Assessment of Reflective Cracking Models for Asphalt Pavements

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ABSTRACT

The research effort documented in this paper is directed toward identifying an analytical model that can be used to predict the resistance of HMA overlays to reflective cracking and predict their long-term performance. Various models were identified and three models were studied and compared in this research effort: 1) Virginia Tech Simplified Overlay Design Model, 2) Rubber Pavements Association (RPA) Overlay Design Model, 3) the New AASHTO model for Reflective Cracking. The identified models were assessed by the research team based on their ability to predict the performance of HMA overlays subjected to reflective cracking. An overlay design was conducted for three different HMA overlay mixes using the three identified overlay design methods. The overlay mixes were manufactured using different aggregate gradations from the Sloan pit in Southern Nevada and a PG76-22 polymer modified asphalt binder. The overlay was designed for 7,000,000 ESALs over the 20 years analysis period. Finally, a comparison was exerted among the various HMA overlay thicknesses required by each method and the material properties associated to such determination to accomplish the design traffic.

Keywords: Reflective Cracking, Hot mix asphalt, Overlay, Flexible Pavements.

INTRODUCTION

One major type of distress influencing the life of an overlay is reflective cracking. When asphalt overlays are placed over jointed rigid pavements or severely cracked flexible pavements, cracks will reflect to the surface in a relatively short period of time. Physical tearing of the overlay occurs because of movements under heavy wheel loads at joints and cracks in the underlying pavement layer. Therefore, the long-term performance of the HMA overlays will depend on their ability to resist reflective cracking (*Elsefi and Al-Qadi, 2003*). Reflective cracking in the overlay allows water to percolate into pavement structure and weakens the HMA and the supporting layers, hence contributing to many forms of pavement deteriorations. Moisture can damage the HMA mix by promoting the stripping of the asphalt binder from the aggregate. It can also significantly reduce the strength of the base and subgrade materials, which would lead to the total failure of the flexible pavement structure (*Sousa et al., 2001 and MEPDG, 2004*). Various methods have been developed to assess the reflective cracking through HMA overlays.

Several research *(Jacobs et al., 1996 and Molenaar and Nods, 1996)* suggested the use of a power law (Paris' law) to calculate the rate of crack propagation through the new overlay thickness:

$$\frac{dC}{dN} = AK^n \qquad (1)$$

where, $\frac{dC}{dN}$ = Crack propagation rate per number of load cycles,
K = stress intensity factor, and
A,n = experimentally obtained constants.

In 2007, the Saint-Gobain Company developed equations for helping in the design of HMA overlays *(Saint Goban, 2007)*. Another method has been proposed by the National Highway Institute (NHI) *(Koerner, 2005)*, based on the Geotextile Industry efforts to provide a design method against reflective cracking in HMA overlays by means of the use of geosynthetics.

The research effort documented in this paper was directed toward identifying an existing analytical model that can be used to predict the resistance of HMA overlays to reflective cracking and predict their long-term performance. Various models were identified and three models were studied and compared in this research effort:

- Virginia Tech Simplified Overlay Design Model
- Rubber Pavements Association (RPA) Overlay Design Model
- The New AASHTO model for Reflective Cracking

The identified models were assessed by the research team based on their technical merit and their ability to predict the performance of HMA overlays subjected to reflective cracking. The technical merit of the models was assessed directly based on the mechanistic theory of pavement structures. An overlay design was conducted for three different HMA overlay mixes using the three identified overlay design methods. The overlay mixes were manufactured using different aggregate gradations from the Sloan pit in Southern Nevada and a PG76-22 polymer modified asphalt binder. The overlay was designed for 7,000,000 ESALs over the 20 years analysis period. Finally, a comparison was exerted among the various HMA overlay thicknesses required by each method and the material properties associated to such determination to accomplish the design traffic.

REVIEW OF SELECTED OVERLAY DESIGN METHODS

Virginia Tech Simplified Overlay Design Model

In 2003, Elseifi and Al-Qadi developed an overlay design procedure to predict the service life of rehabilitated flexible pavement structures against reflective cracking. The researchers used the linear elastic fracture mechanics (LEFM) principles to derive a simple equation based on three-dimensional (3D) finite element (FE) analysis that can be used to predict the number of cycles to failure against reflective cracking for rehabilitated flexible pavements.

The total number of load repetitions (N_{total}) to produce the crack reflection to the pavement surface was defined as the sum of the number of load repetitions for crack initiation and the number of load repetitions for crack propagation.

In order to avoid the time consuming FE analyses, the researchers developed a regression model to predict the number of cycles in ESALs as a function of the significant variables as shown in Equation 2. The developed design equation was based on the results of all the considered cases in this study. The interaction between the different variables was also considered, but was found statistically insignificant.

$$\log W_{t80} = \frac{1}{10^4}(255H_{overlay} + 2.08E_{overlay} + 45.3H_{HMA} + 8.73E_{HMA}$$
$$1.34H_{Base} + 6.93E_{Base} + 1.49E_{subgrade}) \qquad (2)$$

where, W_{t80} = total number of 80-kN single-axle load applications,
$H_{overlay}$ = thickness of HMA overlay (mm),
$E_{overlay}$ = resilient modulus of HMA overlay (MPa),
H_{HMA} = thickness of existing HMA layer (mm),
E_{HMA} = resilient modulus of existing HMA layer (MPa),
H_{base} = thickness of base layer (mm),
E_{base} = resilient modulus of base layer (MPa), and
$E_{subgrade}$ = resilient modulus of subgrade (MPa).

Rubber Pavements Association Overlay Design Model

In 1999, the Rubber Pavements Association (RPA) contracted with Consulpav to develop a mechanistic overlay design method for reflective cracking in HMA overlays that are applied to existing cracked HMA pavements *(Sousa et al., 2001)*. The research project involved the development of mathematical and statistical models based upon 3D finite element method (FEM) to determine the stresses and strains in the HMA overlay above the crack.

This mathematical-statistical model was converted into a practical pavement design method for reflective cracking by reviewing considerable actual field cracking data and material layer properties. The method consists of the seven steps summarized below. For more detailed information refer to *"Development of a Mechanistic*

Overlay Design Method Based on Reflective Cracking Concepts, Final Report for Rubber Pavements Association (Sousa et al., 2001)":

1. *Determination of the moduli and thicknesses of the pavement section layers.*
2. *Determination of representative air temperatures:* It is necessary to compute the weighted mean annual air temperature (w-MAAT) as proposed by the Shell design method.
3. *Selection of design cracking percentage.*
4. *Determination of adjustment factors:*
   a. *Aging Adjustment Factor:* The Aging Adjustment Factor (AAF) is determined from the maximum air temperature.
   b. *Temperature Adjustment Factor:* To take into consideration the combined action of the wheel loads on a daily basis above (or near) the crack and the overlay material above the crack being under tension due to rapidly decreasing or low temperatures.
   c. *Field Adjustment Factor:* The Field Adjustment Factor (FAF) was introduced to relate the predictions obtained using the empirical-mechanistic reflective cracking model with the actual (reported and observed) field performance.
5. *Selection of overlay material modulus.*
6. *Determination of the design value "Von Mises" strain*. With the appropriate modulus and thickness for each layer, the "Von Mises" strain (ε_{VM}) is calculated.
7. *Determination of design equivalent single axle load (ESAL's).*

The New AASHTO model for Reflective Cracking

In the new AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG), the design procedure for HMA overlays of existing HMA surfaced pavements considers distresses developing in the overlay as well as the continuation of damage in the existing pavement structure. However, it should be noted that the reflective cracking models incorporated in the MEPDG were based strictly on empirical observations and were not a result of rigorous mechanistic-empirical analysis (MEPDG, 2004).

The percentage of reflective cracks through the overlay for a cracked HMA pavement is predicted as a function of time using the sigmoidal function shown in Equation 3.

$$RC = \frac{100}{1 + e^{a+bt}} \qquad (3)$$

where, RC = Percent of cracks reflected,

t = Time in years,

$a = 3.5 + 0.75 \times h_{ac}$

$b = -0.688584 - 3.37302 \times (h_{ac})^{-0.915469}$, and

h_{ac} = HMA overlay thickness in inches.

HMA OVERLAY DESIGN USING THE VARIOUS ANALYSIS MODELS

An HMA overlay was designed for a typical flexible pavement section using all three analysis models described before. The existing pavement structure consisted of a 4.0 inch (100 mm) HMA layer with a modulus of 360 ksi (E_{HMA} = 2500 MPa) and a 10 inch (250 mm) base layer with a modulus of 30 ksi (E_{base} = 210 MPa) on top of a subgrade with a modulus of 12 ksi ($E_{subgrade}$ = 83 MPa).

The traffic ESALs are estimated as function of years for an annual average daily traffic (AADT) of 30,000 and a truck percentage of 3.85 percent. The following summarizes the design ESALs over the 20 years analysis period using a truck factor of 0.912, an annual growth rate of 7%, a directional distribution factor of 50%, and a lane distribution factor of 90%: Year 1: 172,600; Year 3: 554,800; Year 5: 992,400; Year 10: 2,384,250; Year 15: 4,337,000; and, Year 20: 7,075,000 ESALs.

The analysis was conducted for three different HMA mixes that were designed using different aggregate gradations from the Sloan pit in Southern Nevada and a PG76-22 polymer modified asphalt binder. The three mixtures consisted of:

- Nevada DOT Type 2C intermediate gradation, designated as T2C.
- Caltrans gradation used for intersections, designated as CT.
- No Rut Mixture gradation, designated as NRM.

Table 1. Pavement Layers Material Properties

Layers		Thickness (inch)	Modulus at 70°F (ksi)	Fatigue characteristics*
HMA overlay	NDOT T2C	--#	790	$N_f = 1.3740 \times 10^{-7} \times \left(\frac{1}{\varepsilon}\right)^{4.4145} \left(\frac{1}{E_{T2C}}\right)^{5.0374}$
	CT	--#	1,045	$N_f = 6.3815 \times 10^{-7} \times \left(\frac{1}{\varepsilon}\right)^{4.3175} \left(\frac{1}{E_{CT}}\right)^{5.0398}$
	NRM	--#	1,375	$N_f = 6.8748 \times 10^{-7} \times \left(\frac{1}{\varepsilon}\right)^{4.6392} \left(\frac{1}{E_{NRM}}\right)^{5.1470}$
Cracked HMA		4.0	360	N.A.
Unbound base		10.0	30	N.A.
Subgrade		--	12	N.A.

*N_f is the number of repetitions to failure, ε is the flexural strain in microns
to be designed according to all three reflective cracking design methods

All three mixes were designed according to the Nevada department of transportation (NDOT) Hveem Mix Design Method as outlined in the NDOT Testing Manual. The optimum asphalt binder contents were 4.2, 4.0 and 3.7 by dry weight of aggregate for the T2C, CT and NRM mixtures, respectively. It should be noted that all mixtures were treated with 1.5% of hydrated lime by dry weight of aggregate following the NDOT specifications.

The dynamic modulus test (AASHTO TP62) was used to develop the dynamic modulus master curve of the various HMA mixtures. Table 1 shows the dynamic modulus ($E_{overlay}$) of the various overlay mixtures at a temperature of 70°F and a loading frequency of 10 Hz. The fatigue characteristics of the HMA mixtures were evaluated using the flexural beam fatigue test "AASHTO T321-03." The fatigue models were determined using the MEPDG constitutive relationship shown in Equation 4 which correlates the number of cycles to failure (N_f) to the tensile strain (ε in microns) and the mixture's stiffness (E in ksi). k_1, k_2, *and* k_3 constants are experimentally determined coefficients. Table 1 shows the fatigue constitutive models of the various evaluated mixes. It should be noted that the fatigue characteristics of the various mixes can only be incorporated in the RPA Overlay Design Method.

$$N_f = k_1 \left(\frac{1}{\varepsilon}\right)^{k_2} \times \left(\frac{1}{E}\right)^{k_3} \tag{4}$$

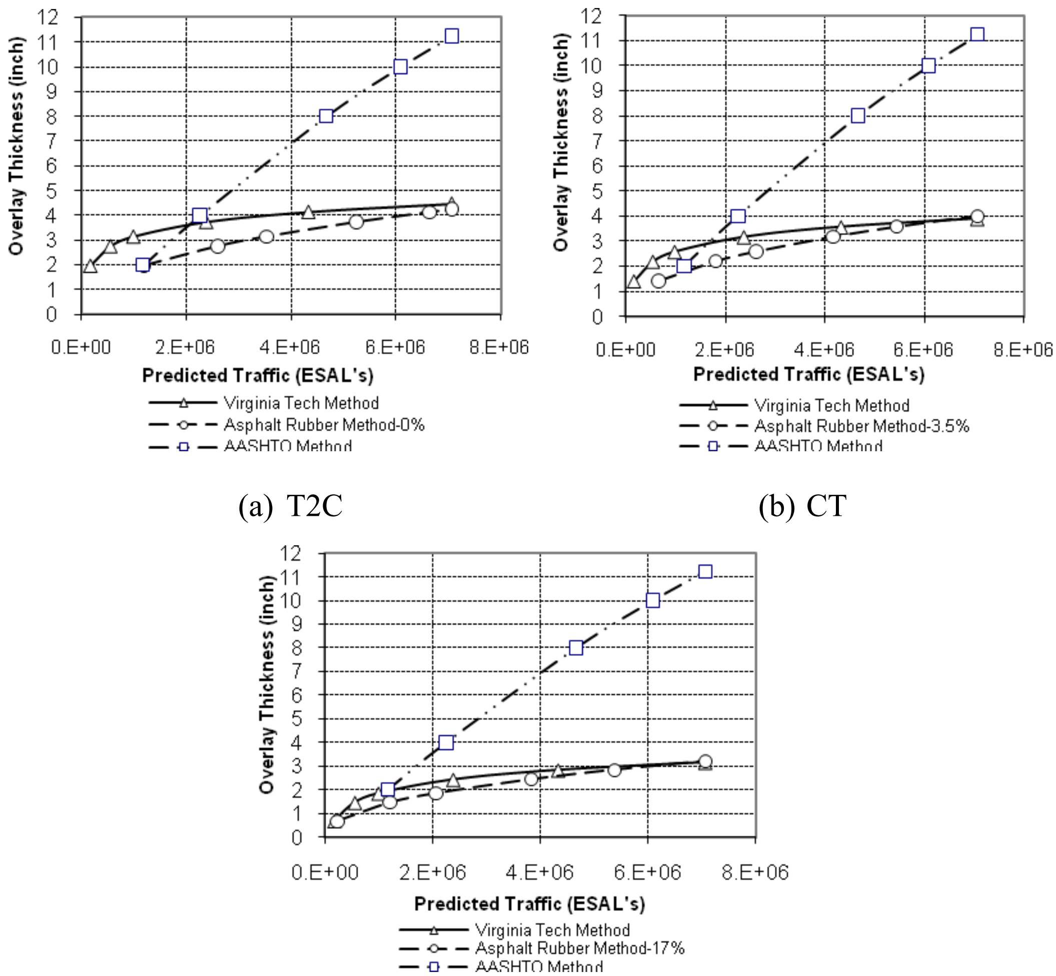
Summary of Design Example

Figures 1.a to 1.c compare the required overlay thickness determined from the Virginia Tech, Rubber Pavements Association, and the new AASHTO analysis methods for all three types of mixtures. The Virginia tech and the Rubber Pavements Association models resulted in a relatively comparable overlay design thicknesses with the Virginia tech method being more conservative. On the other hand, the AASHTO method overestimated the overlay thickness compared to the Virginia Tech and the Rubber Pavements Association methods.

The data in Table 2 show that for the same design ESAL's, a thicker overlay thickness is required for the T2C mix followed by the CT mix and the NRM mix when designing using the Virginia Tech method. On the other hand, the opposite was found when designing using the RPA method where a thinner overlay thickness is required for the T2C mix followed by the CT mix and the NRM mix to reach the same selected percentage of cracking. For example, in the case of 0% reflected cracks, the overlay thicknesses required were respectively 3.60, 4.90 and 15.25 inch (91, 229 and 387 mm) for the T2C, CT and NRM mixtures. Same behavior occurred for the 2%, 5% and 15% reflected cracks.

This analysis shows that the T2C mixture requires a lower thickness than the CT and the highly stiffer NRM mixture. This trend can be explained by the fact that the NRM mixture is designed for rutting resistance and its stiffness is much higher than the other two mixtures. Due to such high stiffness, this mix can be very close to its brittleness limit and the required flexibility for the reflective cracking resistance is reduced. On the other hand, the more flexible T2C mix has the ability to better withstand the reflective cracking effect. The AASHTO MEPDG design method resulted in a 12 inch (305 mm) overlay thickness to reach 100% reflected cracking after 20 years design period regardless of the type of the overlay mix.

In summary when only the stiffness of the overlay mix is considered (i.e., Virginia Tech method), a thinner overlay thickness was found for the stiffer mix whereas, when both the stiffness and the fatigue characteristic of the mix are considered (i.e., RPA method), the overlay thickness depended on the interaction between the two material properties.



(a) T2C (b) CT

(c) NRM

FIG. 1. Required overlay thicknesses using the various analysis models

Table 2. Overlay Design Thicknesses for 20 years Design Period

HMA overlay mix	Overlay thickness (inches)					
	Virginia Tech	Rubber Pavements Association % reflected cracking				AASHTO MEPDG (100% reflected cracks)
		0%	2%	5%	15%	
NDOT T2C	4.50	3.60	2.40	2.00	0.75	12.00
CT	4.00	4.90	4.00	3.00	1.00	12.00
NRM	3.25	15.25	12.50	9.25	3.25	12.00

CONCLUSIONS

The following are the general conclusions concerning the three methods evaluated and compared in this research. For the Virginia Tech Simplified Overlay Design Model the overlay thickness is undoubtedly the major factor in dictating the overlay performance against reflective cracking failure, followed by the thickness of the existing HMA layer. Additionally, it appears that the base thickness and subgrade modulus has the least effect on the overlay performance in resisting reflective cracking.

For the Rubber Pavements Association Overlay Design Model: currently the model has been calibrated for only two materials: Dense graded mixes with PG70-10 binders (HMA-DG) and gap graded mixes with asphalt rubber modified binders (AR-HMA-GG). However, the model can be calibrated for other mixtures by using the appropriate dynamic modulus and fatigue relationship. Also, the various adjustment factors can be calibrated in order to account for other site conditions.

Finally, the AASHTO MEPDG design method resulted in a constant overlay thickness to reach 100% reflected cracking after 20 years design period regardless of the type of the overlay mix and regardless of the mechanic properties of either the HMA overlay or the existing pavement structure.

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