the basin near the loading plate allows for an examination of the modulus characteristics of the adjacent surface layers. A broad basin with minimal curvature indicates that the upper layers of the pavement are more rigid than the sub-grade. Conversely, a basin with an equal peak deflection but higher curvature near the loading plate suggests that the upper layers are weaker than the sub-grade.

4. ESTIMATION OF LAYER MODULUS

Obtaining a dependable estimation of individual layer modulus from the deflections measured during the FWD test is a intricate process. Researchers have made efforts to determine layer modulus by considering the size and shape of radial offset deflections, leading to the development of empirical relations. Additionally, this section provides a review of the pavement theories based on the back-calculation procedure.

4.1 EMPIRICAL MODELS

In this section, we present previous attempts by researchers to estimate layer modulus from measured surface deflections using non-destructive testing (NDT) techniques. A brief review of these efforts is provided below:

AASHTO (1993) [6] recommends *equation 1* for back-calculating subgrade resilient modulus based on a deflection measurement taken from the center of the load. It further suggests that the minimum sensor distance (r) should be estimated based on the radius (ae) of the stress bulb at the subgrade-pavement interface, ensuring that r is equal to or greater than ae. The equation is as follows:

$$\mathbf{E_S \text{ (psi)} = 0.24\, P/\, (dr * r)} \qquad \ldots\ldots\ldots\ldots 1$$

Garg and Thompson (1998) proposed regression *equations 2-3* for estimating the subgrade modulus from FWD tests using pavement deflection. These equations are based on measurements taken at 1097 mm radial distance from the center of the loading plate [7].

For AC pavements:

$$\mathbf{Log\ E_S = 1.51\text{-}0.19\, D_3 + 0.27 \log (D_3)} \qquad \ldots\ldots\ldots\ldots\ldots 2$$

For full-depth AC pavements:

$$\mathbf{Log\ E_S = 24.7\text{-}5.41\, D_3 + 0.31\, (D_3)^2} \qquad \ldots\ldots\ldots\ldots 3$$

Choubane and McNamara (2000) proposed *equation 4* for predicting embankment subgrade modulus from FWD-measured deflection at a radial distance of 1097 mm [8].

$$\mathbf{E_S = 0.03764\, (P/dr)^{0.898}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

Alexander et al. (1989) proposed *equation 5* for subgrade modulus based on the deflection (mils) measured at a radial distance of 1830 mm (D72) from the center of the loading plate for an applied load of 111206 N [9].

$$\mathbf{Es \text{ (psi)} = 59304.82\, (D_{72})^{-098737}} \qquad \ldots\ldots\ldots\ldots 5$$

Roque et al. (1998) derived *equation 6* for the appraisal of subgrade modulus based on the deflections measured at 60 inches radial distance from the middle of the dual plates using a dual load [10].

$$\mathbf{E_S \text{ (ksi)} = 36.334 (D_X /60)^{-1.015}} \qquad \ldots\ldots\ldots\ldots 6$$

Molenaar and Van Gurp (1982) developed *equation 7* to predict subgrade soil modulus from the FWD deflections (in meters) measured at a radial distance of 2000 mm [11].

$$\mathbf{E_S \text{ (MPa)} = 6.614 * 10^{-3} * d_2^{-1.00915}} \qquad \ldots\ldots\ldots\ldots 7$$

Subgrade modulus can also be determined by Harr (1966) from the average deflection value measured during the third, fourth, and fifth drops of the load in a portable falling weight deflectometer (PFWD) using *equation 8*. [12]

$$\mathbf{E_s \text{ (MPa)} = 2\, P\, A\, (1\text{-}\mu^2)\, r\, a/\, d} \qquad \ldots\ldots\ldots\ldots 8$$

Wimsatt (1999) developed a regression *equation 9* using FWD deflection (mm) measured at a distance of 1828.8 mm [13].

$$\mathbf{E_s \text{ (MPa)} = 0.24\, P/(W_7 * 1828.8)} \qquad \ldots\ldots\ldots\ldots 9$$

DISCUSSION

The determination of individual layer modulus relies on an empirically derived relation, which is based on the size and shape of the deflection basin. In essence, the outer deflections describe the modulus of the subgrade, while deflections closer to the loading plate allow for analysis of the near-surface layers. This is predicated on the typical pattern of load distribution or stress zones observed under applied load in flexible pavements. However, developing the subgrade modulus from exterior peak deflection is not a straightforward process. It is crucial to characterize the radial distance from the center of the loading plate to the exterior deflection center. It is well-known that within a specified interval of distance, the applied load doesn't induce any deflection. Hence, AASHTO (1993) defines a minimum radius distance based on the radius of the stress bulb induced by the applied load and suggests that the minimum radius should be equal to or greater than 0.7 times the radius of the stress bulb [6]. Garg and Thompson (1998), Choubane and McNamara (2000), Alexander et al. (1989), Roque et al. (1998), Molenaar and Van Gurp (1982), and Wimsatt (1999) used radius distances of 1097 mm, 1524 mm, 1830 mm, 2000 mm, and 1828.8 mm from the center of the loading plate, respectively [7-11,13].

Furthermore, Equations 1, 4, 8, and 9 are developed using deflection measured at a radial distance from the center of the loading plate, applied load, and radial distance, which are based on the Boussinesq solution, particularly applied to the axis of symmetry. On the other hand, empirical Equations 2, 3, 5, 6, and 7 are solely based on a function of deflection measured at a radial distance from the center of the loading plate. These equations utilize only outer sensor deflection values. Equations 2, 3, 5, 6, and 7 are not widely used due to their reliance solely on deflection, while Equations 1, 4, 8, and 9 are considered significant as they incorporate strength characteristics such as deflection, applied load, and radial distance.

Once again, the load distribution approach is employed to determine the modulus of the granular and surface layers. *Equations 10-13* are functions of surface course thickness and the combination of measured deflection at radial distances of 0, 200, 500, 800, and 1600 mm from the center of the loading plate. Badu et al. (1989) developed these equations [14].

For the Granular layer:

$$\text{Log } E_{BASE}\ (ksi) = 3.280 - 0.03326(t_1) - 0.1179\log(D_7) + 3.3562\log(D_1 - D_2) - 9.0167\log(D_1 - D_4) - 4.8423\log(D_1 - D_5) \quad \ldots\ldots.10$$

For the Bituminous layer:

$$\text{Log } E_{AC}\ (ksi) = 2.215 - 0.2481\ (t_1) - 12.445\log(D_1 - D_2) + 17.205\log(D_1 - D_3) - 5.87\log(D_1 - D_4) \quad \ldots\ldots\ldots\ldots\ldots\ldots.11$$

Roque et al. (1998) developed *Equations 12-13* [10].

For the Granular layer:

$$E_{BASE}\ (ksi) = 105.81136(t_2)^{-1.0785} * (Dx/36 - Dx/60)^{6.02523+2.4888/Dx/60} * (Dy/0 + Dx/12) - 1.15(Dx/36)^{2.1609-1.6202/(Dx/36)-5.302/t_2} * (Dx/60)^{3.6706-0.0498t_1 - 0.686t_{2-3.09/Dx/60)}} \quad \ldots\ldots\ldots\ldots 12$$

For the Bituminous layer:

$$E_{AC}\ (ksi) = 78.2254\ (t_1)^{0.5554} (D_{y/0} - D_{y/305})^{(0.7966-19.1332/t_1)} * (D_{y/0} - D_{x/200})^{17.4791/t_1} \quad \ldots\ldots.13$$

It's worth noting that several combinations of measured deflections have sometimes led to inappropriate modulus results; hence, these are not widely practiced.

4.2 BACK CALCULATION

Back-calculation is a reverse analysis used to determine layer moduli based on pavement response, specifically surface deflection, under the application of a given load. This process involves a numerical technique that encompasses various modeling components depicted in Figure 2: (a) loading model, (b) pavement and material models, (c) a pavement response model, and (d) back-analysis model [4]

The loading model is defined based on the type of applied load, which includes static load, moving load, vibratory load, and impulse load. While dynamic loading models yield more precise results, they introduce extra effects like inertia and resonance. Dynamic impacts excluded from the analysis can lead to a devaluation of the subgrade modulus by half or more, and an exaggeration of the base and subbase moduli by a similar margin [15].

The pavement model encompasses the composition of the pavement, layer thickness, and Poisson's ratio. The material model is crucial for properly representing the behavior of materials under applied load. Granular and subgrade materials exhibit stress-dependent and nonlinear characteristics. The subgrade modulus decreases with increasing stress levels, demonstrating a stress-softening type characteristic.

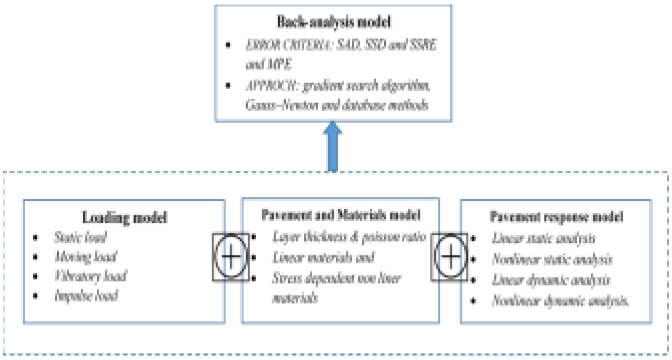

Figure 2 components of back calculation

On the other hand, the modulus of granular materials increases with higher stress states (stress-hardening), especially with confining pressure and/or bulk stress, and slightly with deviator stress.

The response models analyze pavement responses based on the chosen material and loading models. They are typically categorized into four types: (a) linear static analysis, (b) nonlinear static analysis, (c) linear dynamic analysis, and (d) nonlinear dynamic analysis.

In linear static analysis, linear material models and static loading models are employed. Layer thicknesses and Poisson's ratios are known, and only one unknown (elastic modulus) exists for each layer. The widely used program for linear static layered elastic analysis is KENLAYER [16].

Nonlinear static analysis also uses a static loading model, but it differs in the material models, employing nonlinear material models. This introduces more than one unknown model parameter for each layer, and the reliability of the back-calculated values of these parameters is a significant consideration.

Both linear and nonlinear dynamic analyses require time history information of the load and the deflection basin defined by the amplitude values. The time history of deflections can be utilized instead of the peak deflection basin for more accurate results.

The back-analysis phase is based on minimizing the "output error," which is the difference between the calculated and observed surface deflections. Analysts commonly use three measures of output error: (a) the sum of the absolute differences (SAD), (b) the sum of the squared differences (SSD), and (c) the sum of the squared relative errors (SSRE). Various methods have been employed to arrive at a solution that provides a satisfactory match between the estimated and measured deflection basin. One prevalent approach involves using an iterative gradient search algorithm, such as the Gauss–Newton method. Compared to database techniques [17-18] and regression equation-based approaches [19-20], this method generally takes more time due to the need for repeated execution of the forward structural response model.

DISCUSSION

The back-calculation procedure hinges on the alignment of computed and measured pavement deflections, and it involves the following three major steps: (a) selecting a trial set of values for the unknown pavement parameters, (b) performing a forward calculation of pavement response based on the chosen parameter values, and comparing the computed response with the measured response, and (c) adjusting the selected parameter values using an appropriate search algorithm to achieve improved alignment between the computed and measured responses. The accuracy of layer modulus is contingent on the choice of loading, pavement, and material models, as well as pavement response and back-analysis models utilized for the analysis. One widely used example is the application of a linear material model and static loading model in layered elastic programs like KENLAYER. While it only requires finding one unknown parameter (i.e., layer modulus), it does not account for the non-linear characteristics of materials, potentially leading to inaccurate results. To obtain precise results, it is recommended to employ a non-linear dynamic pavement response model. However, this necessitates a computationally efficient PC program, such as the Finite Element Method (FEM).

5. CORRECTION FACTORS

The properties of bituminous mixtures undergo changes with temperature, and modulus values obtained at different temperatures are typically adjusted to a standard temperature for pavement and overlay design. Since the attributes of a granular layer are significantly affected by moisture content, various experts have developed seasonal moisture correction and specific temperature adjustment factors to ensure that moduli and deflection are accurately assessed.

Ullidtz and Peattie (1982) employed deflection data from the AASHO road test and the SHELL procedure to determine mix stiffness, leading to the development of *equation 14* for comparing moduli obtained at two different temperatures [21].

$$E_{T1} / E_{T2} = (2.6277 - 1.38 \log_{10} T_1) / (2.6277 - 1.38 \log_{10} T_2) \quad \ldots\ldots 14$$

Rada et al. (1988) provided an expression for modeling the variation of stiffness with temperature [22].

$$E_{T1} / E_{T2} = 10^{3.245 \times 10^{-4} (T_1^{1.798} - T_2^{1.798})} \quad \ldots\ldots 15$$

Antunes (1993) proposed *equations 16-17*, based on the analysis of back-calculated moduli obtained from the FWD data collected at different temperatures [23].

For Asphalt Concrete:

$$E_{T1} / E_{T2} = (1.635 - 0.0317\, T_1) / (1.635 - 0.0317\, T_2) \quad \ldots\ldots 16$$

For Bituminous Macadam:

$$E_{T1} / E_{T2} = (1.795 - 0.0398\, T_1) / (1.795 - 0.0398\, T_2) \quad \ldots\ldots 17$$

Kim et al (2000) presented the *equations 18-19* for adjusting the deflection value and moduli value for temperatures of 68^0F, where, t is thickness of the Asphalt Concrete (AC) layer (inch) and T is AC layer mid-depth temperature (^{0}F) at the time of FWD testing, α is $3.67 \times 10^{-4} \times t^{1.4635}$ for wheel paths and $3.65 \times 10^{-4} \times t^{1.4241}$ for lane centers [24].

For Deflection:

$$D_{68} = D_T * [10^{\alpha (68 - T)}] \quad \ldots\ldots 18$$

For Modulus:

$$E_{68} = E_T * [10^{0.0153 (68 - T)}] \quad \ldots\ldots 19$$

Chen et al. (2001) suggested *equation 20* for adjusting the layer modulus for a given temperature [25]

$$E_{Tw} = E_{TC} / [(1.8T_w + 32)^{2.4462} * (1.8T_c + 32)^{-2.4462}] \quad \ldots\ldots 20$$

Johnson and Baus (1992) recommended *equation 21* for adjusting the bituminous layer modulus for a standard temperature of 70°F [26].

$$E_{Tw} = E_{TC} / [(1.8T_w + 32)^{2.4462} * (1.8T_c + 32)^{-2.4462}] \quad \ldots\ldots 21$$

Ullidtz (1987) developed a theoretical account for temperature correction based on back-calculated moduli values obtained from AASHO Road Test deflection data [27].

$$E_{To} = (1/3.177 - 1.673 \log_{10} T)\, E_T \qquad \ldots\ldots\ldots\ldots\ 22$$

Baltzer and Jansen (1994) established the temperature correction model (*equation 23*) based on statistical analysis of back-calculated moduli and measured AC temperatures [28].

$$E_{To} = 100.018\,(T-20) * E_T \qquad \ldots\ldots\ldots\ldots\ 23$$

Ali and Slezneva (2000) derived a relationship for estimating AC layer modulus as a function of average AC layer temperature (°C) and temperature gradient in the AC layer (°C/m) [29].

$$E_{AC} = -934 + e^{(9.53-0.033*(T_p)+0.0018*(T_G))} \qquad \ldots\ldots\ldots 24$$

IRC:115-(2014) developed *equation 25*, a temperature correction factor corresponding to a 35°C temperature; this component is valid for temperature ranges of 25°C to 40°C [30]

$$E\,(T_1{}^0 c) = \alpha\, E\,(T_2{}^0 c) \qquad \ldots\ldots\ldots\ldots 25$$

$$\text{Where, } \alpha = [1-0.238 \ln T_1 / 1-0.238 \ln T_2]$$

Granular layer and subgrade materials are susceptible to moisture variation. Therefore, IRC:115-(2014) recommended *equations 26-29* for moisture correction by considering summer and winter season variations for the granular layer and subgrade [30].

For Summer:

$$E_{gran\_Mon} = -\,0.0003 * (E_{gran\_Sum})^2 + 0.9584 * (E_{gran\_Sum}) - 32.989 \qquad \ldots\ldots\ldots 26$$

For Winter:

$$E_{gran\_Mon} = 10.5523 * (E_{gran\_Win})^{0.624} - 113.857 \quad ..27$$

For Summer:

$$E_{sub\_mon} = 3.351 * (E_{sub\_win}{}^{0.7688}) - 28.9 \qquad .....28$$

For Winter:

$$E_{sub\_mon} = 0.8554 * (E_{sub\_sum}) - 8.461 \qquad \ldots\ldots 29$$

DISCUSSION

Bitumen material is highly sensitive to temperature variations, leading to changes in its characteristics. This, in turn, impacts the deflections measured by the FWD. Additionally, granular layer and subgrade materials are significantly affected by moisture variations. Therefore, it becomes imperative to apply correction factors for standard temperature and worst moisture content when designing pavements. While the primary focus of the FWD test is to determine layer modulus, a few researchers have attempted to develop correction factors for deflection. It's important to note that correction factors are influenced by geographical locations, environmental conditions, and specific materials, and they can vary from one place to another. Due to their empirical nature, these factors are not considered standard and need to be specified separately. In Indian conditions, a temperature of 35°C and the modulus measured during the monsoon season are considered standard parameters for pavement design.

6. CONCLUSION

The Falling Weight Deflectometer (FWD) is widely employed for assessing pavement materials due to its reliability, quick operation, and user-friendly nature. It is regarded as a benchmark test for pavement evaluation as it closely simulates actual loading conditions from moving loads. However, in countries like India, the utilization of FWD is limited due to the high cost of internationally available models. Maintaining such expensive equipment has proven to be challenging due to a lack of expertise. Therefore, the development of a cost-effective indigenous FWD holds significant promise for advancing pavement assessment practices in India. The GEOTRAN FWD, an indigenous low-cost option, is a fully automated vehicle-mounted instrument capable of measuring surface deflection with just one operator. Key features include its ability to apply a loading force of up to 100 kN with a pulse duration of around 20-30 milliseconds, and its operation is controlled via a PC/laptop through the DS4000S data acquisition system.

The deflection basin's size and shape enable comprehensive structural investigation of the pavement. While exterior deflections primarily describe the modulus characteristics of the subgrade, the basin near the loading plate allows for an examination of the modulus characteristics of the adjacent surface layers. Several empirical models have been developed to estimate layer moduli based on radially measured deflection basins, often incorporating parameters like applied load and layer thickness. However, it's important to note that these models are effective within specific conditions and construction methodologies for which they were developed. Therefore, their validation under different conditions is necessary. Additionally, due to their empirical nature, these models are not widely employed for estimating layer moduli.

The most extensively used method for estimating layer moduli is the back-calculation method. This procedure hinges on aligning computed and measured pavement deflections. While widely used software like KENLAYER employs a linear material model and static loading model, it does not account for the non-linear characteristics of materials, potentially leading to inaccurate results. For greater accuracy, it is recommended to utilize a non-linear dynamic pavement response model. However, this requires a computationally efficient program like the Finite Element Method (FEM).

Bituminous material is highly sensitive to temperature variations, leading to changes in its characteristics. This variation also impacts the deflections measured by the FWD. Similarly, granular layer and subgrade materials are significantly affected by moisture variations. Therefore, correction factors are needed to account for standard temperature and worst moisture content when designing pavements. These correction factors are influenced by geographical locations, environmental conditions, and specific materials, and may vary from one location to another. Due to their empirical nature, these correction factors are not considered standard and must be specified separately. In Indian conditions, a temperature of 35°C and the modulus measured during the monsoon season are considered standard parameters for pavement design.

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