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COMPARATIVE ANALYSIS OF OVERLAY THICKNESS USING THE ASPHALT INSTITUTE'S AND MEPDG WITH KENLAYER

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ABSTRACT: The Mechanistic-Empirical Pavement Design Guide (MEPDG) is widely regarded as the current state of the art in mechanistic-empirical pavement analysis and design. The guide offers a comprehensive set of procedures for determining overlay thickness, a crucial aspect of pavement design. The objective of this study is to investigate the differences that arise when designing overlay thickness using two distinct methods: the Asphalt Institute's mechanistic-empirical and the MEPDG. This study utilized KENLAYER software, which enables stress and strain analysis by modeling the nonlinear elastic pavement structure. Accordingly, the Asphalt Institute method solely relies on alligator cracking and rut depth as its failure indicators, while the MEPDG encompasses several additional criteria that serve as determinants for evaluating the performance of pavement structure. The subject of this study is flexible pavement situated on a road located in West Java, Indonesia. Following this, a falling weight deflectometer (FWD) test was conducted to obtain the deflection characteristics of the road. This paper provides a detailed explanation of overlay thickness calculation processes employed in both the Asphalt Institute's mechanistic-empirical and the MEPDG method. The Asphalt Institute Method resulted in a slightly thicker overlay of 30 cm, while the MEPDG method produced a thickness of 25 cm. To adapt and apply MEPDG effectively in Indonesia, adaptations such as employing Weigh-In-Motion data for load spectra and conducting local calibration are necessary.

Keywords: AASHTO, Asphalt Institute, Back-Calculation, KENLAYER, MEPDG, Overlay Thickness

1. INTRODUCTION

Indonesia is a developing country and its ggovernment strives to providee adequate and reliable transportation infrastructure for its inhabitants. The government recognizes that making substantial investments in road infrastructure is a key driver of economic growth and development [1–5]. However, to ensure the roads fulfill their intended purpose, it is essential to maintain the performance of the road pavement throughout their service life through effective rehabilitation measures [6].

In road pavement design, two commonly employed methods are the mechanistic and empirical methods. Each method offers distinct perspectives on assessing and predicting the behavior and performance of pavements. The mechanistic method utilizes fundamental principles of physics to determine the reaction of pavement to wheel loads in terms of stress, strain, and deflection. On the other hand, the empirical model relies on observed pavement performance to predict its service life [7,8]. The integration of the mechanistic and empirical models has led to the development of a hybrid method known as the mechanistic-empirical method. This method provides a more comprehensive approach to pavement design and analysis. Furthermore, the hybrid method leverages on its mechanistic aspect to calculate the reaction of pavement (stress, strain, and deflection) and employs the empirical model to estimate transfer functions, encompassing incremental distresses such as rutting, faulting, cracking, and roughness based on critical stresses and strains [9]. Admittedly, analyzing these transfer functions solely with a mechanistic method would be insufficient, thus highlighting the indispensability of the empirical method in pavement design and analysis. By embracing the mechanistic-empirical method, a sustainable and rational framework is established for pavement design and analysis. This method allows for the consideration of various factors and their interactions, leading to more accurate predictions and improved cost-effectiveness [10]. Some notable models that employ the mechanistic-empirical method in the evaluation and design of flexible pavement include the Asphalt Institute [11] and the Mechanistic-Empirical Pavement Design Guide (MEPDG) used in the United States [12].

The MEPDG is a comprehensive method used for road pavement design and evaluation, which combines both the mechanistic and empirical aspects of pavement analysis [13,14]. Within this method, several similarities exist related to road pavement design criteria. The design criteria model incorporates local and global calibration parameters, distinguishing it from previous methods [15–17]. Notably, several studies have been conducted to implement and calibrate the MEPDG method to local conditions in various states within the USA [18–20]. Recent studies have also explored the application of this method to the condition of local pavements in Indonesia [21,22]. By incorporating local calibration parameters, the MEPDG method can adapt to various climate conditions and heavy vehicle loading patterns, depending on the location of the state [23,24]. This localized calibration endeavor enhances the accuracy of the outputs obtained from the method [25].

For this study, the local calibration parameters derived from the State of Oregon were employed, given its climate conditions closely resembling those of Indonesia, a region without a freezing point temperature [26]. Accordingly, in a study conducted by [22], it was confirmed that the usage of local calibration from the State of Oregon is suitable and can be used as the fundamental starting point for further analysis and adaptation. During the course of the experiment conducted in this study, the pavement mixtures, performance, and structure were considered using real pavement conditions in Indonesia, incorporating parameters such as elastic modulus, dynamic modulus, temperature, tensile strain, and pavement thickness. These parameters serve as essential inputs for the distress formula and the overall calculation. Furthermore, the weighted mean Asphalt temperature in West Java, Indonesia, which was 41°C, was considered [27,28].

2. RESEARCH SIGNIFICANCE

The topic of this study focuses on the comparison between the two pavement design method, which are the more recent MEPDG method [12] and the well-established Asphalt Institute method [11]. The objective was to explore the disparities between these two methods and specifically examine and compare the damage models utilized within them. This study aims to compare the obtained overlay thickness design results, discuss damage model differences between the MEPDG method and the Asphalt Institute method, and determine the appropriate procedures for applying the MEPDG method to Indonesian conditions.

3. METHOD

There are three types of pavement in general, namely flexible, rigid, and composite pavements [29,30]. However, this study specifically focuses on flexible pavement and its unique characteristics. The study site selected for this experiment is the Abdul Rahman Saleh–Bandung City, West Java in Indonesia. This specific road section with a total length of 1.1 km, was tested for deflection using a falling weight deflectometer (FWD). It is important to note that this area falls within an urban commercial zone, experiencing heavy daily traffic consisting of various types of freight cargo. The existing pavement layering system is shown in Fig. 1. Regarding the design of flexible pavement overlay thickness, three distinct methods are commonly employed. They include the empirical, mechanistic, and mechanistic-empirical methods. To facilitate an accurate overlay thickness design, it is imperative to initially determine the characteristics of the existing materials through a process called back-calculation. One widely used back-calculation method is AASHTO 1993, which relies on deflection data [31]. This method entails modeling the structure of pavement such that it consists of only 2 layers, namely the subgrade layer and the layer above. Consequently, pavement and base layers are treated as a single layer within this structure.

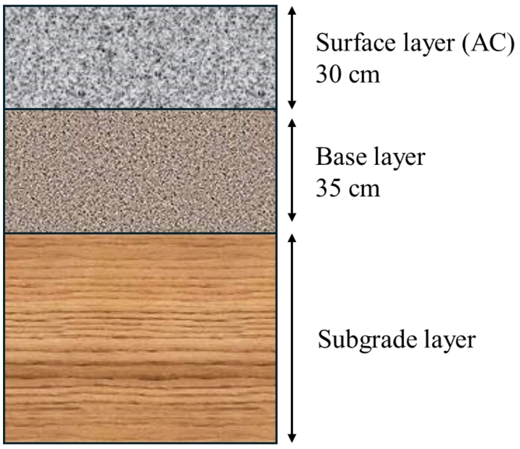

Fig. 1 Pavement Layering System

3.1 Back-Calculation using AASHTO 1993 Method

The initial stage of back-calculation, in accordance with the AASHTO 1993 method, entails analyzing both the traffic load and material properties. Specifically, this involves examining the resilient modulus of the subgrade layer and the effective modulus of the layer immediately above the subgrade [32]. Once these material characteristics in the form of modulus values have been determined through back-calculation, Poisson's ratio (υ) values for each material type were assumed. The Poisson's ratios assigned were 0.4, 0.35, 0.38, and 0.45 for the overlay Asphalt, existing Asphalt, crushed stone base layer, and subgrade layer, respectively [11].

In the subsequent step, strain and stress analyses were conducted at critical points throughout the pavement section using KENLAYER software with a trial overlay thickness. Within the structure of the Asphalt Institute's mechanistic-empirical method, the design criteria revolved around two key factors, namely fatigue cracking and permanent deformation. It is essential to ensure that the number of allowable repetitions surpasses that of the design criteria in order to meet the desired design standards.

3.2 Design Criteria for the Asphalt Institute's Mechanistic-Empirical Method

Fatigue Cracking (Nf) was calculated based on the Asphalt Institute method using Equation 1 as follows.

$$N_f = f_1 . \varepsilon_t^{-f_2} . E_1^{-f_3} \quad (1)$$

where:
N_f = number of allowable load repetitions to control fatigue cracking,
ε_t = tensile strain at the critical review site calculated based on the response of the structural model or tensile strain at the bottom of the surface layer,
E_1 = elastic modulus at the surface layer or HMA layer,
f_1, f_2, and f_3 = criteria coefficient for fatigue cracking.

Following this, Permanent Deformation (N_d) was also calculated based on the Asphalt Institute method using Equation 2 as follows.

$$N_d = f_4 . \varepsilon_c^{-f_5} \quad (2)$$

where:
N_d = number of allowable load repetitions to control rutting,
ε_c = vertical compressive strain above the subgrade layer,
f_4 and f_5 = criteria coefficient for permanent deformation.

The coefficient criteria used in the formula are shown in Table 1.

Table 1 Criteria Coefficient for Fatigue Cracking and Permanent Deformation

Factor	Asphalt Institute	Shell	University Of Nottingham
f_1	0.0796	0.0685	-
f_2	3.2910	5.6710	-
f_3	0.8540	2.3630	-
f_4	1.36E-09	6.15E-07	1.13E-06
f_5	4.4770	4.000	3.571

The MEPDG method incorporates several design criteria to ensure optimal pavement performance. These criteria encompass Rut Depth, Load-Related Cracking, Non-Load Related Cracking – Transverse Cracking, Reflection Cracking, and Smoothness or IRI value [12]. However, it is important to note that, in the context of the climate condition in Indonesia, where freezing point conditions are absent, the design criteria for Non-Load-Related Cracking – Transverse Cracking were not considered in analysis.

3.3 Design Criteria for the MEPDG Mechanistic-Empirical Method

In the determination of Rut Depth using the MEPDG method, the calculation was divided based on the location of the critical point, which was positioned in the middle of each pavement layer (AASHTO, 2015). To calculate the rut depth at the critical point of the Asphalt overlay layer and the existing Asphalt, Equation 3 was used as follows.

$$\begin{aligned}\Delta &= \varepsilon_p \cdot h \\ &= \boldsymbol{\beta_{1r} . k_z . \varepsilon_r . 10^{k_{1r}} . n^{k_{2r} \cdot \beta_{2r}} . T^{k_{3r} \cdot \beta_{3r}}}\end{aligned} \quad (3)$$

where:
Δ = accumulation of permanent deformation in the HMA layer (in.),
ε_p = accumulation of permanent or plastic axial strain in the HMA layer (in./in.),
ε_r = flexible or elastic strain calculated by the structural response model in the center of each sub-layer (in/in),
h = HMA layer thickness (in.),
n = number of load repetitions,
T = pavement temperature (°F),
k_z = depth confinement factor,
k_{1r}, k_{2r}, k_{3r} = global calibration parameter ($k_{1r} = -3.35412$, $k_{2r} = 0.4791$, $k_{3r} = 1.5606$),
β_{1r}, β_{2r}, β_{3r} = local calibration, with a default value of 1.0.

Calculation of load-related cracking in accordance with the MEPDG method was subdivided into two categories, namely the alligator and longitudinal crackings, which had their critical points located at the bottom and the layers on the Asphalt surface, respectively [12]. To determine the allowable repetition for both categories, Equation 4 was employed as follows.

$$N_{f-HMA} = k_{f1} . C . C_H . \beta_{f1} . \varepsilon_t^{k_{f2} \beta_{f2}} . E_{HMA}^{k_{f3} \beta_{f3}} \quad (4)$$

where:

N_{f-HMA} = number of allowable load repetitions for flexible pavement and HMA overlay,

ε_t = tensile strain at critical review location (in./in.),

E_{HMA} = HMA dynamic modulus (psi),

k_{f1}, k_{f2}, k_{f3} = global calibration coefficient; kf1 = 0.007566, kf2 = -3.9492, and kf3 = -1.281,

β_{f1}, β_{f2}, β_{f3} = local calibration coefficient, with a default value of 1.0,

$C = 10^M$.

During analysis, the MEPDG method was used to calculate the incremental fatigue damage index within grid patterns that transverse the HMA layers at critical depths. This incremental damage index (ΔDI) was determined by dividing the actual number by the allowable number of axle loads in accordance with Miner's Law [33]. To calculate the cumulative damage index (DI), which represents the accumulation of all incremental damages over time, Equation 5 was used as follows.

$$DI = \sum(\Delta \mathrm{DI})_{j,m,l,p,T} = \sum\left(\frac{n}{N_{f-HMA}}\right)_{j,m,l,p,T} \quad (5)$$

where:

n = actual number of axle-load applications within a specific period,

j = axle-load interval,

m = axle-load type (single, tandem, tridem, quad, or other special axle configuration),

l = truck type using the truck classification groups,

p = month,

T = median temperature for the five temperature intervals used to subdivide each month, °F.

Calculation of smoothness or IRI value over the design life was carried out using Equation 6.

$$IRI = IRI_0 + C_1(RD) + C_2(FC_{Total}) + C_3(TC) + C_4(SF) \quad (6)$$

where:

IRI_0 = IRI value after construction (in./mi),

SF = site factor,

FC_{Total} = area of fatigue cracking, a combination of alligator cracks, longitudinal cracks, and reflection cracks in the tire lane (% total area multiplied by 1ft for conversion),

TC = length of transverse cracking, including reflection from transverse cracks on the existing pavement (ft/mi),

RD = average rut depth.

4. ANALYSIS OF FWD DEFLECTION DATA

Before adjusting the deflection values for temperature effects, a segmentation process was carried out to ensure that each road segment exhibited a uniformity level value of < 30%. This segmentation technique utilizes statistical method to group data and achieve uniform values. The purpose is to ensure that the road segment targeted for overlaying maintains a consistent and uniform overlay value. The obtained results from this process are presented in Table 2.

5. BACK-CALCULATION WITH AASHTO 1993

To assess the structural condition of the existing pavement, analysis of the available data was carried out. Following this, the deflection characteristics of the road were obtained through the use of FWD test. In this study, back-calculation method employed is AASHTO method [31]. By employing this method, the structural conditions of the existing pavement were analyzed, resulting in the determination of the resilient modulus (MR) of the subgrade and the effective modulus (EP) of each layer located above the subgrade. Consequently, the modulus value of the Asphalt layer and base layer were treated as a single layer within analysis.

The results of back-calculation process using AASHTO are presented in Table 3. Additionally, the elastic modulus calculation results for the base layer are presented in Table 4.

Based on the compilation of Young's modulus for each pavement material type, the elastic modulus for overlay Asphalt used was 2,000,000 kPa. The Poisson's ratio values assigned for each layer were 0.4, 0.35, 0.38, and 0.45 for overlay asphalt, existing asphalt, base, and subgrade layers, respectively.

Table 2 Representative Rebound Deflection

Explanation	Initial STA - Final STA (KM)	Deflection (mm)						
		d1	d2	d3	d4	d5	d6	d7
Segment 1	0+000 - 0+600	258.51	211.17	179.88	159.76	144.67	119.93	61.78
Segment 2	0+600 - 1+100	339.08	277.73	220.39	160.09	122.37	78.91	46.80

Table 3 The Results of Back-calculation using AASHTO 1993 Method

Explanation	Initial STA – Final STA (KM)	M_R (kPa)	E_P (kPa)
Segment 1	0+000 - 0+600	35,991	241,893
Segment 2	0+600 - 1+100	47,133	172,696

Table 4 Calculation of the Elastic Modulus of the Base Layer Results

Explanation	Initial STA – Final STA (KM)	E *Base* (kPa)
Segment 1	0+000 - 0+600	179,956
Segment 2	0+600 - 1+100	235,669

6. STRESS-STRAIN ANALYSIS WITH KENLAYER

Mechanistic analysis was conducted in this study to obtain the value of vertical strain, horizontal strain, vertical stress, and horizontal stress by utilizing the resilient modulus and effective modulus in the structural analysis of the existing pavement. Furthermore, in the context of overlay thickness experiment conducted during the mechanistic analyses, six different thickness were tested, namely 50, 80, 100, 130, 150, and 200 mm, with each segment experimented once. For the input of the mechanistic-empirical calculation based on the design criteria of the Asphalt Institute [11] and the MEPDG method [12], only the strain values were required as input. Additionally, the analysis results, specifically the strain values obtained using KENLAYER software for Segment 1 as an example, are presented in Table 5 and Table 6.

7. THE RESULTS OF DESIGN CRITERIA CALCULATION USING THE ASPHALT INSTITUTE – HUANG MECHANISTIC-EMPIRICAL METHOD

The mechanistic-empirical method utilized by the Asphalt Institute, as outlined by [11], relies on the consideration of fatigue cracking and permanent deformation. This method employs a formula derived from the Asphalt Institute to assess these factors. Accordingly, the results for the design criteria pertaining to Segment 1, as an example, are presented in Table 7.

Table 5 Results of Strain Value Analysis using the Asphalt Institute Method for Segment 1

Mechanistic-Empirical Input of the Asphalt Institute - Huang (2004)		
Overlay Thickness (mm)	Fatigue Cracking	Permanent Deformation
50	2.58E-04	1.47E-03
80	2.33E-04	1.32E-03
100	1.92E-04	1.23E-03
130	1.70E-04	1.09E-03
150	1.55E-04	1.00E-03
200	1.48E-04	8.20E-04
250	9.03E-05	5.81E-04

Table 6 Results of Strain Value Analysis using the MEPDG Method for Segment 1

Mechanistic-Empirical Input of the MEPDG (2015)						
Overlay Thickness (mm)	Permanent Deformation				Fatigue Cracking	
	Overlay Asphalt	Existing Asphalt	Base	Subgrade	Alligator	Longitudinal
50	2.36E-04	1.99E-03	7.43E-04	1.41E-03	2.58E-04	3.78E-04
80	1.99E-04	1.76E-03	6.93E-04	1.27E-03	2.33E-04	3.71E-04
100	1.88E-04	1.59E-03	6.55E-04	1.18E-03	1.92E-04	3.64E-04
130	1.73E-04	1.35E-03	5.99E-04	1.05E-03	1.70E-04	3.53E-04
150	1.54E-04	1.22E-03	3.22E-04	9.66E-04	1.55E-04	3.40E-04
200	1.32E-04	9.42E-04	4.85E-04	7.95E-04	1.48E-04	3.34E-04
250	9.25E-05	5.42E-04	2.37E-04	5.69E-04	9.03E-05	3.15E-04

Table 7 Design Criteria Calculation Analysis using the Asphalt Institute Method for Segment 1

Overlay Thickness (mm)	CESA (2021-2030)	Strain	Fatigue Cracking	Explanation	Strain	Permanent Deformation	Explanation
50	2.57E+06	2.58E-04	1.11E+06	NOT OK	1.47E-03	6.64E+03	NOT OK
80	2.57E+06	2.33E-04	1.55E+06	NOT OK	1.32E-03	1.05E+04	NOT OK
100	2.57E+06	1.92E-04	2.94E+06	OK	1.23E-03	1.48E+04	NOT OK
130	2.57E+06	1.70E-04	4.36E+06	OK	1.09E-03	2.54E+04	NOT OK
150	2.57E+06	1.55E-04	5.95E+06	OK	1.00E-03	3.65E+04	NOT OK
200	2.57E+06	1.48E-04	6.88E+06	OK	8.20E-04	8.93E+04	NOT OK
250	2.57E+06	9.03E-05	3.51E+07	OK	5.81E-04	4.17E+05	NOT OK
300	2.57E+06	5.14E-05	2.24E+08	OK	3.63E-04	3.42E+06	OK

8. DESIGN CRITERIA CALCULATION RESULTS WITH THE MEPDG METHOD

The MEPDG method [12] used in this study incorporates five key design criteria, namely rut depth, load–related cracking (alligator and longitudinal cracking), non–load related cracking (specifically transverse cracking), and smoothness. However, calculation for transverse cracking was not performed due to the absence of freezing temperatures in Indonesia. The results of the design criteria calculation for Segment 1, as an illustrative example, are shown in Table 8.

9. OVERLAY THICKNESS COMPARISON WITH THE ASPHALT INSTITUTE METHOD AND MEPDG METHOD

Following the completion of the mechanistic-empirical calculation using the Asphalt Institute method [11] and MEPDG method [12], a comparison analysis of overlay thickness was conducted to determine the appropriate thickness for each method. Accordingly, the output recapitulation of the Asphalt Institute method and MEPDG method based on their respective design criteria is shown in Fig. 2. It is important to note that an overlay thickness of 30 cm was obtained for the Asphalt Institute method and 25 cm for the MEPDG method.

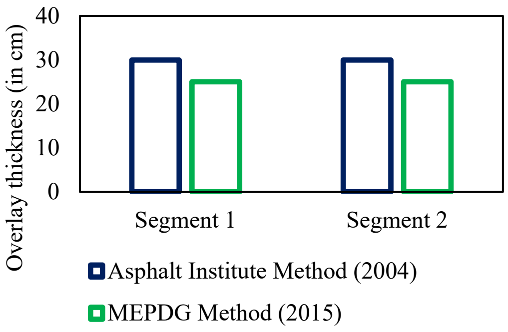

Fig. 2 Overlay Thickness of Each Segment from the Asphalt Institute Method and MEPDG Method

The obtained results showed that Asphalt Institute Method yielded a slightly thicker overlay of 30 cm while the MEPDG method yielded 25 cm of overlay thickness. This finding is also aligned with previous study in Indonesia that considered MEPDG method as the more economical design [22].

10. CONCLUSIONS

The study compared the Asphalt Institute and MEPDG methods for pavement design, focusing on overlay thickness output. Notable differences were found, including criteria for fatigue cracking and permanent deformation. In the Asphalt Institute method, the design criteria for fatigue cracking were determined at the point of the Asphalt bottom layer. On the other hand, the MEPDG method considered alligator cracking at the Asphalt bottom layer and longitudinal cracking at the Asphalt top layer. Regarding permanent deformation, the Asphalt institute established the design criteria at the top layer point of the subgrade, while the MEPDG method considered each midpoint of overlay Asphalt, existing Asphalt, base layer, and above the subgrade layer.

The Asphalt Institute method only utilized the fatigue cracking design criteria, particularly alligator cracking and rut depth. In contrast, the MEPDG method, being the latest pavement design method, incorporated additional design criteria such as longitudinal cracking, reflection cracking, and smoothness, which played a role in determining the performance and thickness of pavement. The results indicated that the Asphalt Institute Method resulted in an overlay thickness of 30 cm, whereas the MEPDG method produced a slightly thinner overlay thickness of 25 cm.

Implementing MEPDG in Indonesia requires adjustments, including using Weigh-In-Motion data for load spectra and local calibration. Further research should establish local calibration values aligned with Indonesia's climate zones, utilizing field tests and AASHTOWare software training for effective results.

Table 8 Design Criteria Calculation Analysis using the MEPDG Method for Segment 1

Overlay Thickness (mm)	Permanent Deformation (inch)	CHECK < 0,50 inch	Fatigue Cracking		CHECK < 20%	IRI (m/km)	CHECK < 4 m/km
			Alligator Cracking (%)	Longitudinal Cracking (%)			
50	2.95	NOT OK	4.02	8.42	OK	5.79	NOT OK
80	2.06	NOT OK	3.71	8.30	OK	5.25	NOT OK
100	1.37	NOT OK	3.13	8.07	OK	4.83	NOT OK
130	0.64	NOT OK	2.83	7.93	OK	4.39	NOT OK
150	0.36	OK	2.61	7.83	OK	4.23	NOT OK
200	0.06	OK	2.52	7.78	OK	4.05	NOT OK
250	0.00	OK	1.61	7.24	OK	3.98	OK
300	0.00	OK	0.96	6.67	OK	3.96	OK

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