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Recommended Changes to Designs Not Meeting Criteria Using the Mechanistic-Empirical Pavement Design Guide

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Abstract: The newly Mechanistic-Empirical Pavement Design Guide (MEPDG) allows engineers to design pavement structural layers to sustain predefined limits of distress levels due to traffic loads and environmental conditions based on nationally/locally calibrated performance models. Users are required to input variables related to traffic, environment, and materials. In addition, reliability and limiting values of the distresses are required inputs. MEPDG in its current version is an analysis procedure rather than a design tool. However, it is intended to be also used as a design tool. Thus, the design process of the pavement structure in MEPDG is a trial process. It starts with assuming a structure and material properties and then performing the analysis. If the proposed trail did not meet the criteria, then the material properties and/or layer(s) thicknesses are changed until the design meets the criteria. This paper presents a reference document to assist pavement designers in identifying the most important MEPDG key inputs to modify such that the predicted distresses meet predefined design criteria. Results showed that, pavement structural design should be coupled with the mix design and selection of material properties in order to achieve an economic design complying with the criteria.

Key words: *Fatigue cracking, HMA, Longitudinal cracking, MEPDG, Rutting, Performance.*

Introduction

Pavement design is the process of estimating the most economical pavement structure (layers thicknesses and material characteristics) in order to sustain the expected traffic loads and environmental conditions and provide the user with a safe and good ride quality throughout the pavement service life. Over years, the process of pavement design has been an empirical procedure in nature based on experience and observation [1]. Currently, several mechanistic-empirical (M-E) design methods such as Caltrans Mechanistic-Empirical Pavement Design (CalME), and the Mechanistic-Empirical Pavement Design Guide (MEPDG), are available [2, 3, 4]. These methods allow engineers to design pavement structural layers to sustain predefined limits of distress levels due to traffic loads and environmental conditions throughout the pavement service life. Failure occurs when pavement distresses exceed those limits.

MEPDG which was developed under the NCHRP 1-37A research project is a tool that mechanistically calculates the structural response (stresses, strains, and deflections), within a pavement system, based on material properties, traffic characteristics, and environmental conditions using multilayer elastic theory and/or finite element methods. Moisture and temperature variations within the pavement structure are also calculated internally using the Enhanced Integrated Climatic Model (EICM). The calculated stresses are then transformed into distresses (permanent deformation, bottom-up and top-down fatigue cracking, thermal cracking, and roughness) using empirical transfer functions. These transfer functions are nationally calibrated using 94 Long Term Pavement Performance (LTPP) sections distributed throughout the United States [2]. The software also allows the user to input his/her calibration coefficients (local or regional) to reflect local conditions.

In the current version of MEPDG, pavement design is an iterative process starts with the designer defines a trial pavement section (layers arrangement, layer thicknesses, and material properties) then conducts analysis to predict pavement performance. If the predicted performance meets the design criteria, then the trial section is accepted. If not then the designer should modify the section and performs the analysis again until it meets the predefined design criteria. Usually these modifications are either material quality related or layer thickness related.

Normally the design inputs which affect pavement performance have two main categories. The first category includes the controllable inputs (variables), which the designer can modify in order to comply with the required specifications. These controllable variables include layers thicknesses (asphalt concrete and bound/unbound base and subbase) and material properties such as; binder grade, aggregate gradation, binder content, mix air voids, etc. On the other hand, the uncontrollable variables are the variables that the designer cannot modify and they are specific to each design project. Site location, which determines the climatic characteristics and foundation properties (subgrade modulus, depth to ground water table, depth to bedrock,), and traffic volume and loading characteristics are examples of the uncontrollable variables.

One major difference between MEPDG and the current design practice in the U.S. and many countries in the world, which mostly rely on empirical procedures such as AASHTO 1993 or earlier versions, is the linkage between the Hot-Mix-Asphalt (HMA) design properties and the structural design of the pavement. Thus, several studies have been performed over the last few years to define sensitivity of the MEPDG predicted performance to key parameters. However, none of these studies comprehensively covered the influence of the position and stiffness of the asphalt

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concrete (AC) layer within the pavement structure on predicted performance.

Objectives

The primary objective of this research is to develop a reference document to assist pavement designers in identifying the most important key inputs to modify such that longitudinal cracking, alligator fatigue cracking, and rutting meet predefined design criteria. In addition, this paper aims at investigating the impact of the position and characteristics of the HMA sub-layers within the pavement structure on the MEPDG predicted pavement performance.

Literature Review

Results of several research work found in literature regarding permanent deformation and fatigue cracking were studied and summarized in Tables 1 and 2 [2, 5-10]. In these tables the controllable and uncontrollable factors affecting the magnitude of the pavement distresses as well as those factors having little or no influence are identified. The level of significance of each parameter on each predicted pavement performance is indicated in these tables. The level of significance was determined based on the percentage difference of the MEPDG predicted performance at the two typical low and high values used for each input parameter. Detail of the data inputs used for those studies can be found elsewhere [2, 5-10].

Factors Influencing Fatigue Cracking

Literature studies show that the load associated HMA alligator and longitudinal fatigue cracking are affected not only by the HMA layer(s) volumetric properties and stiffness but also by the foundation layer quality [8, 9, 11]. High foundation modulus yields a reduction in the bottom-up alligator fatigue cracking and an increase in the top-down longitudinal fatigue cracking. In addition, the higher the mix stiffness the higher is the fatigue cracking (top-down and bottom-up), in case of thin HMA thickness layers. Moreover, increasing the HMA effective binder content (Vbe) significantly decreases both types of fatigue cracking [8]. On the other hand, increasing the mix air voids leads to a significant increase in both types of cracking. Literature studies also show that, longitudinal fatigue cracking is higher for pavement structures with 6 inches of HMA layer thickness while alligator cracking peaks in flexible pavement systems with 3 to 5 inches of HMA thickness [9]. Unfortunately this range is the most widely range of HMA

Table 1. Factors Influencing AC Fatigue Cracking.

	Property	Fatigue Cracking: Top-Down (Longitudinal)	Fatigue Cracking: Bottom –UP (Alligator)	Remarks
C	AC Mix Stiffness (Thin AC Layer) ▲	Very Significant Specially at High SG Modulus ▼	Very Significant Specially at Low SG Modulus▲	Quality of the Foundation Material is Very Important High SG Modulus Reduces Bottom-up Cracking Low SG Modulus Reduces Top-down Cracking
C	AC Mix Stiffness (Thin AC Layer) ▲	Very Significant Specially at High SG Modulus ▼	Insignificant at Very Thick AC Layer Thicknesses -▼	
C	AC Thickness ▲	Very Significant Specially at High SG Modulus	Very Significant Specially at Low SG Modulus	Longitudinal Cracking Peaks at 6 in AC then Decreases Alligator Cracking Peaks at 3–5 in AC then Decreases
C	AC Mix Air Voids ▲	Very Significant ▲	Very Significant ▲	
C	Effective AC Content ▲	Very Significant ▼	Very Significant ▼	
U	MAAT ▲	Very Significant ▲	Very Significant ▲	MAAT Must be Combined with AC Thickness and Stiffness for Both Types of Cracking
U	Subgrade Modulus ▲	Very Significant ▲	Very Significant ▼	
U	Traffic Volume ▲	Very Significant ▲	Very Significant ▲	
U	Traffic Speed ▼	Insignificant, for Thin AC, -▲ Insignificant, for Thick AC, -▼	Insignificant, for Thin AC, -▲ Insignificant, for Thick AC, -▼	
U	Bedrock Depth ▲	Very Significant ▼	Very Significant ▲	
U	Depth to GWT ▲	Very Significant ▲	Significant at Llow SG Modulus -▼	

-▲ Very Slight Increase -▼ Very Slight Decrease ▲Increase ▼Decrease
C = Controllable Property U = Uncontrollable Property

Table 2. Factors Influencing the HMA Permanent Deformation (Rutting).

	Property	AC Rutting	Remarks
C	AC Mix Stiffness (Thin AC layer) ▲	Insignificant	Small AC Rutting Large Base Rutting Large Subgrade Rutting
C	AC Mix Stiffness (Thick AC Layer) ▲	Very Significant ▼	Thick AC Layer Rutting Much Greater Than Thin AC Layer Rutting Small Base and Subgrade Rutting
C	AC Thickness ▲	Very Significant ▼	The Highest Rutting in AC Layer at 3-5 in AC, Lowest at 1 in AC Thickness
C	AC Mix Air Voids ▲	Significant ▲	Air Voids Less Than 2-4 %
C	Effective AC Content ▲	Significant ▲	
U	Mean Annual Air Temperature (MAAT) ▲	Significant ▲	Use high AC Stiffness at High Temperatures to Reduce AC Rutting
C	Base Thickness ▲	Insignificant	Base Thickness Significantly Affect the Subgrade Rutting Specially at Low Subgrade Modulus
C	Base Quality ▲	Insignificant	
U	Subgrade Modulus ▲	Insignificant	For AC Layer Thickness > 3 in. Subgrade Modulus is Insignificant on Base Rutting
U	Traffic Volume ▲	Very Significant ▲	At High Traffic Use High AC Stiffness
U	Traffic Speed ▲	Very Significant at Creep Speeds (Intersections) ▼	Affects the AC Mix Stiffness (Time Rate of Loading)
U	Bedrock Depth ▲	Insignificant	
U	Depth to GWT ▲	Insignificant	Very Significant at Low SG Modulus

-▲ Very Slight Increase　　-▼ Very Slight Decrease　　▲ Increase　　▼ decrease

C = Controllable property　　U = Uncontrollable Property

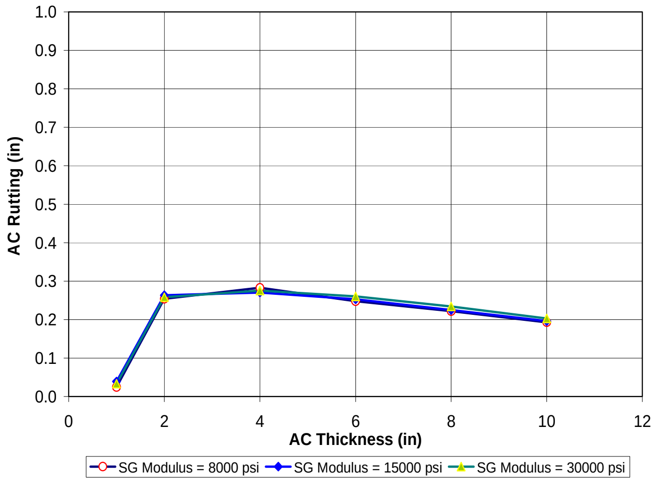


Fig. 1. Effect of Subgrade Modulus on Predicted AC Rut Depth at Different AC Thicknesses [9].

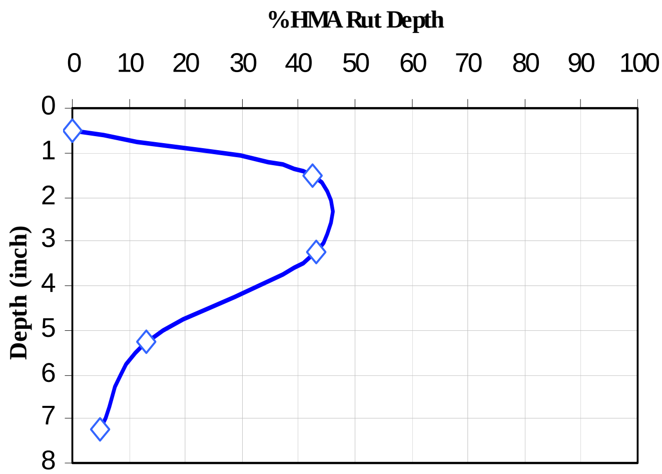


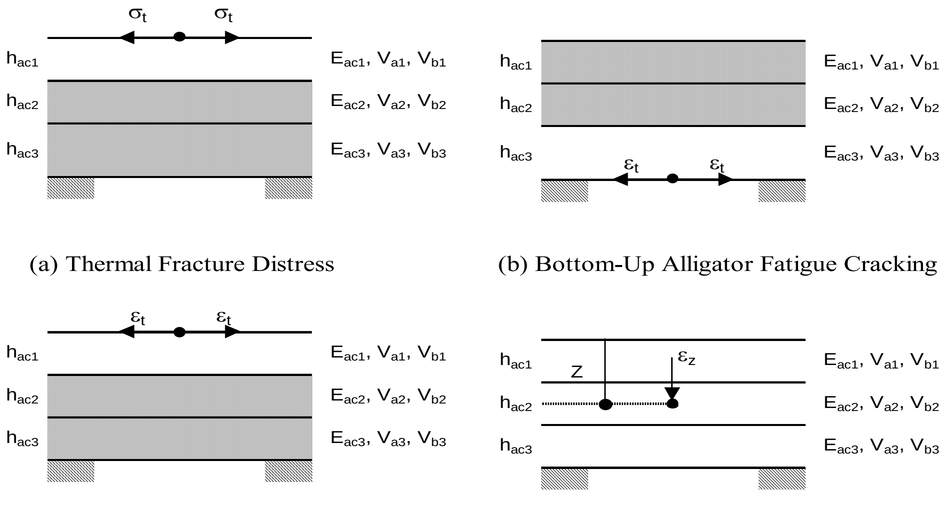
Fig. 2. Relationship between Average Percent AC Rutting and Depth.

thickness that is being used in practice. It should be noted that the results of these literature studies are based on one HMA layer rather than multi-HMA layers with different stiffness characteristics.

Factors Influencing AC Permanent Deformation

Table 2 summarizes the key structural and material factors influencing the HMA rutting distress based on literature studies [2, 8, 10]. These studies show that asphalt concrete (AC) layer rutting is only a function of the AC layer thickness, mix volumetric properties, stiffness, temperature, and traffic. Higher AC rut depths are predicted at lower AC mix stiffness values. At lower HMA binder contents, less AC rutting is predicted. Furthermore, higher mix air voids results in higher AC rutting.

An important conclusion from the investigated literature is that that base/subbase layer thicknesses and properties, quality of subgrade and depth to bedrock have very little to no effect on the HMA rutting [10]. Fig. 1 shows that the foundation (subgrade) modulus has almost no influence on the predicted AC rut depth. Fig. 2 depicts another important conclusion from literature which is that AC rutting usually peaks in pavement structures with HMA layer thicknesses between 3 to 5 inches [10]. Fig. 2 also shows that most



(a) Thermal Fracture Distress

(b) Bottom-Up Alligator Fatigue Cracking

(c) Top-Down Longitudinal Cracking

(d) AC Rut Depth

Fig. 3. Impact of HMA Structure on Distress Prediction [12].

of the AC rutting occurs within the top 4+ inches with almost no rutting within the top 1 inch. [2, 8] This is a very important conclusion as it informs the designers that, HMA volumetric properties and stiffness of the intermediate AC layer (binder course) has the greatest influence on the rutting potential of the AC layer.

Design Parameters Used in the Study

To understand the role of the properties and structure of the HMA layers on pavement performance, those studies found in literature were extended in this research. Two pavement structures with varied HMA properties were run using MEPDG. The following subsections describe the pavement structures, environmental conditions, and other factors used in the analyses.

Pavement Structure

In order to select the pavement structure to use in the analysis, it was first important to study each distress predicted by MEPDG. It was also important to understand and recognize the impact of the position of the AC layer within the pavement structure on pavement performance. Fig. 3 illustrates the relationship between the position of the AC layer within the pavement structure and the main distress types. This figure shows that the AC layer can be divided into three sub-layers with different properties relevant to the type of distress expected to occur in this sub-layer. The thermal stresses at the surface of the pavement caused by temperature drops are responsible for the thermal cracking distress (Fig. 3(a)). In this distress type, only AC mix properties (V_{a1}; air voids, V_{b1}: binder content, and E_{ac1}: AC modulus) of the surface layer are considered to resist the thermal fracture distress. The mixture properties of the other AC sub-layers as well as properties of the foundation do not affect the thermal fracture distress (transverse cracking).

Fig. 3(b) shows that the bottom-up fatigue cracking results from the horizontal tensile strain at the bottom of the lowest AC sub-layer. Hence only AC mix properties of this layer (V_{a3}, V_{b3} and E_{ac3}) play the critical role in resisting the bottom-up alligator fatigue cracking. However the total thickness of all AC sub-layers plays an important role in affecting the state of stress and strain at the bottom of the lowest AC sub-layer as well as the compressive stresses in the underlying layers. In addition, the foundation layer properties (modulus) affect the fatigue cracking at the bottom of the HMA layer as well as the longitudinal cracking at the surface of the pavement as illustrated before.

The top-down longitudinal cracking mechanism is shown in Fig. 3(c). This figure implies that the horizontal tensile strain at the pavement surface is the main reason for this distress type. Thus, the surface AC sub-layer properties (V_{a1}, V_{b1} and E_{ac1}) affect the longitudinal cracking distress. The properties of the bottom AC sub-layers do not contribute to the resistance of the top-down longitudinal cracking. Like the alligator cracking, longitudinal cracking is a function of the modulus of the foundation.

Fig. 3(d) depicts the fact that AC rutting distress occurs due to the compressive strain within the AC sub-layers. It is clear that all AC layer properties affect the AC rut depth. However, most of the AC rutting usually occurs in the top 1 to 4+ inches as shown previously in Fig. 2. Further, the foundation layer properties have no impact on the AC rutting. On the other hand, the higher the stiffness of the AC layer(s), the lower is the amount of rutting in the foundation and consequently the lower the amount of total pavement rutting.

Thus, two pavement structures were used in this study. The first structure is the "Control Section, CS" which consists of a typical 3-layer conventional pavement system of 6 inches (15.24 cm) thick HMA layer of medium stiffness and a granular A-1-b base layer of 10 inches (25.4 cm) thickness and a resilient modulus of 38,000 psi (262 MPa) over an A-6 subgrade foundation with a resilient modules of 15,000 psi (103 MPa) as shown in Fig. 4(a). The second pavement structure shares the same base layer thickness and properties, same subgrade foundation properties as well as the total thickness of the HMA layer. However, the HMA layer in this section

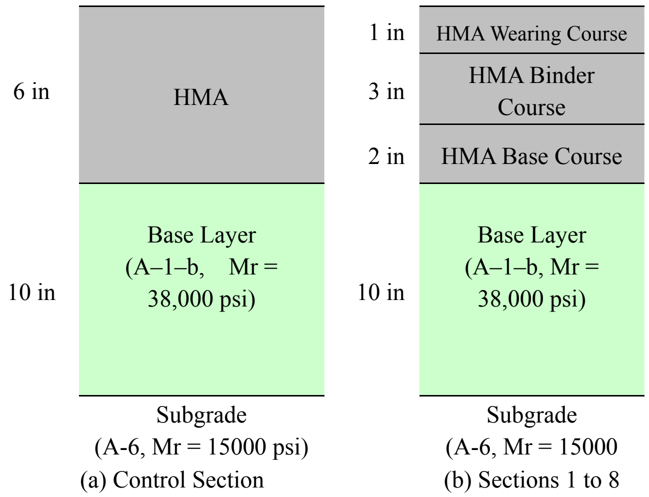


Fig. 4. Pavement Cross-Sections used in the MEPDG Simulation Runs.

Table 3. Asphalt Mixture Properties.

Variable	Low Mix	Medium Mix	High Mix
Air Voids (%)	7	7	8
Effective Binder Content, V_{be} (%)	12	11	10
VFA (%)	63	61	55
% Retained ¾”	0	11.62	30
% Retained 3/8”	1.16	35.3	47
% Retained # 4	27.65	52.64	52.8
% Passing # 200	11.12	7.28	8.38
PG Grade	46-34	58-28	76-16
Binder A	11.504	11.01	10.015
Binder VTS	-3.901	-3.701	-3.315

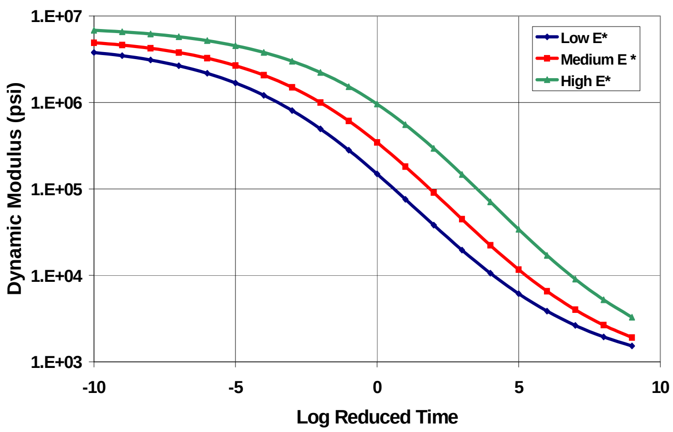


Fig. 5. HMA E* Master Curves.

was divided into three sub-layers {(1 in (2.54 cm) wearing course, 3 in (7.62 cm) binder course and 2 in (5.08 cm) base course} as shown in Fig. 4(b). Each layer was assigned a different stiffness.

Environmental Conditions

All MEPDG computer simulations runs were conducted at three different environmental conditions. The environmental conditions were chosen to cover a broad range of climate as follows:

Cold: means annual air temperature (MAAT) = 40.4°F (4.7°C).
Moderate: MAAT = 60.5°F (15.8°C).
Hot: MAAT = 77.8°F (25.4°C).

Design Life

A design life of 10 years was selected to reduce the run time of the software.

Design Traffic

El-Badawy et al. showed that there is a direct relationship between traffic level, expressed in ESALs, and fatigue damage [11]. In addition, Sotil proved that there is also a direct relationship between traffic level, expressed in ESALs, and AC rutting [13]. Thus, only one traffic load level equivalent to 2 million classical 18-kips single axle load (E18kSAL) repetitions over the 10-year design period was applied in all conducted runs. The traffic speed used for all runs was 45 mph (72.4 km/hr).

Asphalt Mix Characteristics

Three different AC mixtures properties covering a wide range of stiffness (E*) were used in this study. The E* data utilized in this research were selected from a large database of historic AC mixtures [8, 9]. Table 3 shows the mixture properties as well as the Superpave performance binder grade used in the selected mixtures. The mixtures E* master curves are shown in Fig. 5. In addition to the properties shown in Table 3, the effective binder content (V_{beff}) and air voids were also changed. This is explained later.

MEPDG Computer Simulation Runs

A total of 27 computer simulation runs were conducted using MEPDG version 0.70. These simulation runs were conducted using the two prescribed pavement structures. The HMA properties of the “CS” structure were chosen to reflect the mediums stiffness condition shown in Table 3. The “CS” structure was run three times, using MEDPG, and each run was conducted at one of the three climatic conditions (cold, moderate, and hot). The other structure with the three AC sub-layers was also run at the same three climatic conditions using different E* for the three AC sub-layers as well as binder and air voids contents as shown in Table 4.

Results and Analysis

The results of the MEPDG computer simulation runs for the moderate climatic condition are summarized in Table 4. These results show the achieved reduction in the pavement distresses (top-down cracking, bottom-up alligator fatigue cracking, AC rut depth and the total pavement rutting) for eight different pavement cross-sections compared to the Control Section just by utilizing the proper mix volumetric properties and stiffness for each AC sub-layer. Compared to the Control Section, Section 1 shows better resistance to all load associated pavement distresses. By using soft AC mixture (Low Mix) for the upper AC sub-layer, stiff AC mix (High Mix) for the intermediate sub-layer and Medium Mix for the

Table 4. Impact of HMA Structure Properties on MEPDG Distress Prediction for Moderate Temperature Climate.

ID	HMA Structure	Longitudinal Cracking (ft/mile)	Alligator Cracking (%)	AC Rutting (in)	Total Rutting (in)
Control Section	6 in Med. Stiffness HMA	1520	2.69	0.252	0.547
Section 1	1 in Low Stiffness HMA 3 in High Stiffness HMA 2 in Med. Stiffness HMA	809	2.19	0.131	0.422
	Percent Reduction in Predicted Distress	47%	19%	48%	23%
Section 2	1 in Med. Stiffness HMA 3 in High Stiffness HMA 2 in Med. Stiffness HMA	1160	1.87	0.109	0.394
	Percent Reduction in Predicted Distress	24%	30%	57%	28%
Section 3	1 in Med E*, High Vbeff 3 in High Stiffness HMA 2 in Med. Stiffness HMA	384	1.97	0.112	0.398
	Percent Reduction in Predicted Distress	75%	27%	56%	27%
Section 4	1 in Med. Stiffness HMA 3 in High Stiffness HMA 2 in Med E*, High Vbeff	1260	0.856	0.112	0.399
	Percent Reduction in Predicted Distress	17%	68%	56%	27%
Section 5	1 in Med E*, Low Va 3 in High Stiffness HMA 2 in Med. Stiffness HMA	156	1.74	0.107	0.39
	Percent Reduction in Predicted Distress	90%	35%	58%	29%
Section 6	1 in Med. Stiffness HMA 3 in High Stiffness HMA 2 in Med E*, Low Va	1040	1.62	0.105	0.387
	Percent Reduction in Predicted Distress	32%	40%	58%	29%
Section 7	1 in Med. Stiffness HMA 3 in High E*, Low Vbeff 2 in Med. Stiffness HMA	1090	1.72	0.101	0.384
	Percent Reduction in Predicted Distress	28%	36%	60%	30%
Section 8	1 in Med. Stiffness HMA 3 in High E*, Low Va 2 in Med. Stiffness HMA	1040	1.62	0.096	0.379
	Percent Reduction in Predicted Distress	32%	40%	62%	31%

lower AC sub-layer, a 47% reduction in the longitudinal cracking, 19% in the alligator cracking, 48% in the AC rutting, and 23% percent reduction in the total rutting were achieved compared to the Control Section. The reduction in the alligator cracking was of course due to the stiff intermediate AC sub-layer, which led to a decrease in the state of stress and strain at the bottom of the lower AC sub-layer.

By increasing the stiffness of the upper layer from Low to Medium, Section 2 shows greater reduction in AC rutting and less reduction in longitudinal cracking compared to Section 1. Sections 3 and 4 illustrate the effect of increasing the amount of binder (V_{be}) in the wearing course and binder course layers, respectively. As shown in Table 4, an increase in the effective binder content from 11% to 15% (high V_{beff}) led to a decrease in the top-down longitudinal fatigue cracking by about 75 % compared to the Control Section and 67 % compared to Section 2. The same behavior occurred with Section 4 but now an increase in V_{beff} from 11 % to 15 % for the bottom AC sub-layer yielded about 68 % reduction in the bottom-up cracking compared to the Control Section and 54% compared to Section 2. The reduction in the AC rutting of both sections (Sections 3 and 4) was almost the same meaning that both the upper thin AC sub-layer and the lower AC sub-layer did not contribute to the AC rutting.

Sections 5 and 6 show the influence of changing the air voids (V_a) of the upper AC sublayer (wearing course) and the lower AC sub-layer (base course) on both types of fatigue cracking (longitudinal and alligator). The results of Section 5 show about 90% reduction in the longitudinal cracking just by reducing the air voids content of the upper AC sub-layer from 7% to 4% (low V_a). While for the same air voids reduction in the base course layer (Section 6), about 40% reduction in the alligator fatigue cracking was achieved. A very good reduction in the AC rutting still being achieved compared to the Control Section (58%) with using a stiff (high E*) HMA for the intermediate sub-layer while changing the properties of the upper and lower HMA sub-layers.

It is interesting to notice that the change in the predicted AC rut depth was quite small when the properties of the upper and lower AC sub-layers were changed (the decrease in the AC rutting ranged

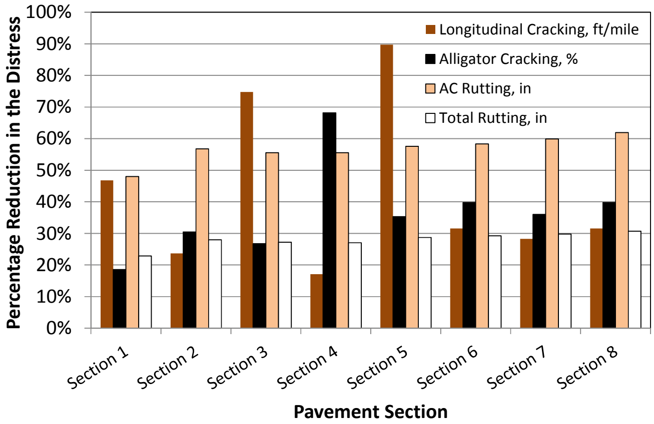


Fig. 6. Percentage Reduction in MEPDG Predicted Distresses Compared to the Control Section (Moderate Climate).

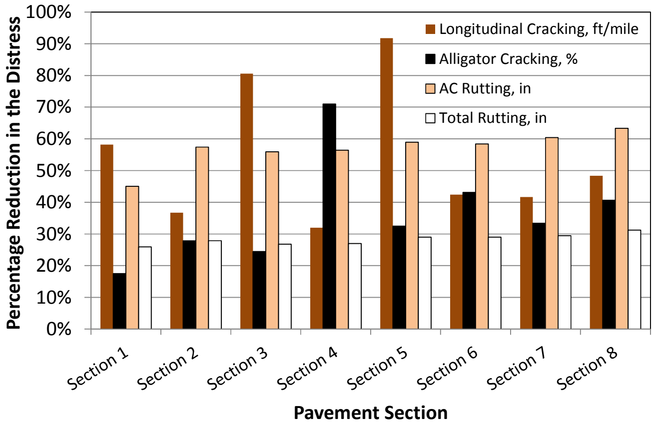


Fig. 7. Percentage Reduction in MEPDG Predicted Distresses Compared to the Control Section (Cold Climate).

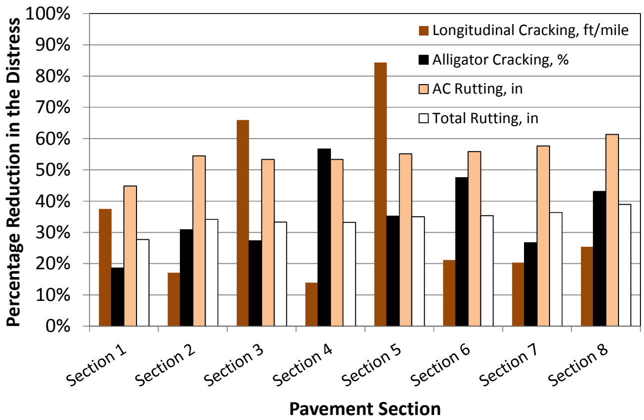


Fig. 8. Percentage Reduction in MEPDG Predicted Distresses Compared to the Control Section (Hot Climate).

between 48-62% for Section 1 to 8 compared to the Control Section). This means that most of the predicted rutting was a function of the intermediate layer properties which agrees quit well with Fig. 2. The very low rutting in the upper most AC sub- layer may be contributed to a hydrostatic state of stress at the surface of the pavement.

Looking carefully into Sections 3 and 5 another important conclusion could be drawn. Reducing the air voids of the upper AC sub-layer was more significant than increasing the effective binder content on the predicted longitudinal fatigue cracking. While for better resistance to alligator cracking, increasing the effective binder content of the bottom AC sub-layer was more significant than decreasing the mix air voids of this layer. This is shown in Table 4 for Sections 4 and 6.

Sections 7 and 8 illustrate the influence of changing the air voids and the effective binder content of the intermediate AC sub-layer on the AC rutting. It is clear from Table 4 that decreasing the air voids and the binder content lead to a decrease in the AC rutting.

This achieved reduction in MEPDG predicted distresses compared to the “CS” section for the moderate climate condition is shown graphically in Fig. 6. Figs. 7 and 8 depict the archived reduction in MEPDG predicted distresses for the cold and hot climate conditions, respectively. For all practical purposes, these figures show very similar trends as well as percentage reduction of the predicted distresses compared to the Control Section.

Conclusions

This research work aims to develop a reference document to assist pavement designers in identifying the most important key inputs to modify such that the pavement performance meets the design criteria. Significant findings of this research are as follows:

- The designer should recognize and fully understand the critical role of the HMA structure in resisting pavement distresses.
- Pavement structural design should be coupled with mix design and selection of the material properties in order to achieve an economic design complying with the criteria.
- For high volume roads, MEPDG results show that it is better to divide the AC layer into three sub-layers with each layer having the appropriate mix volumetric properties and stiffness according to the location of this layer as follows:
    - Wearing course (surface AC sub-layer) with low AC stiffness, high AC content, and low air voids to resist both thermal fracture and top-down longitudinal cracking.
    - Binder course (intermediate AC sub-layer) with very high stiffness, coarse aggregate gradation, low AC content and mix air voids to resist rutting.
    - Base course (bottom AC sub-layer) with low stiffness, high AC content and low air voids to resist bottom-up alligator cracking.
- Thicker HMA layer thickness leads to a reduction in the stress and strain states at the bottom of the AC layer as well as top of the base/subbase and subgrade hence reduces the alligator cracking at the bottom of the HMA layer and rutting of the base and subgrade.
- AC fatigue cracking is affected not only by the HMA layer volumetric and stiffness but also by the foundation layer properties. High foundation modulus values leads to a decrease in the bottom-up alligator cracking and an increase in the top-down (longitudinal) cracking.
- Unlike fatigue cracking, AC rutting is only a function of the HMA properties (V_a, V_b and E*). Furthermore, most of the AC rutting occurs within the top 4+ inches with almost no rutting

within the top 1 in due to a hydrostatic state of stress at the surface of the pavement.

- The effect of changing the properties of the upper and lower AC sub-layers on the AC rutting compared to the intermediate AC sub- layer properties is quite small.
- With regard to longitudinal fatigue cracking, reducing the air voids of the upper AC sub-layer is more significant than increasing the effective binder content. While for better resistance to alligator cracking, increasing the effective binder content of the bottom AC sub-layer is more significant than decreasing the mix air voids of this layer.

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