Jordan Journal of Civil Engineering, Volume **15**, No. **3**, **2021**

Mechanistic-Empirical Design of Overlay Based on Vertical Interface Stress and Curvature Index of Deflection Basin

Manoj Kumar Sahis [1) *], Partha Pratim Biswas [2)] and Geetam Saha [3)]

[1)] Assistant Professor, Department of Construction Engineering, Jadavpur University, Kolkata, India.
* Corresponding Author. E-Mail: manojkumar.sahis@jadavpuruniversity.in
[2)] Professor, Department of Construction Engineering, Jadavpur University, Kolkata, India.
E-Mail: drppb@jadavpuruniversity.in
[3)] Undergraduate Student, Department of Construction Engineering, Jadavpur University, Kolkata, India.
E-Mail: sahageetam@gmail.com

ABSTRACT

The objective of putting an overlay on the existing damaged pavement is to limit stress, strain and deflection at different layer interfaces of the multi-layered system in a pavement. However, the objective of the present study is to determine the bituminous overlay thickness on the top of the in-service flexible road pavement by limiting the vertical interface stress at pavement -overlay interface. In the present paper, a new overlay with old pavement has been considered as a two-layered system. The vertical stress at pavement - overlay interface due to wheel load on the surface has been determined using Boussinesq's theory after the required transformation of the two-layered system by Odemark's method. The vertical stress thus obtained has been made equal to the allowable vertical stress found from Danish and Huang's empirical findings to estimate the overlay thickness for different axle loads and pavement deflections. The overlay thickness obtained using the present methods and the Asphalt Institute method have been compared in this paper. The convergence of results between two stress-based overlay design methods was found reasonable. Base layer index as a measure of the curvature of overlay under wheel load has been considered as a performance criterion. Comparative analysis of the index obtained for different overlay thicknesses from stress-based and deflection-based criteria has been presented in this paper. It was found from the base layer index that the overlay thickness estimated using the stress-based methods was reliable and safe against cracking. Sensitivity analysis shows that the modulus of the bituminous mix is more sensitive in comparison to axle load repetitions for estimation of overlay thickness.

KEYWORDS: Base layer index, Interface deflection, Odemark's method, Overlay, Vertical interface stress, Sensitivity.

INTRODUCTION

The design of overlay is an integrated part of the strengthening of existing road pavement. The required thickness of overlay essentially depends on the strength of *in-situ* multi-layered pavement which can be estimated from pavement deflection obtained from non-destructive tests on the pavement (AI, 1983). The higher value of pavement deflection indicates lower strength of pavement and *vice versa*. Therefore, the damage and distress of pavement can be quantified using pavement deflection data. The objective of putting an overlay on the existing pavement is to limit stress, strain and deflection at different layer interfaces of the multi-layered system in the pavement to make the pavement durable and functionally more efficient from its serviceability point of view. Several correlations have been developed between allowable numbers of load repetitions (Huang et al., 1984 b, c) with allowable vertical stress and modulus of subgrade for analysis of pavement performance. An analytical-empirical relationship (Ullidtz. 1997) based on the AASHTO road test may be used to determine the stress developed on

Received on 14/4/2021.
Accepted for Publication on 14/6/2021.

unbound materials before failure. The regional factor in this relationship is an important parameter to be carefully chosen. NCHRP-128 guide may be referred to for values in detail. Amongst those, Boussinesq's, Danish and Huang's criteria are found to be effective in finding the stress level at the desired depth. To apply the aforementioned principles, Odemark's method of equivalent thickness has been used to transform the depth at which the required stress is to be calculated. Several researchers (Haung, Ullidtz and Horak) have found Odemark's method useful in transforming the depth into equivalent depth to be readily applicable for methods that require the medium to be homogeneous. Interface deflection (Huang 1969c; Purakayastha et al., 2020) is an important criterion for a two-layer new pavement or overlay design. Overlay design has also been carried out based on various considerations; for examples, Soos et al. (2016) developed an overlay design method that is based on area parameters of the deflection bowl using Odemark's transformation technique for strain calculation. E. Horak (2008) examined the equivalent-layer-thickness (ELT) concept for the evaluation of the structural capacity of pavement. In this analysis, FWD (Aggarwal et al., 2006, Solanki et al., 2016, Loganathan et al., 2019, Naughton et al., 2019, Rabbi et al., 2021) deflection basin parameters were found to be correlated with the remaining service life of the pavement. E. Horak et al. (2014) illustrated a semi-mechanistic empirical analysis technique using deflection bowl's parameters to develop the relative benchmarking methodology. The mode of analysis was found to be in good agreement with Australian design systems by optimizing the limitations of the curvature parameter.

Alessandra et al. (2018) proposed a methodology of overlay thickness design considering the structural capacity of existing bituminous materials by evaluating the remaining support strength of *in-situ* bituminous layers. The proposed method may be used for the optimization of the fund by limiting the overlay design of an in-service pavement. Sarkar et al. (2016) presented a mechanistic-empirical approach for overlay thickness design for low-volume pavements through a combination of non-destructive deflection testing and pre-established pavement damage models. The method was found to be more reliable in terms of structural performance and economy. Saleh et al. (2016) proposed a computational technique to find remaining service life in rutting and fatigue criteria by establishing a correlation between normalized area and compressive strain at the top of subgrade and surface curvature and tensile strain at the bottom of the asphalt. István Fi et al. (2013) developed a mechanical–empirical-based asphalt overlay design procedure that considered equivalent pavement modulus to simplify the calculation. The current Hungarian asphalt overlay practice has also been presented. B.H. Setiadji (2018) evaluated critical parameters of the deflection bowl for optimum use in analyzing the different parameters of road pavement structure in detail. The study suggested a simplification and reformulation of the parameters to find the sub-grade modulus more accurately. Fabricio Leiva-Villacorta et al. (2017) established a correlation between the deflections of the pavement surface and probable permanent deformation. The suggested model has also been found very effective as it requires reduced numbers of parameters in predicting deflection and residual life of the pavement. AASHTOWare is a comprehensive ME pavement design software based on NCHRP mechanistic-empirical pavement design guide. This state-of-the-practice tool optimizes pavement designs and can be used for future designs as well as detection of distress, performance analysis and pavement management in the long term.

Ghazi et al. (2020) developed an experimental PSI pavement evaluation model based on regression analysis. The present serviceability rating (PSR) and the roughness were also measured along with linear fatigue and rutting cracking, rut depth, raveling, patching, debonding and potholes for thirty-five rural highways. Linear cracking and rut depth were identified as the most significant parameters and PSR was found to be most affected by slope variance in the case of smooth pavement in comparison with rough pavement. Moudjari et al. (2019) proposed a more efficient technique to analyze the deflection basin by Lacroix Deflectograph and Falling Weight Deflectometer (FWD). The study also presented an approach to find deflection based on back-calculation as obtained from FWD and ELMOND6 program which includes analytical equations comprising Odemark's and Boussinesq's formulae. A comparative study has also been carried out which shows the relevance of adopting such a simple analytical method in the field of structural evaluation of flexible pavement. Loay et al. (2011) developed a two-dimensional finite element model, using ABAQUS software, to find the effect of static repeated wheel load on rutting formation and pavement response. The FWD has been used for the validation of the results. The study has also undertaken a sensitivity analysis to investigate the most dominant parameters which have the most impact on rut depth as pavement response. The study reveals that with the increment of temperature and tire pressure, rut depth was found to be increased, while it was found to be decreased as subgrade strength increases.

Against this backdrop, the present paper tries to make new contributions in the field of overlay design and present a comprehensive critical comparative comment concerning the so-called widely used AI method. Moreover, a sensitivity analysis has also been carried out within a very simple framework to identify the most significant parameters to impact overlay thickness.

OBJECTIVE

The objective of the present study is to determine the bituminous overlay thickness on the top of the in-service flexible road pavement by limiting the vertical interface stress at the pavement overlay interface. The allowable vertical stress obtained from the empirical relationship established from large-scale field studies has been used in the present paper for the estimation of overlay thickness. To assess the durability of overlay, the curvature index in the form of Base Layer Index (BLI) has been determined analytically from the deflection basin of pavement with overlay under a wheel load and compared with acceptable standards.

METHODOLOGY

In the present paper, the overlay on the top of the existing flexible road pavement has been considered as a two-layered system. The system consists of a stiffer layer of the overlay on top with an elastic modulus (E_1) followed by weaker existing pavement with an elastic modulus of (E_2), which requires further strengthening. The equivalent elastic modulus of existing multilayered pavement has been estimated in this study based on pavement deflection before overlay by using Equation 1, recommended by Boussinesq.

$$E_2 = \frac{2(1-\nu_2{}^2)qa}{\delta} \qquad (1)$$

where,

a = Contact radius of the loaded area between tire and pavement.

δ = Rebound deflection of pavement before the overlay.

q = Contact stress on pavement due to wheel load.

μ = Equivalent Poisson’s ratio of the multilayered system before overlay which has been assumed as 0.5.

To determine the vertical stress by Boussinesq’s theory at pavement overlay interface along the centerline of the loaded area, the proposed two-layered system has been transformed into a homogenous system by using Odemark's method.

ODEMARK’s METHOD

In this method, a two-layered system with an overlay on top with thickness h_1, followed by the *in-situ* pavement may be transformed into a homogeneous half-space for application of Boussinesq's equation to determine the vertical stress, strain or deflection at the required depth. Transformation of a two-layered system into a homogeneous system can be done by Odemark’s method with a concept of equivalent layer thickness (h_e), as shown in Figure 1.

Odemark's method is based on the assumption that the stresses and strains below a layer are depending on the stiffness of that layer only. If the thickness, modulus and Poisson's ratio of a layer are changed, but the stiffness remains unchanged, the stresses and strains below the layer should also remain unchanged.

So, the two-layer system with a modulus of overlay (E_1) with thickness h_1 and Poisson’s ratio ν_1 resting on the bottom layer of *in situ* road pavement with the modulus (E_2) and Poisson’s ratio ν_2, may be represented by an equivalent thickness (h_e), as shown in Equation 2.

$$h_e = f h_1 \sqrt[3]{\frac{E_1(1-\nu_2{}^2)}{E_2(1-\nu_1{}^2)}} \qquad (2)$$

where f is the Odemark's correction factor, which depends on the type of layer interface and varies between 0.8 and 1.0. However, in the present analysis, the value of Odemark's correction factor has been considered as 0.8. If the Poisson's ratios of the layers are assumed approximately the same for the two layers under consideration, the equivalent thickness corresponding to the two-layered system may be expressed as:

$$h_e = f h_1 \sqrt[3]{\frac{E_1}{E_2}} \quad (3)$$

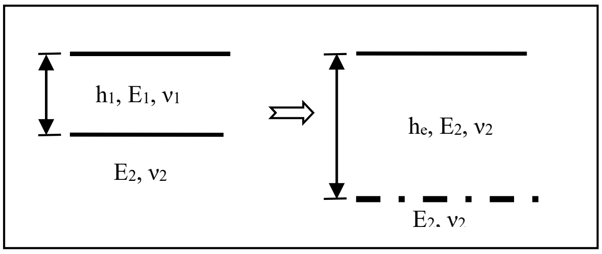

Figure (1): Transformation of a two-layered system by Odemark's approach

However, to determine the vertical stress on the top of the existing pavement at pavement –overlay interface, Boussinesq's equation can be used after the transformation of the two-layered system into a homogeneous system. Therefore, vertical interface stress at the overlay-pavement interface for a wheel load as uniformly distributed circular load (q) when acting on the top of overlay, may be determined by Boussinesq's Equation 4, considering $z = h_e$.

$$\sigma_z = q\left[1 - \left(\frac{z}{\sqrt{a^2+z^2}}\right)^3\right] \quad (4)$$

where a = Radius of contact between wheel load and overlay surface.

The principle followed in this paper for the design of overlay is to limit the vertical interface stress on in-*situ* road pavement by putting the required thickness of overlay with the desired modulus. The correlation to determine the permissible vertical stress on the top of any unbound layer has been recommended in Danish criteria and shown in Equation 5. According to Danish criteria, the permissible vertical stress (σ_{zu}) depends on anticipated axle load repetitions before failure and the elastic modulus of the unbound layer.

$$\sigma_{zu} = 0.164\left[\frac{NR}{10^6}\right]^{\frac{-1}{3.26}}\left[\frac{E_2}{160}\right]^{\alpha} \quad (5)$$

where N = Number of load repetitions before failure of the granular unbound material.

R = Regional factor which has been assumed to be 0.2 for the semi-arid region in this paper [NCHRP-128 guide may be referred to for values in detail].

$\alpha = 1.16$ if $E \leq 160$ MPa; else $\alpha = 1.00$.

In the present analysis, the value of modulus (E_2) has been obtained from Equation 1 using rebound deflection data before overlay.

Thereby solving Equations 4 and 5, the required thickness of overlay can be determined corresponding to different rebound deflection before overlay and anticipated axle load repetitions leading to failure. The overlay thicknesses thus obtained are shown in Figure 4 to Figure 11.

Moreover, Huang recommended a correlation between the permissible vertical stress on subgrade which relates the allowable number of stress repetitions to limit permanent deformation of pavement and the modulus of subgrade as shown in Equation 6. The sub-grade soil of the pavement is considered as the foundation of paving layers, which can be idealized as homogeneous, elastic, isotropic and semi-infinite.

Huang's formulation considers that the failure criterion of pavement is governed by the failure of subgrade when the actual stress on subgrade due to wheel load repetitions exceeds the allowable value.

In the present analysis, the existing pavement with multilayered elastic materials including subgrade has been considered as the foundation of the overlay. The existing pavement with a multilayered system has been characterized in this paper by an equivalent elastic modulus (E_2) as a homogeneous medium based on rebound deflection before overlay as explained earlier in Equation 1. Therefore, the existing old pavement with the equivalent elastic modulus (E_2) may be considered as a homogeneous layer that acts as a foundation of overlay in a two-layered system. In this backdrop, Huang's formulation to determine the permissible stress on subgrade has been used in this paper to determine the permissible stress (σ_{zh}) on the unbound layer in the pavement.

$$\sigma_{zh} = \left[\frac{N}{4.873\times10^{-5}\times E_2{}^{3.583}}\right]^{\frac{-1}{3.734}} \quad (6)$$

where N = Allowable number of stress repetitions to limit permanent deformation of pavement. E_2 = Equivalent elastic modulus of the existing pavement estimated from rebound deflection.

Therefore, solving Equations 4 and 6, the overlay thickness may be determined corresponding to different pavement deflections before overlay with specified axle load repetitions. The overlay thickness thus obtained based on permissible stress on unbound materials using Danish criteria has been presented in Figure 4 to Figure 11. To compare the overlay thickness using the present methods, the thickness of overlay has also been estimated in this paper using Asphalt Institute (AI) method using pavement deflection and axle load as a design parameter. The overlay thickness thus obtained from the AI method has been compared with the overlay thickness estimated from two other stress-based approaches presented in the paper.

ESTIMATION OF DEFLECTION BASIN OF OVERLAY

Condition monitoring of existing pavement is done by non-destructive tests by which the deflection basin of the pavement is obtained. The curvature of the deflection basin under a wheel load is an important indicator of the strength of the *in-situ* multilayered pavement. Therefore, to evaluate the durability of overlay thickness using different methods proposed in this paper, the Baselayer Index (BLI) under wheel load has been considered as a design parameter. The BLI is considered as an indicator of overlay performance, precisely against cracking, which may be obtained from the deflection basin of pavement. In this backdrop, the deflection basin of pavement after overlay has been estimated using a mechanistic approach which has been illustrated in this section. In the present paper, the value of BLI has been estimated based on the correlation as shown in Equation 7.

$$BLI = D_0 - D_{200} \quad (7)$$

where D_0 is the vertical interface deflection (in mm) at the overlay-pavement interface along the centerline of the loaded area and D_{200} is the vertical interface deflection (in mm) at the overlay-pavement interface at a radial distance of 200 mm from the centerline of the load.

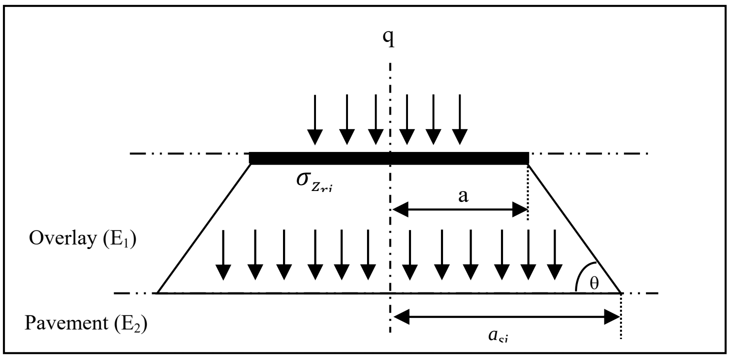

Figure (2): Interface stress and deflection of a two-layered system

VERTICAL INTERFACE DEFLECTION AT OVERLAY PAVEMENT INTERFACE

In the present section, the section of overlay followed by the *in-situ* road pavement has been considered as a two-layered system to determine the interface deflection at the pavement overlay layer interface. The vertical interface deflection thus obtained on the top of the existing pavement after putting overlay has been assumed as the deflection of pavement after overlay. Considering the higher elastic modulus of the overlay concerning *in-situ* pavement with lower elastic modulus, the assumption to consider the interface deflection as pavement deflection in a two-layered system is reasonably good for estimation of overlay thickness.

The vertical interface stress at the overlay pavement interface has been determined using Boussinesq's method by transforming the two-layered systems using Odemark's approach as explained in Equation 4. The vertical interface stress (σ_{z_o}) is shown in Equation 8, which is the vertical stress along the centerline of the circularly loaded area at a depth z = h_e, where h_e is the transformed thickness of the overlay:

$$\sigma_{z_0} = q\left[1 - \left(\frac{h_e}{\sqrt{a^2+h_e{}^2}}\right)^3\right] \quad (8)$$

However, using Boussinesq's approach, the vertical interface stress z_{ri}at the overlay pavement interface at a different radial distance (r) from the centerline of the loaded area may be determined using Equation 9.

$$\sigma_{z_{ri}} = \sigma_{z_0}\left[\frac{1}{1+\left(\frac{r_i}{h_e}\right)^2}\right]^{\frac{5}{2}} \quad (9)$$

In a falling weight deflectometer (FWD), the vertical deflection in constituent layers in a multilayered pavement is measured at different radial distances ranging between 0 and 1500 mm with the suitable spacing of geophones to get the deflection basin under a wheel load. To estimate the deflection bowl of the pavement with overlay, the vertical interface stress and deflection at different radial distances have been analytically obtained in this paper by using Boussinesq's method. The vertical interface stress obtained at the pavement overlay interface has been used to determine the vertical interface deflection at a different radial distance for estimation of the deflection bowl. It is relevant to mention that the effect of wheel load stress at pavement surface gets reduced at the overlay-pavement interface due to dispersion of stress through a layered medium with a higher elastic modulus to a lower one. Therefore, the effect of reduced vertical interface stress at overlay pavement interface may be explained with the increase in a larger area for stress dispersion in a two-layered system as shown in Figure 2. The vertical interface stress along the center of the loaded area is highest at depth z = h_e, which reduces with an increase in radial distance (r) and has been used in Equation 9 for estimation of vertical interface deflection.

The radius of dispersed area $a_{si}$of vertical interface stress at the layer interface may be obtained from Equation10.

From Figure 2,

$$\pi a^2 q = \pi a_{si}{}^2 \sigma_{z_{ri}} \quad (10)$$

where q is the surface stress intensity due to wheel load, acting on a circular area of radius (a) on the pavement surface.

$$a_{si} = a\sqrt{\frac{q}{\sigma_{z_{ri}}}} \quad (11)$$

Therefore, the interface deflection at any radial distance at a horizontal plane at a depth z = h_e from the surface of the overlay may be determined from Equation 12.

$$d_{sri} = \frac{1.5 a_{si} \sigma_{z_{ri}}}{E_2} \quad (12)$$

However, by substituting the value a_{si} from Equation 11 into Equation 12, the interface deflection at different radial distances may be expressed as:

$$d_{sri} = \frac{1.5a\sqrt{q\sigma_{z_{ri}}}}{E_2} \quad (13)$$

Therefore, the vertical interface deflection at a different radial distance may be obtained using Equation 13 from which BLI can be determined as shown in Equation 14.

$$d_0 - d_r = A[1 - B] \quad (14)$$

where $A = \frac{1.5a\sqrt{q\sigma_{z0}}}{E_2}$ and $B = \left[\frac{1}{1+\left(\frac{r_i}{h_e}\right)^2}\right]^{\frac{5}{2}}$

The BLI values for the pavement with different overlay thicknesses estimated using different methods are reported in this paper for comparative analysis.

INPUT PARAMETERS USED IN OVERLAY DESIGN

The following input parameters have been used in the present analysis for comparative study of overlay thickness obtained from two recommended models in this paper with the Asphalt Institute method.

Deflection values (δ) before overlay have been considered as 0.508, 1.016, 1.524, 2.032, 2.54, 3.048, 3.556 and 4.064 mm.

The equivalent modulus of existing pavement (E_2) has been calculated using Equation 1 corresponding to the deflection value of pavement before overlay. The resilient modulus of overlay mix (E_1) has been considered as 3500 MPa with Poisson's ratio value of (μ) = 0.5 and the Odemark's correction factor (f) as 0.8. The wheel load stress (q) = 0.483 MPa, with a wheel load of 40 kN has been considered in this analysis with a radius of the contact between tire and pavement as 163 mm. The permissible pavement deflection after overlay may be obtained from the empirical correlation used in the AI method which correlates the permissible deflection with maximum axle load repetitions before failure. The pavement deflection after overlay thus estimated corresponding to specified axle load repetitions has been used in all the methods of overlay design reported in this paper for comparative analysis.

The flow diagram of the adopted methodology is shown in Figure 3.

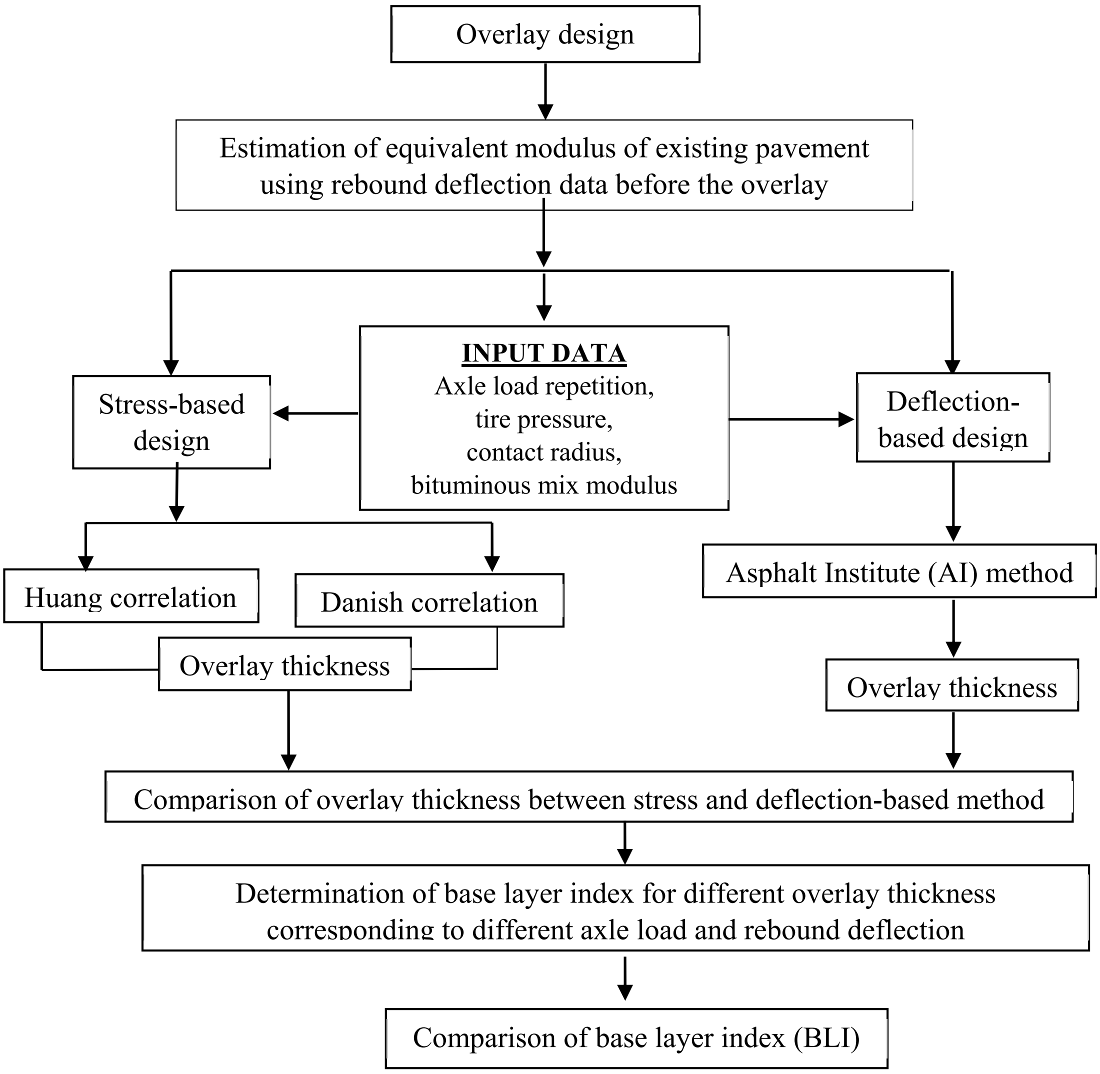

Figure (3): Flow diagram of the adopted methodology

RESULTS AND DISCUSSION

Primarily, the overlay thickness based on surface deflection has been estimated from the Asphalt Institute method for different axle load repetitions. The overlay thicknesses thus obtained for different axle load repetitions using the AI method and two other recommended stress-based methods have been presented through Figure 4 to Figure 11. It is evident from those figures that an increase in pavement deflection results in a higher thickness of overlay. However, the rate of increase of an overlay thickness was found highest in the AI method with respect to other recommended models of overlay design in this paper. It is relevant to mention that the deflection and the overlay thickness values at the point of intersection of three different curves reduce with the increase in axle load repetitions. This means the overlay thickness was found to be converging within a deflection range of 1.5 mm to 2.5 mm.

However, the overlay thickness obtained by limiting the vertical interface stress using Danish and Huang's correlations is quite close for different axle load repetitions. Here, it is to be noted that the design of overlay in the AI method is based on limiting the deflection on overlay, whereas the methods proposed in the present paper for estimation of overlay thickness are based on limiting vertical stress at overlay pavement interface. Moreover, in all the methods, Odemark's approach has been used for the transformation of layered systems to a homogeneous system. The overlay design curves obtained from the stress-based approach were found to intersect with each other with a flatter gradient. It has also been observed that overlay thickness is higher for lower deflections with lower axle load repetitions in two stress-based methods in comparison to the Asphalt Institute method.

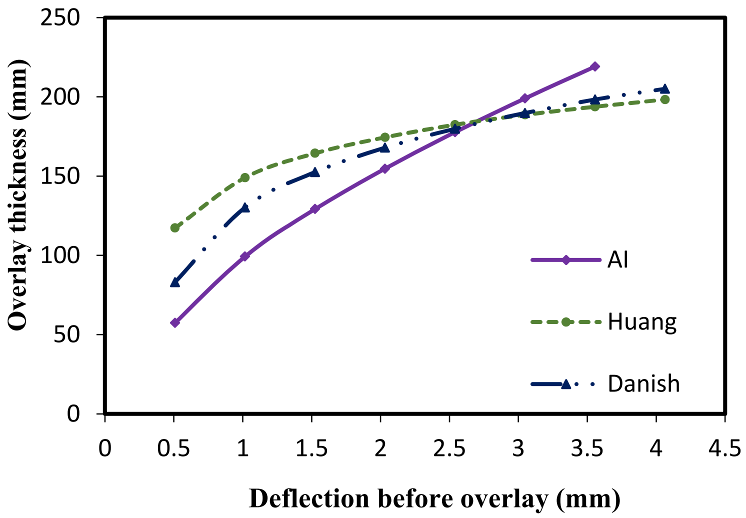

Figure (4): Variation of overlay thickness with pavement deflection before overlay (2 MSA)

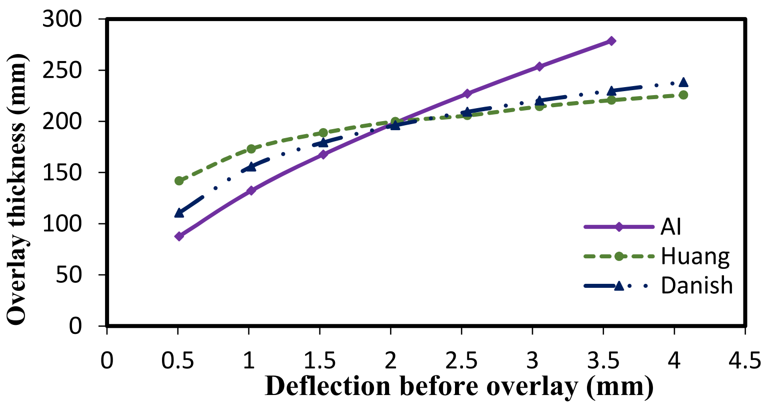

Figure (5): Variation of overlay thickness with pavement deflection before overlay (5 MSA)

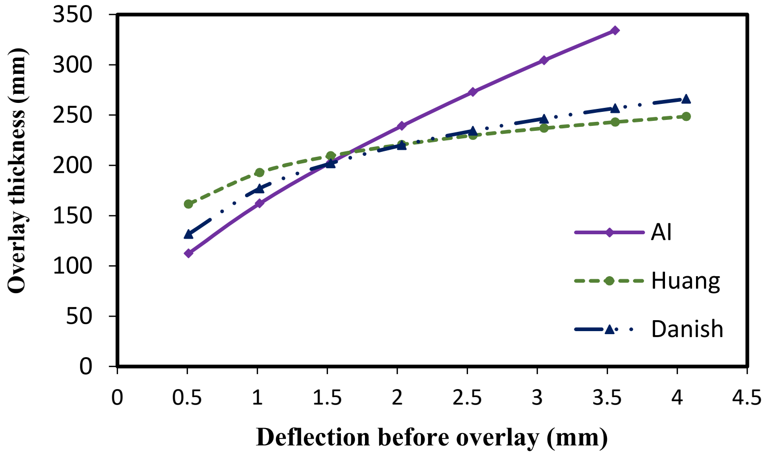

Figure (6): Variation of overlay thickness with pavement deflection before overlay (10 MSA)

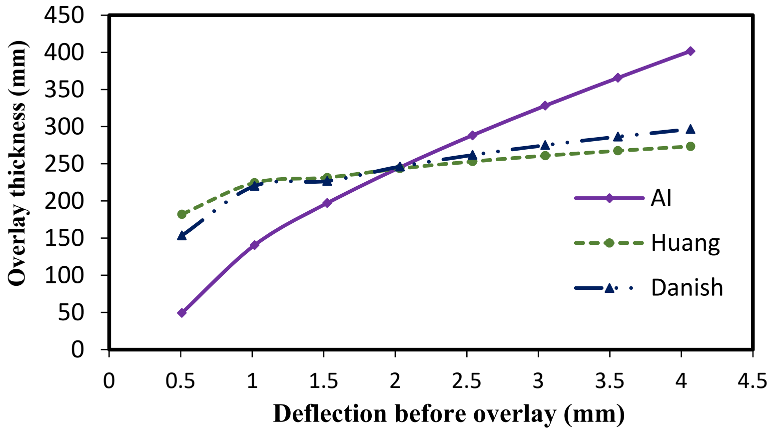

Figure (7): Variation of overlay thickness with pavement deflection before overlay (20 MSA)

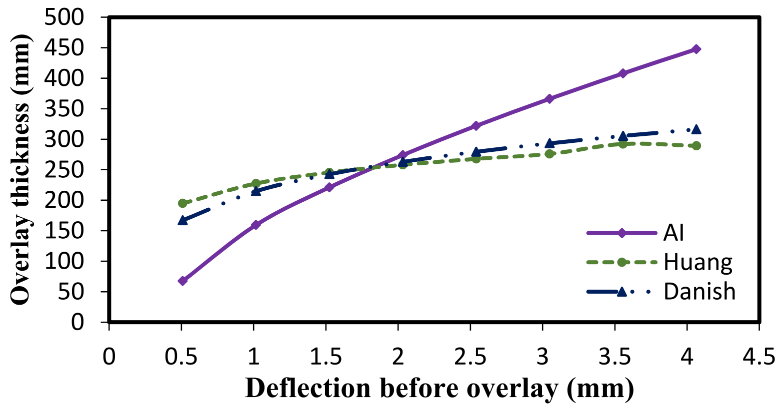

Figure (8): Variation of overlay thickness with pavement deflection before overlay (30 MSA)

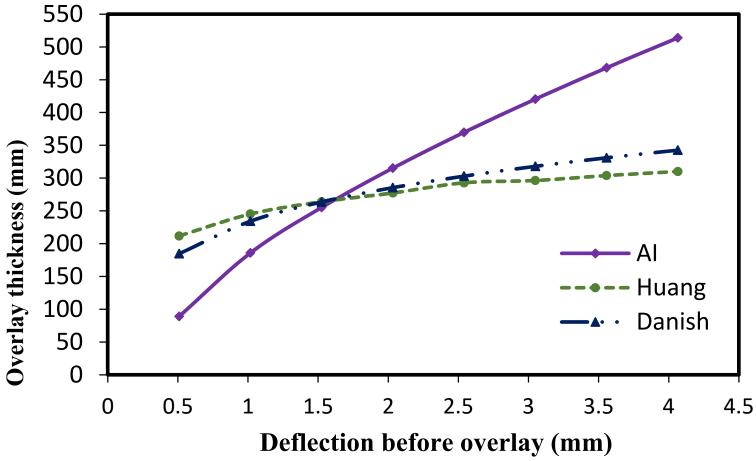

Figure (9): Variation of overlay thickness with pavement deflection before overlay (50 MSA)

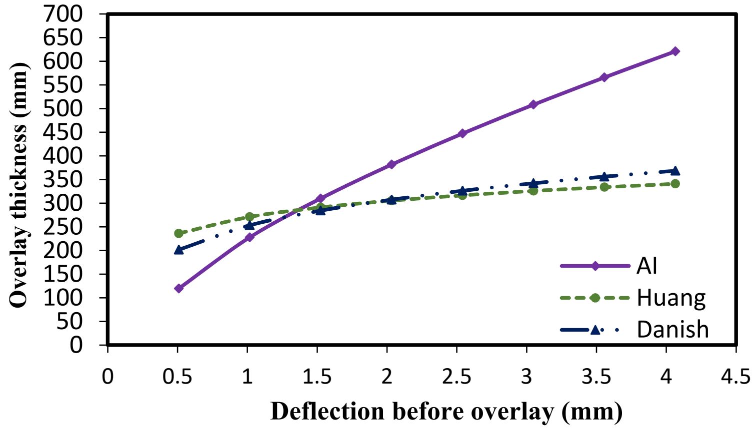

Figure (10): Variation of overlay thickness with pavement deflection before overlay (100 MSA)

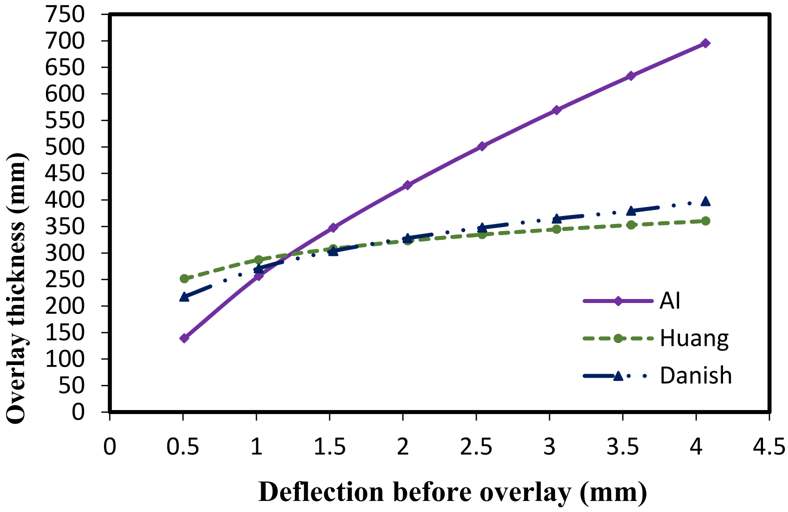

Figure (11): Variation of overlay thickness with pavement deflection before overlay (150 MSA)

Detailed analysis of the deflection bowl is required to evaluate the probable extent of damage and distress for condition monitoring of road pavement. The deflection basin can be estimated by non-destructive tests on the pavement by using a different deflectometer from which the pavement layer index, like BLI, can be estimated. But the correlation of BLI with pavement strength requires extensive study to assess the pavement performance. In this context, the deflection bowl parameters, like Base Layer Index (BLI), have been considered in the present work to evaluate its impact on pavement strength. The allowable value of BLI has been suggested by Horak et al. as 0.20, which means that the overlay thickness which shows a BLI less than 0.2 is well within a factor of safety in terms of its susceptibility to cracking. It is relevant to note that the BLI value depends on the strength and thickness of the overlay, which change with axle load repetitions and pavement deflection.

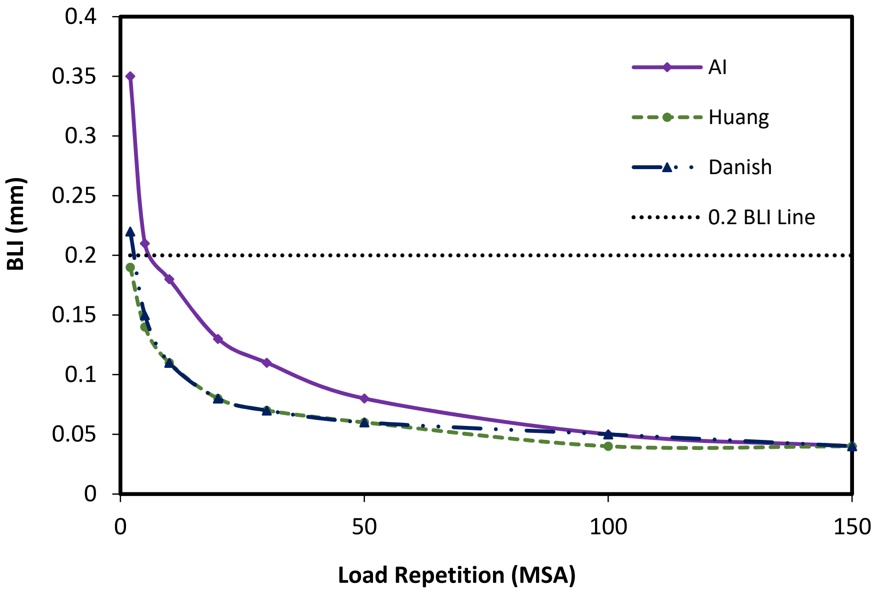

Figure (12): Variation of overlay thickness with axle load repetitions

Table 1. Comparison of BLI for overlay estimated using AI method, Danish stress-based approach and Huang stress-based approach

Axle load (MSA)	Asphalt Institute overlay	Danish stress-based overlay	Huang stress-based overlay
	Base layer index	Base layer index	Base layer index
2	0.35	0.22	0.19
5	0.21	0.15	0.14
10	0.18	0.11	0.11
20	0.13	0.08	0.08
30	0.11	0.07	0.07
50	0.08	0.06	0.06
100	0.05	0.05	0.04
150	0.04	0.04	0.04

In the present paper, the average BLI value for different pavement deflections ranging from 0.5 mm to 4.0 mm for a specified axle load repetition has been determined using a mechanistic approach and considered as characteristic BLI. The BLI values for overlay sections thus obtained from two stress-based methods and the deflection-based AI method are presented in Table 1. The axle load variations from 2 to 150 MSA have been considered for estimation of BLI in Table 1. It has been found that the BLI values obtained for the overlay thickness estimated using the AI method range between 0.35 and 0.04, whereas the BLI has been found to range between 0.21 and 0.04 using Danish correlation and between 0.19 and 0.03 using Huang's correlation. It has been observed from the data in Table 1 that the overlay thickness obtained by all three methods is safe against cracking for the sections above the load range of 5 MSA. However, the overlay thickness values estimated using the AI method and Danish correlation for a load range of 2 MSA were found marginally unsafe under fatigue. The variation of BLI with axle load repetitions is presented in Figure 12, from which it can be concluded that the overlay thickness obtained using two stress-based approaches in this paper are reasonably safe in terms of cracking.

Table 2. Overlay thickness for change in elastic modulus of the bituminous mix for 50 MSA load repetitions

Surface deflection (d_0) (mm)	**Load repetition (50 MSA)**					
	Modulus of the bituminous mix (MPa)					
	3500	3150	2800	2450	2100	1750
0.5	86	90	94	99	105	113
1.0	182	190	199	210	224	244
1.5	251	261	274	290	311	339
2.0	310	323	340	360	386	421
2.5	363	380	399	423	454	497
3.0	413	432	454	482	518	567
3.5	461	481	506	538	578	634
4.0	506	528	556	591	635	697

Table 3. Overlay thickness for change in axle load repetition for bituminous mix modulus of 3500 MPa

Surface deflection (d_0) (mm)	**Modulus of bituminous mix (E_1 = 3500 MPa)**					
	Load repetition (MSA)					
	50	45	40	35	30	25
0.5	86	82	77	71	65	57
1.0	182	177	171	164	157	148
1.5	251	243	236	227	217	207
2.0	310	301	291	281	269	256
2.5	363	353	342	330	316	301
3.0	413	402	389	375	360	343
3.5	461	448	434	418	401	382
4.0	506	491	476	459	441	420

A sensitivity analysis has also been carried out to find the most dominant parameters between axle load repetition and modulus of bituminous mix, which may affect the pavement overlay thickness. The pavement deflection before overlay was considered from 0.5 mm to 4.0 mm in this study. For sensitivity analysis, overlay thicknesses have been calculated once by keeping axle load repetition as 50 MSA and varying the modulus of bituminous mix from 3500 MPa to 1750 MPa at the rate of incremental reduction of 10% and similarly, by varying the axle load repetitions at the same incremental proportion from 50 MSA to 25 MSA, where overlay thickness has been estimated with a fixed bituminous mix modulus of 3500 MPa. Overlay thickness values thus obtained for different combinations of bituminous mix modulus and axle load repetitions are presented in Table 2 and Table 3. The values presented in Table 2 and Table 3 show that the percentage change in overlay thickness was more due to variation in bituminous mix modulus than axle load repetitions. Therefore, it may be concluded with a limited data trial that the mix modulus is more sensitive than axle load repetition in the estimation of overlay thickness.

CONCLUDING REMARKS

It is evident from the results and discussion that the design of overlay by limiting the vertical interface stress may be considered as a reliable method for strengthening existing bituminous road pavement. Comparative analysis of overlay thickness obtained from stress-based approach and deflection-based AI method has been made in this paper, which reveals that the rate of change of overlay thickness with pavement deflection is reasonably higher in the AI method than in the two other stress-based methods. However, it has been observed that the deflection and the overlay thickness values at the point of intersection of the three different curves reduce with the increase in axle load repetitions. This means that the overlay thickness was found to be converging between the three methods within a deflection range of 1.5 mm to 2.5 mm. The durability of overlay has been characterized by BLI value after estimating the deflection basin under a wheel load. It has been found that the overlay thickness obtained from the stress-based approach is reasonably safe in terms of cracking as evident from the curvature index of the deflection basin. Moreover, it has been observed in this study that the change in BLI is significant up to an axle load repetition of 50 MSA beyond which the variation becomes insignificant. From sensitivity analysis, it can be concluded that the modulus of the bituminous layer is more sensitive than axle load repetition if other parameters remain unchanged. The present paper deals with the estimation of overlay thickness based on BLI which relates largely to the overlay performance under fatigue. But the safety of overlay against rutting has to be considered by estimating the lower layer index of the pavement after placing an overlay on it. However, in the design of overlay to limit both cracking and rutting on the overlay, a rigorous method of sensitivity analysis may be considered as a future scope of study.

REFERENCES

Agarwal, Pradeep, and Chakroborty, Partha. (2006). “Simple model for structural evaluation of asphalt concrete pavements at the network level”. Journal of Infrastructure Systems, 12. DOI: 10.1061/(ASCE) 1076-0342(2006)12:1(41)

Al. (1983). “Asphalt overlays for highway and street rehabilitation”. Manual Series No. 17, Asphalt Institute.

Alessandra Bianchini, Carlos R. Gonzalez, and Haley P. Bell. (2018). “Correction for the asphalt overlay thickness of flexible pavements considering pavement conditions”. International Journal of Pavement Engineering, 19 (7), 577-585. DOI: 10.1080/10298436. 2016.1198480.

Al-Khateeb, Loay. (2011) “Rutting prediction of flexible pavements using finite element modeling”. Jordan Journal of Civil Engineering, 5, 173-190.

Boussinesq, V.J. (1885). “Application des potential sal'etude de l'equilibre et du mouvement des solid eselastiques avec des notes etenduessur divers points de physique mathematique et d'analyse”. Gauthier-Villars, Paris.

Burmister, D.M. (1943). "The theory of stresses and displacements in layered systems and applications to the design of airport runways". Proceedings, Highway Research Board, 23, 126-144.

Burmister, D.M. (1945). "The general theory of stresses and displacements in the layered system", J. Appl. Phys., 16, 89-94.

Ghazi G. Al-Khateeb and Nagham Y. Khadour. (2020). “Distress-based PSI models for asphalt pavements of rural highways”. Jordan Journal of Civil Engineering, 14 (2), 281-293.

Horak, E. (2006). “Application of equivalent-layer-thickness concept in a mechanistic rehabilitation design procedure”. Transportation Research Record, 1207, 69-74.

Horak, E. (2008). “Benchmarking the structural condition of flexible pavements with deflection bowl parameters”. Journal of the South African Institution of Civil Engineering, 50 (2), 2-9, Paper 652.

Horak, Emile, Hefer, Arno, Maina, James, Emery, Steve, and Kubu. (2014). "Structural number determined with the falling weight deflectometer and used as benchmark methodology". December 2014. DOI: 10.13140/2.1. 1459.6165, Conference: CEEE, Kowloon, Hong Kong, Proceedings.

Huang. (2004). “Pavement analysis and design”. Pearson Prentice Hall, Edition 2. ISBN: 0131424734, 9780131424739.

Leiva-Villacorta, Fabricio, Vargas-Nordcbeck, Adriana, and Aguiar-Moya, Jose. (2017). “Permanent deformation and deflection relationship from pavement condition assessment.” International Journal of Pavement Research and Technology. DOI: 10.10.1016/j.ijprt.2017.03.005.

Loganathan, K., Isied, M.M., Coca, A.M. et al. (2019) "Development of comprehensive deflection parameters to evaluate the structural capacity of flexible pavements at the network level". Int. J. Pavement Res. Technol., 12, 347-355 (2019). https://doi.org/10.1007/s42947-019-0041-0

Lopes, F.M., and Fortes, R. (2013). “Flexible pavements: Structural evaluation based on deflection basin parameters”. International Journal of Pavements-Conference, São Paulo, Brazil, 163-1-8.

Md. Fazle Rabbi, and Debakanta Mishra. (2021). “Using FWD deflection basin parameters for network-level assessment of flexible pavements”. International Journal of Pavement Engineering, 22 (2), 147-161. DOI: 10.1080/10298436.2019.1580366

Moudjari, M., and Belachia, M. (2019). “Comparative study of the deflection of a flexible pavement under the effect of low traffic”. 2019 International Review of Civil Engineering (IRECE), 10 (5), 249-255. DOI: https://doi.org/10.15866/irece.v10i5.16539.

National Cooperative Highway Research Program (NCHRP). (1972). “Evaluation of AASHTO interim guides for design of pavement structures". Highway Research Board, Report 128.

Naughton, P., and Hall, Gerard. (2019). "Pavement condition from falling-weight deflectometer testing". Proceedings of the Irish Transport Research Network Conference, September 2019, Belfast.

Odemark. (1949)." Investigations as to the elastic properties of soils and design of pavements according to the theory of elasticity". No. Meddelande 77. StatensVaginstitut, Stockholm, Sweden.

Priyanka Sarkar, Erol Tutumluer, and Scott Lackey. (2016). "Non-destructive deflection testing-based mechanistic-empirical overlay thickness design approach for low-volume roads: Case studies". Procedia-Engineering, 143, Third International 945-953. Advances in Transportation Geotechnics 3. ThirdInternational Conference on Transportation Geotechnics, (ICTG 2016).

Purakayastha, S., Biswas, P.P., and Sahis, M.K. (2020). “Determination of bituminous overlay thickness of flexible pavement by a mechanistic-empirical approach based on concentration factor.” ISSN: 1997-1400. DOI: https://doi.org/10.1007/s42947-020-0166-1. Chinese Society of Pavement Engineering. Production and Hosting by Springer Nature.

Saleh Mofreh. (2016). "A mechanistic-empirical approach for the evaluation of the structural capacity and remaining service life of flexible pavements at the network level”. Canadian Journal of Civil Engineering. University of Canterbury, Civil and Natural Resources.

Setiadji, Bh. (2018). “Application of deflection bowl parameters for assessing different structures of road pavement”. MATEC Web of Conferences. 195. 04002.10.1051/matecconf/201819504002.

Soós, Zoltán, and Csaba Tóth. (2017). "Simple overlay design method for thick asphalt pavements based on the method of equivalent thicknesses". Periodica Polytechnica Civil Engineering, 61 (3), 389-397. https://doi.org/10.3311/PPci.9721.

Solanki, Ujjval, Gundaliya, P., and Barasara, M. (2016). "Structural evaluation of flexible pavement using falling-weight deflectometer". DOI: 10.1201/b20013-23.

Ullidtz. (1998). "Modeling flexible pavement response and performance". Lyngby, Polyteknisk Forlag, Denmark, 26-27.