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Research paper

Evaluation of the Impact of Existing Condition and Overlay Characteristics on Asphalt Overlay Design and Performance based on a Mechanistic-Empirical Approach

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Abstract

The present study sought to determine how the overlay design and performance of asphalt concrete (AC) were affected by existing pavement condition and overlay material properties. To that end, this study was performed in different scenarios of traffic and structure with the latest AASHTO design software AASHTOWare (version 2.3). The modulus and rut depth of existing layers, the interface condition between AC overlay and existing pavement, and the AC overlay properties of Poisson’s ratio and performance grade were addressed in the current study. Besides the overlay thickness design, the investigation also focused on pavement performance to determine how separate distresses were impacted by existing pavement condition and the properties of the overlay material. The investigation produced three major outcomes, as follows: the current AC layer thickness and design traffic determined the extent to which the existing AC layer condition affected the overlay design thickness; the overlay performance and design were not significantly affected by the existing base and subgrade condition; and fatigue cracking was more strongly influenced by the existing AC layer modulus and interface bonding condition compared with the rutting potential.

Keywords: *AASHTOWare, existing pavement condition, MEPDG, overlay design, pavement performance.*

1. Introduction

Dealing with surface conditions like low skid resistance and improving the structural capacity of a pavement subjected to extensive traffic volumes and/or heavy traffic loads are just two of the diverse applications of asphalt concrete (AC) overlays. AC overlay design requires the existing pavement to be characterized and impact of that condition on overlay performance to be determined.

In the context of the National Cooperative Highway Research Program (NCHRP) Project 1-37A [1] and NCHRP Project 1- 40D [2], Mechanistic-Empirical design of New and Rehabilitated Pavement Structures (MEPDG) was proposed as a novel and accurate technique of pavement design, which is distinguished by characterization of traffic loads as distributions of single, tandem, tridem, or quad axles with varying load magnitudes, modelling of environmental impact on pavement material and structure through integration of data of solar radiation, historical temperature, wind speed, precipitation, and cloud cover every hour, measurement of long-term incremental damage accretion, and use of empirical performance functions and mechanistic-based models calibrated with field data to anticipate pavement distresses.

MEPDG differs from the AASHTO 1993 pavement design framework in that it takes into account the key determinants of pavement performance, such as environment, traffic, paving, materials and structure. The impact of input parameters on thickness design outcomes and pavement performance has been the focus of several studies. For instance, Kim et al. [3] varied one or two inputs concomitantly to investigate the sensitivity of two flexible pavement systems in Iowa, discovering that, besides layers thickness, volumetric properties, the performance grade (PG) of binder, annual average daily truck traffic (AADTT) and climate had to be modified as well in order to diminish distresses. Meanwhile, the sensitivity of rigid pavement systems was examined by Guclu and Ceylan [4] by assessing the degree of importance of input factors with screening methods, reporting that the input factors of highest sensitivity for rigid pavement design were the curling/warping effective temperature discrepancy and PCC thermal properties.

In another study, the input factors of traffic volume, dynamic modulus (E*), hot-mix asphalt (HMA) thickness, subgrade type, and base course thickness were examined via statistics-based factorial analysis to determine how sensitive they were to pavement distresses [5]. Every anticipated pavement distress was observed to be related to traffic volume, whereas the factor ranked second exhibited variation according to type of pavement distress. Meanwhile, new flexible pavements, continuous reinforce concrete pavements (CRCP), and jointed plain concrete pavements (JPCP) were subjected by Schwartz et al. [6] to both local and global sensitivity analysis, revealing that there was variation in design input sensitivities to anticipated flexible pavement performance according to type of distress, including load related vs. non-load related and rutting vs. cracking, as well as according to type of pavement to some degree.

The AC overlay mechanistic-empirical design has received far less attention from researchers than new pavement design in the context of MEPDG-based sensitivity analysis, despite views that AC overlay material properties and other parameters (e.g. current layer modulus back-calculated from approximated pavement condition survey, existing layer distresses, existing layer-AC overlay interface bonding condition or non-destructive testing) characterizing the current pavement condition to determine the thickness of the overlay design.

Wang and Nie [7] evaluated the effects of overlay material property and different thickness of existing pavement condition on asphalt concrete (AC) overlay design and performance using old version of ME software which is DARWin-ME. The researchers concluded that the sensitivity of overlay design thickness to the existing condition AC layer depends on design traffic and the existing AC layer thickness.

The present study employed AASHTOWare (version 2.3) to subject the AC overlay pavement design to sensitivity analysis. A new generation of DARWin-ME® pavement design software (AASHTOWare) is based on MEPDG and refines the features in the corresponding prototype computational software.

2. Objectives

The present study was concerned with scope to which overlay design was affected by overlay material properties and existing pavement condition, taking into account several factors, such as existing layer modulus and rut depth, AC overlay-existing pavement interface condition, and the PG and Poisson's ratio properties of AC overlay.

3. Case Study and Control Section

A system with five layers consisting of AC overlay, existing AC layer, base, subbase, and subgrade represent the pavement structure that was the focus of this investigation. The existing pavement structure was representative of typical pavement structures in Expressway No.1-Iraq (section R4/B), with 12cm or 25cm AC layer, 15cm bitumen base, 20cm subbase and subgrade layer as shown in Figure 1. Section R/4A begins at station 00+00 Km at Baghdad city and ends at station 49+00 Km at Mussaib and Suwaira. More than one level of existing pavement rutting and AC overlay-existing pavement interface bonding condition was taken into account, and the existing pavement layer moduli was back-calculated from previous studies. Variation caused by material and construction quality was reflected by enhancing and diminishing the AC modulus that was back-calculated by 30%. Furthermore, the back-calculated moduli were rectified to those obtained from back-calculated resilient modulus based on adjustment factors of 0.25 and 0.50 for subgrade soil and granular base, respectively. Additionally, data from dynamic modulus test with two binder types were employed for the properties of the overlay material and Poisson's ratio of asphalt mixtures was determined based on two different assumptions (constant vs. modulus-dependent). The applied analysis matrix is presented in Table 1.

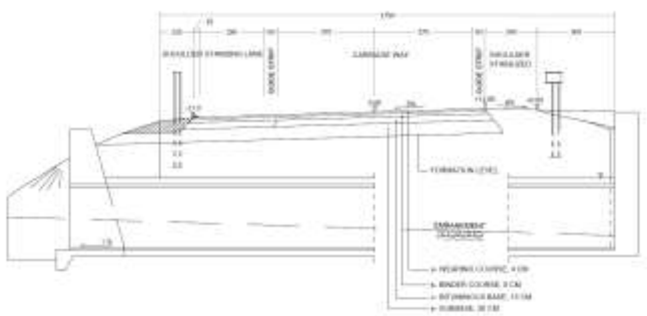


Fig. 1: Typical pavement structures in Expressway No.1-Iraq (section R4/B)

Table 1: The analysis matrix associated with current pavement condition and properties of overlay material

	Factor	Control	Range
Existing pavement condition			
1	Existing AC layer rut depth	0.75 cm	0, 0.25 and 0.5 cm
2	Exiting base layer rut depth	0.50 cm	0 ,1.5 and 2.5 cm
3	AC modulus	1951 MPa	Modulus multiplied by 1.3 and 0.7.
4	Base/Subgrade moduli	333 MPa /96 MPa	Correction factor for base/subgrade=0.50/0.25
5	Interface coefficient	1.0 (full bonded)	0 and 0.5
Overlay material properties			
6	Binder performance grade	PG64-22	PG 76-22
7	Poisson's ratio	0.35	* Poisson's ratio (Calculated)

*Poisson's ratio calculated using the following equation ($\mu = 0.15 + \frac{0.35}{1+e^{-1.63+3.84\times10^{-6}\times E}}$) where E is AC modulus (psi)

4. Results and Discussion

4.1 The Design of Overlay Thickness in Different Settings

Different structure and traffic scenarios were implemented in the design of AC overlay thickness, with an overview of traffic volume data associated with three traffic levels being provided in Table 2. The analysis focused on the truck traffic classification for expressways (TTC1: multi-trailer<2%, bus>2%, mostly single-trailer trucks) with axle load spectra (level 3) and the default vehicle class distribution. Furthermore, the load equivalent factor in AASHTO 1993 pavement design guide was used for comparison purposes to convert traffic data over the two-decade period of design into ESALs.

The Enhanced Integrated Climatic Model (EICM) is used for simulation of environmental conditions in the AASHTOWare. The climate station chosen in the present study was Taxes (station 133191) since there is no weather station related to Iraqi region in the software, and this area is close to the Iraq weather. Material properties variation over the course of a day and a season was anticipated by integrating the EICM-derived computed temperature and moisture profiles with the properties of the input material. This gave 90 % design reliability and Table 3 provides the default design criteria for different performance indicators. AC fatigue cracking (top-down and bottom-up) and permanent deformation (both AC and base rutting) were among the pavement distresses associated with load that were examined in this study. Specifically, assessment of overlay structure rutting is based on permanent deformation in the two existing layers and overlay, while assessment of bottom-up cracking is performed at the base of existing AC layer and AC overlay, and assessment of top-down cracking is performed at the top of AC overlay.

Table 2: Data related to traffic volume

	Traffic Level		
	Low (L)	Medium (M)	High (H)
Total ESAL	5 million	10 million	15 million
AADTT	1000	3000	6000
Design speed (km/h)	80	80	80
Truck in design direction (%)	50	50	50
Truck in design lane (%)	95	95	95
Growth rate	3%	3%	3%

Table 3: The Design Criteria of the overlay layer (software defaults)

Performance criteria	Limit
Initial IRI* (m/km)	1.0
Terminal IRI (m/km)	2.71
AC top-down fatigue cracking (m/km)	379
AC bottom-up fatigue cracking (%)	25
AC thermal fracture (m/km)	189
Permanent deformation - total pavement (cm)	1.90
Permanent defamation - AC only (cm)	0.63

*IRI= International Roughness Index

Table 4 presents the prediction of distress and the design thickness associated with the control group, indicating that the increase in AC overlay design thickness was directly proportional with traffic intensification and the sensitivity of design thickness was greater when the thickness of the current AC layer was thin. In the majority of instances, AC layer permanent deformation was the failure criterion; however, in the first scenario, when the overall thickness of the asphalt layer, comprising existing layer and overlay, did not exceed 21 cm, top-down cracking was of great importance.

Table 4: Distress prediction and design thickness associated with the control group

Scenario	1	2	3	4	5	6
Existing AC layer thickness (cm)	12	12	12	25	25	25
Traffic level	L	M	H	L	M	H
Design life (year)	10	10	10	10	10	10
Overlay design thickness (cm)	9	17	25	6	8	9
Terminal IRI (m/km)	2.41	2.55	2.60	2.22	2.37	2.50
AC bottom-up fatigue cracking (percent)	1.5	1.32	1.3	1.45	3.22	15.4
AC top-down fatigue cracking (m/km)	**271.1**	128	26.5	92.4	50	71.6
Permanent deformation - AC only (cm)	0.50	**0.50**	**0.42**	**0.32**	**0.36**	**0.45**

4.2 The Impact of Existing Pavement Condition on Overlay Design

As indicated by the outcomes of thickness design and the data in Table 5, the design traffic and the thickness of existing AC layer were the significant factors of the impact of existing pavement condition on overlay design thickness. In the second and third scenarios, where existing AC layer thickness was thin and design traffic was considerable, the existing pavement condition had no effect on overlay design thickness. Meanwhile, in the first, fourth, fifth and sixth scenarios, decrease in current AC layer modulus or rut depth determined an increase in overlay design thickness. However, irrespective of traffic volume and pavement structure, the overlay design thickness was insignificantly affected by base and subgrade condition. Nevertheless, in the first and sixth scenarios, overlay design thickness was markedly impacted by interface bonding condition.

Table 5: Impact of existing pavement condition on overlay design thickness

Scenario	1	2	3	4	5	6
Existing HMA thickness (cm)	12	12	12	25	25	25
Traffic level	L	M	H	L	M	H
Existing AC rut depth (cm)	Overlay thickness (cm)					
0	11	18	25	8	9	11
0.25	10	18	25	6	8	10
0.50	9	17	25	6	8	9
0.75	9	17	25	6	8	9
Modulus of Existing AC (MPa)	Overlay thickness (cm)					
1951MPa	9	17	25	6	8	9
2536 MPa (1.3 factor)	9	17	25	6	8	9
1366 MPa (0.7 factor)	15	17	25	8	10	12
Existing base rut depth (cm)	Overlay thickness (cm)					
0	9	17	25	6	8	9
0.5	9	17	25	6	8	9
1.5	9	17	25	6	8	9
2.5	9	17	25	6	8	9
Base and subgrade modulus	Overlay thickness (cm)					
No correction factor	9	17	25	6	8	9
Correction factor (0.50/0.25)	9	17	25	6	8	9
Interface bonding coefficient	Overlay thickness (cm)					
0	15	17	25	6	8	12
0.5	15	17	25	6	8	12
1.0	9	17	25	6	8	9

An identical pavement structure was employed in the analysis of AC overlay performance to gain more insight into the impact of overlay material property and existing pavement condition and, revealing that underestimation of overall AC rutting occurred when current AC layer rut depth was neglected (Figure 2). The reason for this was that the hardening traffic effect before overlay led to slow accumulation of existing layer rutting in the overlay period.

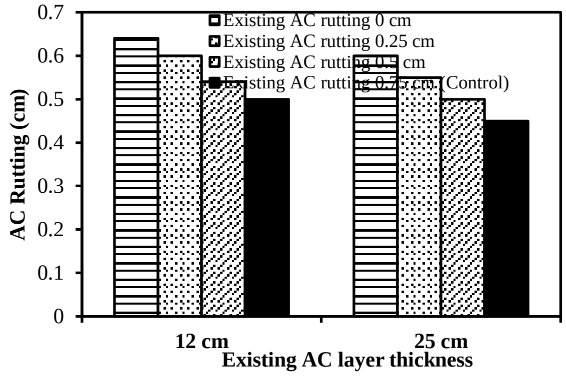
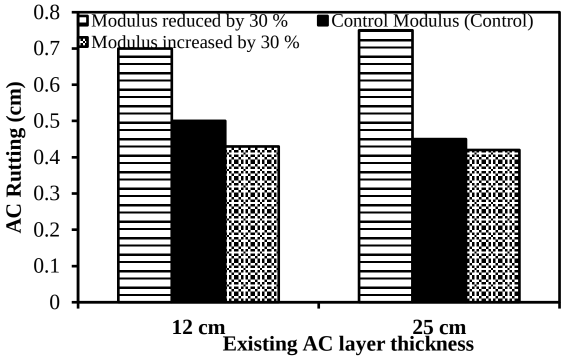
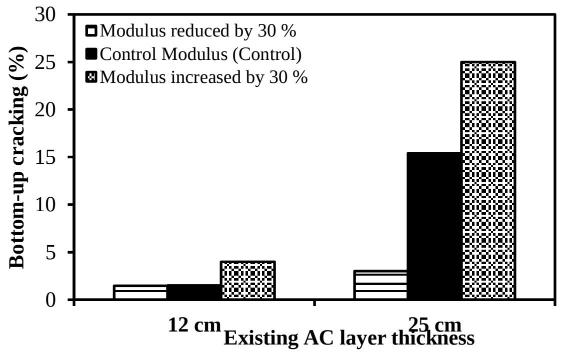


Fig. 2: Impact of rutting of existing AC layer (9 cm) on AC rutting

The impact of the modulus of the existing AC layer on pavement performance is shown in Figure 3(a) for AC rutting, in Figure 3(b) for bottom-up and in Figure 4(c) for top-down cracking, suggesting that, compared to rutting, cracking was more markedly affected by the current AC layer modulus. In the case of pavement structure with 12 cm old AC layer (Existing) and a 9cm overlay, both AC rutting and top-down cracking went over the failure criteria during 30 % decrease in AC modulus in conditions of low traffic volume. Meanwhile, in the case of pavement structure with a 25 cm old AC layer and a 9 cm overlay, both AC rutting and bottom-up cracking went over the failure criteria in conditions of high traffic volume.



(a)



(b)

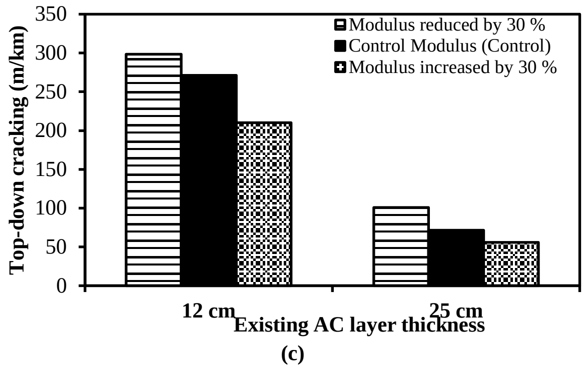


Fig. 3: Impact of modulus of existing AC layer on overlay performance (9 cm) in the context of (a) AC rutting; (b) bottom-up cracking; and (c) top-down cracking

As reflected by the interface parameter with 0-1 range, the impact of interface bonding on pavement performance for bottom-up cracking and top-down cracking is presented in Figures 4(a), (b) and (c), while the impact on rutting is neglected due to being insignificant. During partial interface bonding, overlay performance depended crucially on fatigue cracking, and performance outcomes did not differ for interface parameters smaller than those employed in AASHTOWare.

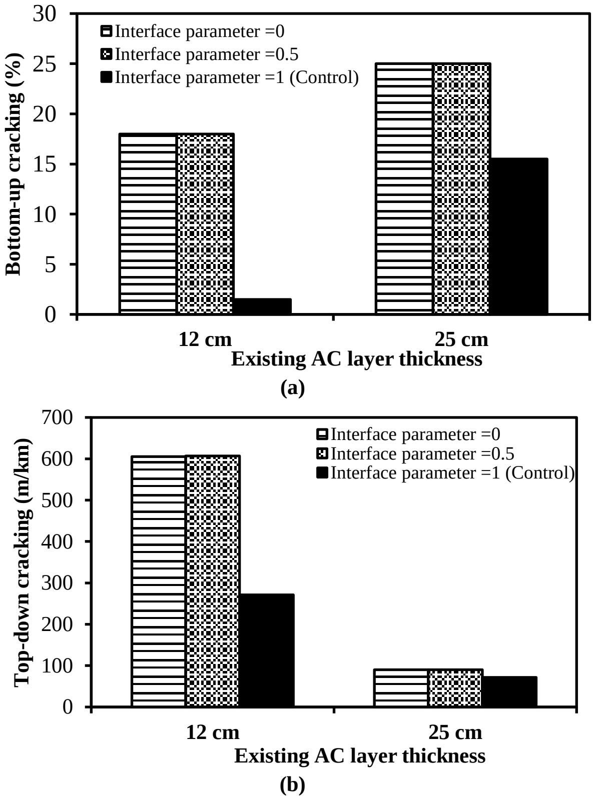


Fig. 4: Impact of interface bonding on overlay performance (3.5 cm) in relation to (a) bottom-up cracking; and (b) top-down cracking

4.3 The Impact of the Properties of Overlay Material on Overlay Design

The impact of overlay material properties on overlay design thickness can be seen in Table 6. In the second and third scenarios, the overlay thickness exceeded the current AC layer thickness, enabling observation of the impact of Poisson's ratio and binder grade on overlay design thickness. It is noteworthy that, under conditions of thin thickness of existing AC layer and considerable traffic volume, the overlay design thickness was significantly decreased by the modulus-based Poisson's ratio.

Table 6: Impact of the properties of overlay material on overlay design thickness

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
Existing HMA thickness (cm)	12	12	12	25	25	25
Traffic Level	L	M	H	L	M	H
Performance grade of overlay binder	Overlay thickness (cm)					
PG 64-22	9	17	25	6	8	9
PG 76-22	9	17	20	6	8	9
Poisson' ratio of overlay binder	Overlay thickness (cm)					
0.35	9	17	25	6	8	9
Calculated from a, b	9	10	16	6	8	9

The impact of overlay binder type on pavement performance is illustrated in Figure 5(a) for AC rutting and Figure 5(b) for top-down cracking, both conditions being reduced by rise in high-temperature grade of binder. Meanwhile, the impact of Poisson's ratio on pavement performance is illustrated in Figure 6(a) for AC rutting and Figure 6(b) for top-down cracking. Rutting was reduced by the modulus-based Poisson's ratio, unlike the constant Poisson's ratio of 0.35, most likely because horizontal deformation and applied stress conveyance were accentuated to the detriment of vertical deformation by the considerably high Poisson's ratio employed at high temperature.

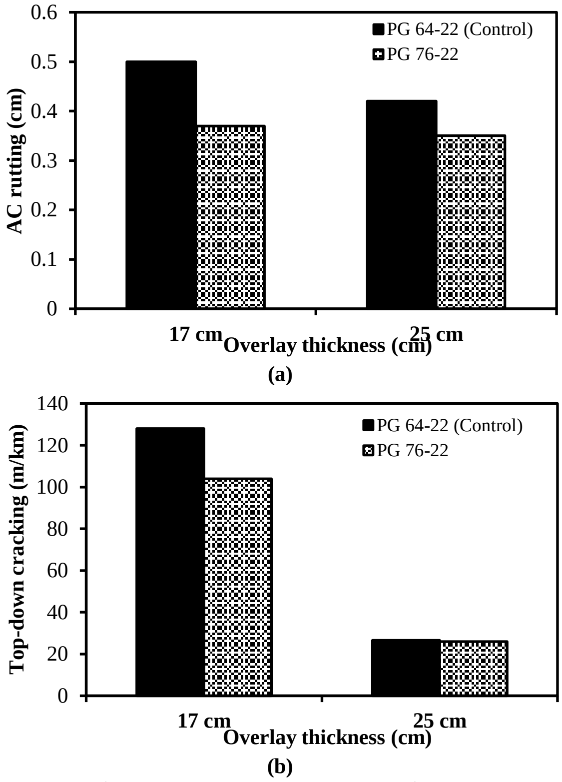
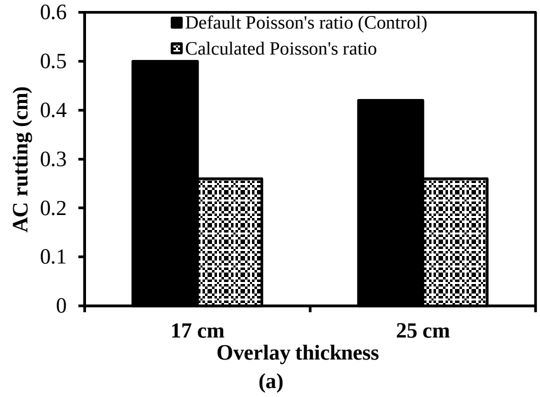
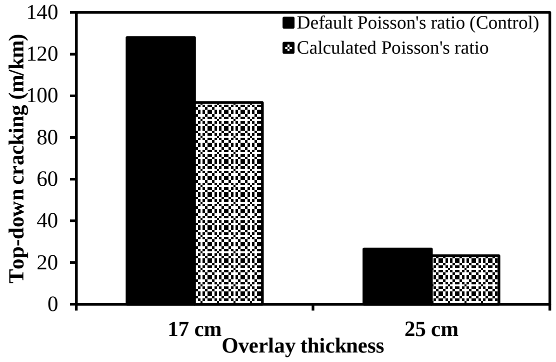


Fig. 5: Impact of overlay binder type on overlay performance using 12 cm existing AC layer thickness in relation to (a) AC rutting; and (b) top-down cracking





(b)

Fig. 6: Impact of Poisson's ratio (for AC overlay) on overlay performance using 12 cm existing AC layer thickness in relation to (a) AC rutting; and (b) top-down cracking

5. Conclusions and Recommendations

Several conclusions were drawn from the findings of the present AASHTOWare-based investigation into the impact of overlay material properties and existing pavement condition on overlay design and performance. The following conclusions are drawn based upon the software results:

1. The current AC layer thickness and design traffic determined the magnitude of the effect of current AC layer condition on overlay design thickness. Under circumstances of current AC layer of thin thickness and low traffic volume, the decrease in current AC layer rut depth or modulus led to increase in overlay design thickness, while under circumstances of current AC layer of significant thickness and high traffic volume, deterioration of interface bonding caused increase in overlay design thickness.
2. Compared to rutting potential, fatigue cracking was more substantially impacted by current AC layer modulus and interface bonding condition.
3. Regardless of traffic volume and pavement structure, overlay design thickness was not significantly impacted by base and subgrade condition.

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