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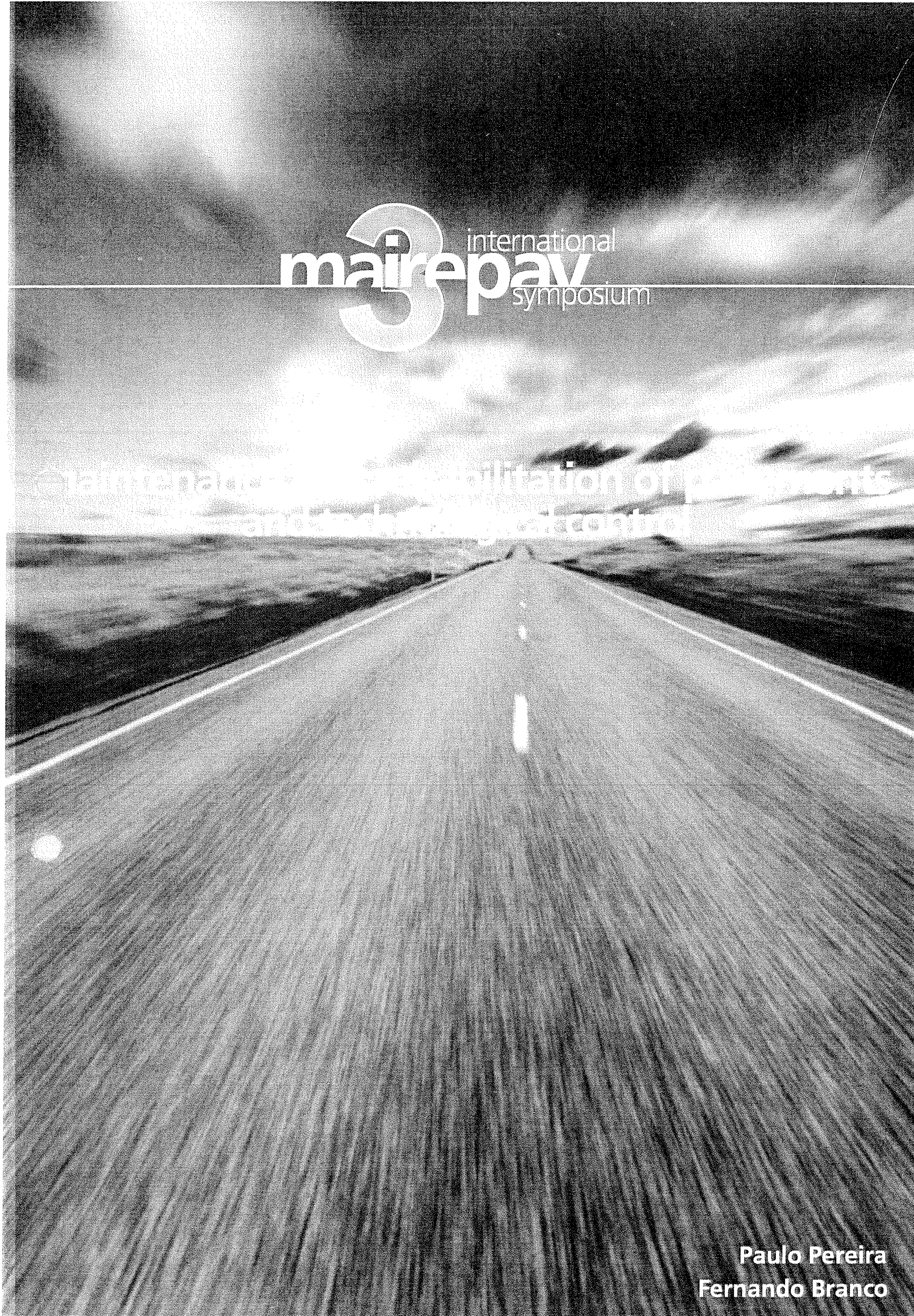

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Paulo Pereira
Fernando Branco

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The Reflective Cracking in the Pavement Overlay Design

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ABSTRACT: This paper describes a new pavement overlay design method that takes into account the reflective cracking as the most predominant type of overlay distress. This phenomenon is characterized as the propagation of old cracks to the new pavement layer. The models proposed are based on a finite element model that closely approximates actual field phenomena based on measurements done on Arizona and Portugal. Test sections have been constructed to access the effect of overlay thickness, crack width and load to validate the design method. Crack activity under the effect of traffic loads was initially calculated and compared with field results, and strains in the zone above cracks were calculated. Expected performance of asphalt-rubber hot mix and conventional asphalt overlay was calculated using the proposed model and a conventional overlay design simulation was made.

KEY WORDS: Pavements, Reflective cracking, Overlay design.

1. INTRODUCTION

The overlay design method presented in this paper was developed by Consulpav International and the University of Minho under the direct sponsorship of the Rubber Pavement Association (RPA) and close association with the Arizona Department of Transportation (ADOT). The ADOT does not provide any direct funding, however it has contributed in kind support with regard to materials samples, test pavements, data, pavement coring and some sample testing. The RPA and the ADOT are both supportive of this research because the research is directed toward discovering why asphalt rubber hot mixes do a better job of reducing reflective cracking. The purpose of this research project is to develop a new mechanistic overlay design method, which will help to reduce reflective cracking distress observed in thin overlays.

This paper is a condensed version of an eight chapter, 200 page report, entitled "Development of a Mechanistic Overlay Design Method Based on Reflective Cracking Concepts" (Sousa et al, 2001 and Sousa et al, 2002).

The research project first involved the development of a model based on the Finite Element Method (FEM). To calibrate the FEM-modeled crack movements, actual field measurements with a Crack Activity Meter (CAM) and a Falling Weight Deflectometer (FWD) were both conducted, in Portugal, Arizona and California.

The next phase of the research involved laboratory testing to simulate observed field crack movements and measure stresses and strains in test specimens to simulate actual field conditions. Two typical mixes were prepared and tested in Portugal. One conventional HMA mix consisted of a dense graded aggregate similar to that used in Arizona and California, hereinafter called HMA-DG. The second mix consisted of an eight percent AR-HMA gap-graded mix (hereinafter called ARHMA-GG) similar to those used in Arizona and California.

Beams of HMA-DG and AR-HMA-GG were tested with the four-point bending beam fatigue test developed during the Strategic Highway Research Program (SHRP).

To convert this mathematical statistical model into a practical pavement design method for reflective cracking, it was necessary to review considerable actual field cracking data and material layer properties. From these data, the estimated traffic to cause reflective cracking was calculated from the layer thicknesses and layer moduli in a variety of pavements. These calculated numbers were compared to both the actual (observed) number of equivalent axle loads and the (observed) percent cracking. A very novel relationship was derived, which indicates that as long as the ratio between the estimated and actual traffic to cause reflective cracking stays below one, no cracking will occur. For ratios above one, different levels of percent cracking are calculated and observed. Aging and temperature adjustment factors were also a novel adjunct to this new approach.

The final product of this research is a spreadsheet where the pavement design engineer inputs the expected design level of cracking, the thicknesses of the layers, and their elastic moduli.

2. FINITE ELEMENT MODELATION

This section describes a FEM used for modelling the pavement immediately above a crack (Figure 1). The FEM used the 3D linear elastic model based on the SAP2000 software and calibrated using crack activity measured on in service pavement in Arizona, California and Portugal.

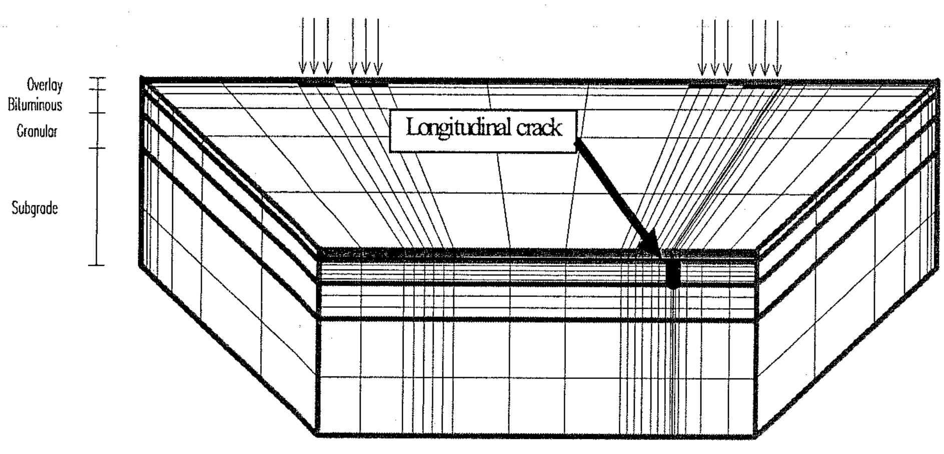

Figure 1: 3D representation of finite element mesh

The 3D FEM was used to evaluate the state of strain in the zone above crack. The influence of pavement characteristics on state of stress and strain was made defining a strain deviator such as the von Mises stress deviator. This strain, called the "von Mises strain" was calculated as expressed in Equation 1.

$$\varepsilon_{VM} = \sqrt{\frac{1}{2}\left((\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_3)^2\right)} \qquad (1)$$

where:

ε_{VM} = "von Mises" strain

ε_1, ε_2, ε_3 = Principal strains

For beam fatigue test conditions subjected to four-point bending, ε_{VM} can also be written as:

$$\varepsilon_{VM} = \varepsilon_1 (1 + \upsilon) \qquad (2)$$

where:

υ = Poisson ratio

Subsequently, a statistical model was developed for ε_{VM}, expressed as:

$$\varepsilon_{VM}\ (1x10^{-6}) = a * [Overlay\ thickness\ (m)]^b \qquad (3)$$

$$a = \prod_{i=1}^{6} [a_{1i} * \ln(X_i) + a_{2i}] \qquad (4)$$

$$b = \prod_{i=1}^{6} [b_{1i} * \ln(X_i) + b_{2i}] \qquad (5)$$

where:

a_{ij} and b_{ij} are coefficients given in Table 1.

Table 1: Statistical coefficients for the ε_{VM} model (Equation 3) [R^2=0.98]

I	X_I	a_{1i}	a_{2i}	b_{1i}	b_{2i}
1	Cracked thickness (m)	-1.038E-04	-1.446E-01	7.169E-03	1.314E-01
2	Granular thickness (m)	2.777E-01	-4.022E+00	9.773E-05	-6.368E-01
3	Overlay modulus (MPa)	-1.173E+00	1.212E+01	-4.946E-01	7.069E+00
4	Cracked modulus (MPa)	1.281E+00	5.070E-01	3.923E-02	2.641E+00
5	Granular modulus (MPa)	-5.160E-01	6.964E+00	3.265E-02	-1.287E+00
6	Subgrade modulus (MPa)	-1.775E-01	2.385E+00	1.875E-03	-8.167E-01

3. BITUMINOUS MATERIALS FATIGUE LIFE

In this study two asphalt-aggregate mixes were used. A conventional dense grade mix and a gap-graded asphalt rubber mix.

The binders used were a PG 70-10 and a PG 64-16 (PEN 35/50) for the neat asphalt mixes. For the AR mixes, the PG 64-16 asphalt cement was interacted with 20% crumb rubber from California for one binder type, generally referred to as the Arizona "Type A" AR Binder. For the California AR binder, AR-4000 asphalt cement was mixed with California crumb rubber, natural rubber, and extender oil in a manner consistent with routine California work (generally called the "Type B" AR binder).

The binder content for the neat asphalt HMA-DG mix was 5% and for the AR gap-graded mix (AR-HMA-GG) it was 8%, consistent with typical Arizona and California mix types and designs.

Flexural fatigue tests were conducted according to the AASHTO TP 8-94 (Standard Test Method for Determining the Fatigue Life of Compacted HMA Subjected to Repeated Flexural Bending). All tests were carried out at 20°C and at 10 Hz frequency rate of loading and the following fatigue life laws were obtained:

$$ESALs = 4.1245E19x\varepsilon_{VM}(1x10^{6})^{4.9761} \quad (6)$$

for asphalt rubber binders derived from the wet process, with a 19% - 20% rubber content and a gap-graded mix, and:

$$ESALs = 6.4467E19x\varepsilon_{VM}(1x10^{6})^{5.93} \quad (7)$$

for conventional PG70-10 binders and a dense graded mix.

4. REFLECTIVE CRACKING MODEL CALIBRATION

The calibration of the model was made based on an iterative process involving the development of an aging adjustment factor (AAF), a temperature adjustment factor (TAF) and a field adjustment factor (FAF).

4.1. The Aging Adjustment Factor (AAF)

This factor captures the effect of aging in the overlay as a function of the maximum air temperature. For the available database, the Aging Adjustment Factor may be expressed as:

$$AAF = 0.0449 * T(\max air) - 0.2435 \quad \text{(for Conventional PG70-10 binders)} \quad (8)$$

$$AAF = 0.0088 * T(\max air) + 0.7296 \quad \text{(for Asphalt Rubber binders)} \quad (9)$$

4.2. The Temperature Adjustment Factor (TAF)

This factor captures the effect of the combination of the two most important effects passing wheel loads on a basis above (or near) the crack and the material (overlay) above the crack being under tension due to rapidly decreasing or low temperatures. For the database available, the Temperature Adjustment Factor (TAF) may be expressed as:

$$TAF = -0.092 * 2.558 \quad \text{(for Conventional AC 40 binders)} \quad (10)$$

$$TAF = -0.072 * RCT + 1.745 \quad \text{(for Asphalt Rubber binders)} \quad (11)$$

where:

$$RCT = T\text{ (min air)} + 0.5 \times [T\text{ (average air mean monthly)} - T\text{ (min air)}] \quad (12)$$

The average air mean monthly temperature is defined as proposed by the Shell design method (Claessen et al, 1977). This temperature is a weighted temperature. The weight factor (w-factor) is function of the mean monthly air temperature (MMAT) and can be obtained by the equation presented in Figure 2 that express the Shell chart for this determination.

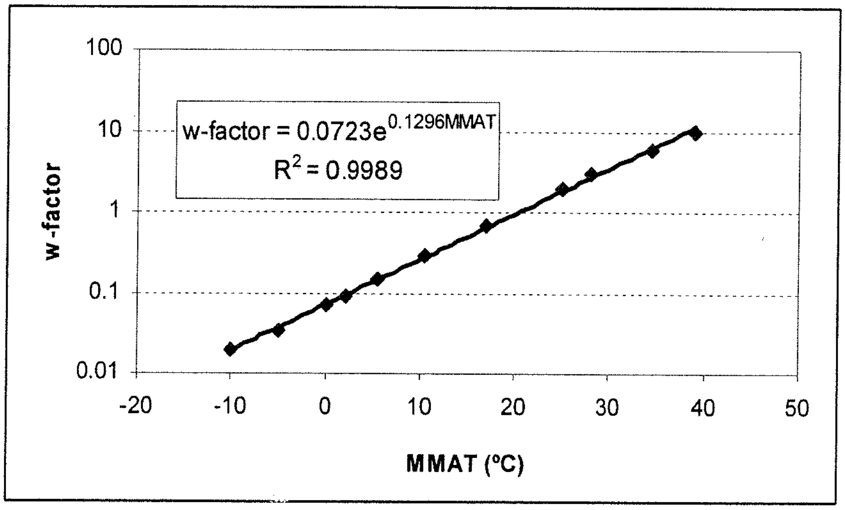

Figure 2: Shell w-factor as function of temperature

The weighted mean annual air temperature (w-MAAT) is obtained using the equation from the Figure 3, resulted from the Shell chart.

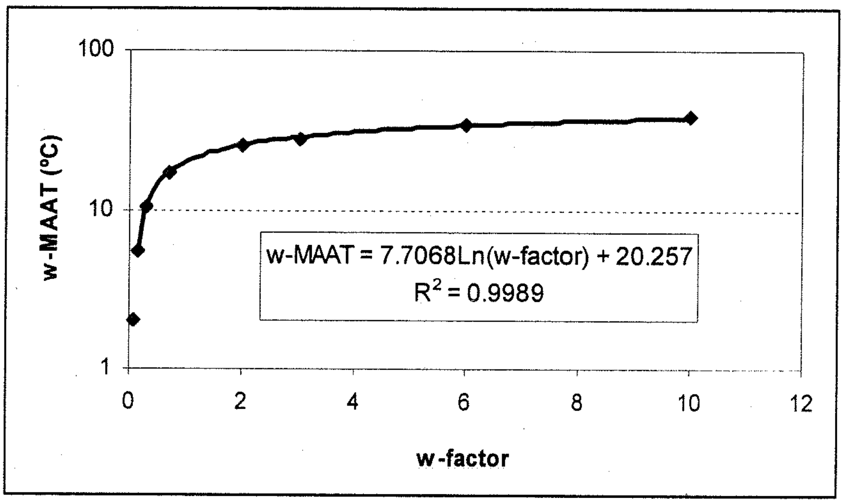

Figure 3: Shell w-MAAT as function of w-factor

4.3. Field Adjustment Factor (FAF)

The Field Adjustment Factors (FAF) was introduced to relate the predictions obtained using the empirical- mechanistic reflective cracking model with actual (reported and observed) field performance. This value was initially determined following the same steps identified above.

Cracking is only expected when FAF is greater than 1. For FAF values less than 1, cracking should not have occurred. If the model predicts otherwise, the model is incorrect. It should be noted that the reported percent cracking may go up and down from year to year due to maintenance crack sealing activities which introduces greater scatter in the reported data.

It can be observed that for the vast majority of points where the FAF was below 1, no cracks were reported. When cracks were reported by ADOT, the FAF was higher than 1. This follows a clear trend that can be expressed by Equation 13, where PC is the percent cracking.

$$FAF = e^{0.2303*PC} \tag{13}$$

5. PROPOSED REFLECTIVE CRACKING DESIGN METHOD

The method consists of the seven steps presented below. Currently the model has been calibrated for only two materials: Dense graded mixes with PG70-10 binders (HMA-DG) or gap graded mixes with asphalt rubber modified binders (AR-HMA-GG). The asphalt rubber binder must be produced using the "wet" process and it must contain approx. 19-20% crumb rubber.

5.1. Determination of the Moduli and Thicknesses of the Pavement Section Layers

This can be accomplished using FWD backcalculation methods or other forms of estimating cracked pavement section moduli. Care must be taken in the selection of modulus representative of the most damaged sections. As such, the 90th or 95th percentile of deflections (or backcalculated moduli) should be selected. Coring for determination of layer thicknesses should be carried out as close to the locations where the 90-95th percentile FWD test points were selected.

5.2. Determination of Representative Air Temperatures

The maximum and minimum air temperature determined with the desired reliability should be obtained for the location where the pavement is to be overlaid. Furthermore, it is necessary to compute the mean average monthly air temperature as proposed by the Shell design method.

5.3. Selection of Design Cracking Percentage

The percent cracking should be keeping with that previously discussed. The value selected should be in keeping with an agencies overlay policy. ADOT generally has observed less than five percent cracking over a period of ten years when an asphalt rubber surface mix is used.

5.4. Determination of Adjustment Factors

Several adjustment factors must be calculated for the location where the overlay will be placed and for the desired cracking level at the end of the overlay's design life: the Aging Adjustment Factor (AAF) (Equations 8 and 9); the Temperature Adjustment Factor (TAF) (Equations 10 and 11) and the Field Adjustment Factor (FAF) (Equation 13).

5.5. Selection of Overlay Material Modulus

Two types of materials for the overlay may be selected: Conventional HMA-DG or AR-HMA-GG, with the rubberized binder prepared through the wet process @ ~19-20% crumb rubber in the binder.

For these materials, the modulus and flexural fatigue life are obtained through flexural fatigue tests, as presented in Figure 3. Other moduli can be computed and introduced in the method based on actual tests performed on other types of materials. However, it must be assumed that the Temperature Adjustment Factor or the Aging Adjustment Factor will either be identical to that of the HMA-DG material or the AR-HMA-GG material.

5.6. Determination of the Design Value, ε_{VM}

The modulus of the overlay must be multiplied by the computed Aging Adjustment Factor. With the modulus and thickness for each layer, the ε_{VM} value for the overlay is determined.

The ε_{VM} value obtained through these equations must be multiplied by 86/132 (to convert ε_{VM} from 130-kN to 80-kN axle loads), and also by the Temperature Adjustment Factor (TAF). The value obtained in this process is thus the design ε_{VM}.

5.7. Determination of Design ESALs

Using the appropriate flexural fatigue equation 6 or 7, determine the number of ESALS that can be sustained by the overlay prior to the onset of reflective cracking.

Multiply the design ESAL by the FAF. The resulting number should represent the number of ESALs required for the overlay to reach the selected percentage of cracking.

Other fatigue curves can be determined and used by this method, based on actual flexural fatigue tests performed on the specific asphalt (whether conventional or modified) material type proposed with due consideration to all adjustment factors.

An EXCEL spread sheet (Figure 4) was created with all the formulas presented in this paper. The input values are entered in column C and the graph regenerates itself for the new pavement and environment conditions selected. From the demanded traffic the required thickness can be determined for conventional and asphalt rubber mixes. Generally in most cases the asphalt rubber mix will give an overlay about half as thick as the conventional mix for the same design traffic level.

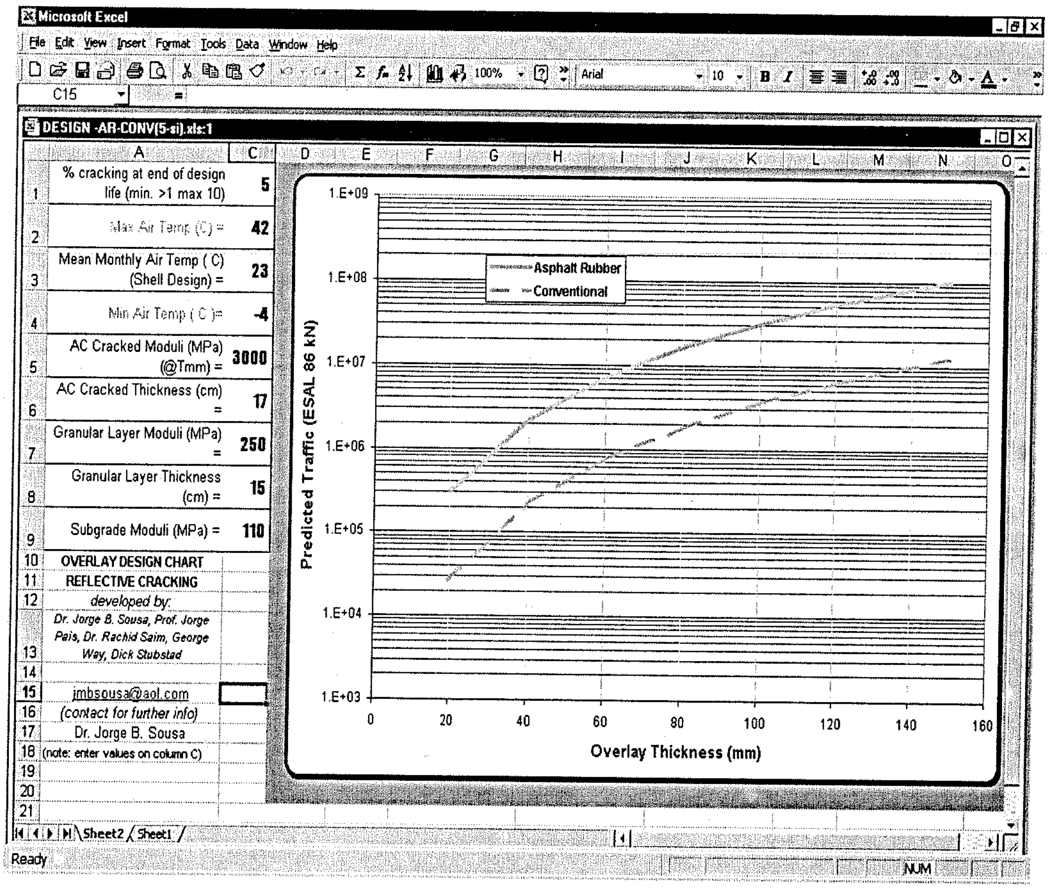

Figure 4: Applicability of reflective cracking model implement in an EXCEL sheet

6. EXAMPLE OF APPLICATION

The application of this overlay design method that takes into consideration the reflective cracking phenomenon will be made to the design of the overlay for two cross-sections of a cracked pavement. Both cross-sections have the same layers thickness: the bituminous cracked layer of 20 cm and a granular layer with 60 and 64 cm. The layers stiffness was obtained with FWD measurements and the values are presented in Table 2.

The expected traffic for 10 years overlay is 64×10^6 (80 kN), the mean monthly air temperature, obtained using the Shell method, is 15°C.

The application of the Excel sheet gives for these two cross-sections the Figuras 5 and 6, from which it can be observed that, for cross-section 1 the overlay thickness should be 14 cm of conventional asphalt mix, and 17 cm for cross-section 2m using the same material.

Table 2: Characterization of cross-sections

Cross-section (CS)	Thickness (m)		Stiffness (MPa)		
	Bituminous	Granular	Bituminous (20°C)	Granular	Subgrade
1	0.20	0.60	2800	310	60
2	0.20	0.64	2100	150	65

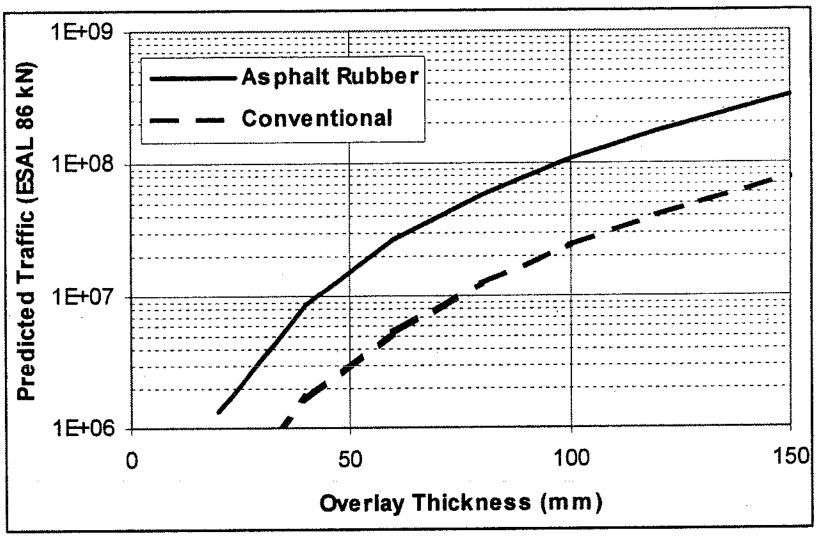

Figure 5: Application of the overlay design method to cross-section 1

This overlay design, taking into account the reflective cracking, for these two cross-sections, was compared with the traditional overlay design, where the overlay thickness is obtained by application of a fatigue life law for the calculated strain at the bottom of the asphalt layers. This strain level was calculated by using the multi-layer elastic system based computer program, such as ELSYM5.

The conventional overlay design was made using the ELSYM5 computer program and the results, in terms of strain level in the bottom of the asphalt concrete layer, are presented in Figure 7, where CS1-C represents the influence of overlay thickness on tensile strain level at the bottom of the existing asphalt layer, taking into consideration that the overlay is adherent to the old pavement of cross-section 1. The CS1-D represents the influence of overlay thickness on tensile strain at the bottom of overlay layer, taking into consideration that the overlay is not adherent to the old pavement of cross-section 1. The CS2-C and CS2-D represent the same influence for cross-section 2.

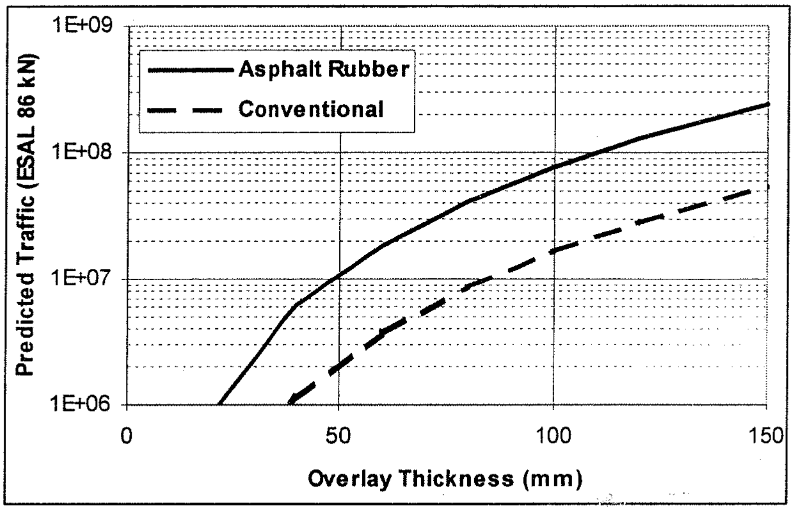

Figure 6: Application of the overlay design method to cross-section 2

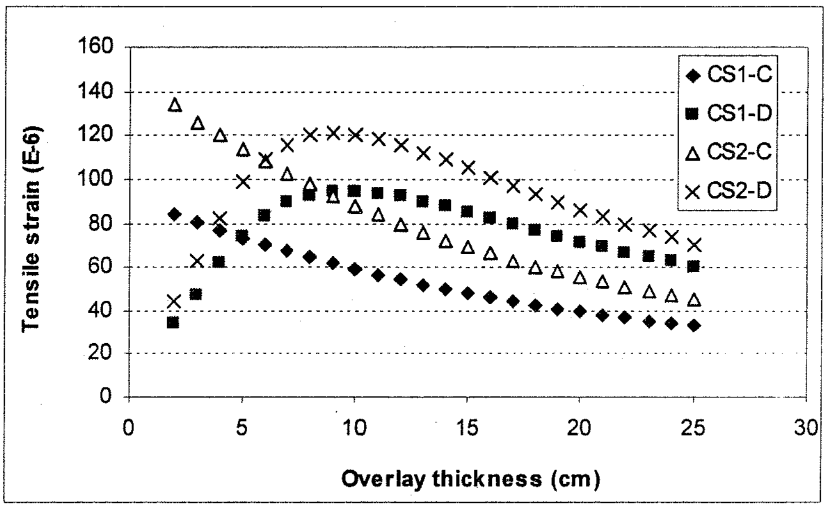

Figure 7: Application of conventional overlay design to CS1 and CS2

The overlay thickness (Table 3) for these 4 design types was obtained by applying the fatigue life Shell design method where the strain level of 74x10-4 is obtained for an expected traffic of 64x106 (80 kN).

Table 3: Overlay thickness as function of overlay design method

Cross-section	Overlay thickness (cm)		
	Adherent overlay	Reflective cracking	Non-adherent overlay
1	6	14	19
2	14	17	24

These results allow to conclude that the reflective cracking design method give values between the traditional adherent overlay situation and the non-adherent overlay.

7. CONCLUSIONS

This research project successfully completed lab and field work to develop a mechanistic empirical method to design hot mix asphalt overlays to resist reflective cracking. The specific design method is good for dense graded asphalt hot mixes and gap graded asphalt rubber hot mixes used in Arizona. It probably can also be applied to Southern California and Western Texas.

The generalized approach is applicable to any type of asphalt hot mix provided the fatigue properties of the mix are determined, the in place FWD deflections and the history of cracking is available. The following are the main technical findings of the study:

- The Falling Weight Deflectometer can be used in place of the Crack Activity Meter to represent the degree of vertical crack movement.
- The 3D linear elastic model based on the SAP2000 software was used to model the development of average shear stresses above the crack zone as well as to model the crack activity before and after the overlay.
- Field validation showed excellent correlation between the values of the crack activity measured and predicted thus offering a high level of reliability to the value of the average shear stress predicted by the model.
- Statistical models were developed in conjunction with an Excel spreadsheet based on the results of more than 15000 finite element computations. The statistical model and spreadsheet eliminates the need for running a tedious and complex 3D FEM computer program.
- The Finite Element Method (FEM) was successfully used to develop a statistical mathematical model to derive the amount of thickness needed to control reflective cracking.
- The statistical model indicated that the crack width did not appear to relate to the amount of overlay to control a reflective crack.
- The statistical model confirms that asphalt rubber mixes have a much higher capability to resist reflective fatigue cracking. Also, the reduction in overlay thickness by a factor as large as one half is substantially validated by this study.

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