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Application of the reflective cracking phenomenon in the pavement overlay design

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Abstract

An asphalt concrete overlay layer placed above a cracked layer is subjected to four primary distress mechanisms due to traffic loads: tensile strain at the bottom of the overlay; tensile strain at bottom of the existing surface course; compressive strain at the top of the unbound layers, and reflective cracking. Existing overlay design methods usually only take into account the first three of these primary distress mechanisms. In these cases, the propagation of existing cracks through the new overlay is not directly considered. This paper presents a design method that directly includes a criterion for the fourth pavement distress mechanism — reflective cracking.

The development of this new design method is based on the estimation of the crack activity after overlay, using a 3D finite element model. This crack activity after overlay is used to perform laboratory reflective cracking test where this crack activity is applied and the reflective cracking fatigue life is obtained.

1. Introduction

One of the failure modes in pavement layers is the appearance of cracks in the pavement surface. Initial hairline cracks can progressive evolve and degrade the pavement in the vicinity of the cracks. This will lead to water intrusion and the subsequent reduction of the soil bearing capacity, increase in IRI, which will lead to discomfort for the users and reduce safety.

Overlays are the most commonly method for rehabilitating cracked pavements but, however, they often do not perform as expected because the existing cracks propagate rapidly to the new pavement overlays. This phenomenon, named reflective cracking, is caused by thermal effects, by repetitive traffic loads or by a combination of these two mechanisms. However only reflective cracking due the repetitive traffic load is considered in this paper.

Load associated reflective cracking is governed simultaneously by a horizontal opening and/or closing and a vertical shearing at the crack zone. The simulation of this process must consider the simultaneity of these two modes of opening in the analysis of this problem.

The overlay design methods do not generally provide crack reflection criteria and usually the cracking propagation is delayed or minimized by increasing the overlay thickness, modifying the bituminous mixture properties or placing stress-relieving interlayer. Even so, only empirical evidence has mostly governed the overlay design criteria and in many cases the existing cracks propagate to the new pavement layer sooner then expected.

One of the most promising methods to retard the crack reflection is the modification and optimization of the bituminous mixture properties based on results from dynamic laboratory tests (Pais, 1999). If these tests can suitable simulate the cracking reflection phenomenon, the results expressed as a "reflective cracking fatigue life", can be used in a design method.

Because the crack reflection is a phenomenon of a repetitive nature, the bituminous mixture resistance to the reflective cracking can be evaluated using laboratory dynamic tests applying displacements representing the overlay solicitations.

This paper reports research where the crack activity (the relative horizontal and vertical movements between the edges of a crack) was used to define a solicitation to perform displacement controlled dynamic tests.

2. Reflective cracking

Overlays are the most commonly used method for rehabilitating cracked pavements. However, they often do not perform as expected because of existing cracks that propagate through the newly constructed overlay within a short period of time (Haas and Joseph, 1989).

This problem is called "reflective cracking" and is well identified when an overlay shows a crack pattern identical to that existing in the old pavement. When an overlay is placed on a cracked pavement, the cracks in the old pavement surface will propagate through the overlay and will appear in the surface.

Reflective cracking is caused by thermal contraction, by repeated traffic loads, or by a combination of these mechanisms. In addition, the temperature dependent stiffness of the materials and flaws in the overlay (i.e. built-in cracks during construction) as reported by Halin et al, 1987 can have an important effect.

Existing overlay design methods do not take into account reflective cracking. The only form of cracking typically mechanically modeled is flexural fatigue, which only captures the following phenomena:
  1. *Tensile strain at the bottom of the overlay* — especially for thicker overlays when the neutral zone is above the bottom of the new overlay.
  2. *Tensile strain at the bottom of the existing asphalt concrete* — especially for relatively intact (uncracked) pavements.
  3. *Compressive stresses or strains at the top of the unbound materials* — when the failure mechanism is not the fatigue cracking.

However, to minimize or delay crack propagation, some other experienced based techniques are used which include the increase of overlay thickness, modification of asphalt properties or a stress-absorbing interlayer placed between the existing pavement and the overlay layer.

Even so, the existing cracks propagate up to the new pavement surface producing a too early failure of the entire pavement with high costs for the Highways Agencies and for the road users. Thus, the development of an overlay design method, which includes a criterion for reflective cracking, is of great importance for road maintenance.

A design method to take into account the reflective cracking must consider the discontinuity produced by the cracks on existing pavement. This cracking condition only can be modeled using a special numerical technique such as finite element analysis, which is associated with fracture mechanics concepts. In this work, finite element modeling was used to estimate crack movements, which are employed to define displacement level to perform laboratory tests.

3. Crack Movements

Crack edges are subject to relative movements mainly as a function of wheel load position and pavement properties. Irwin (1957) proposed a model that showed that crack movements occur through three modes: Mode 1 represents bending; Mode 2 represents shear; and Mode 3 represents tearing. This is illustrated in Figure 1 (Colombier, 1989).
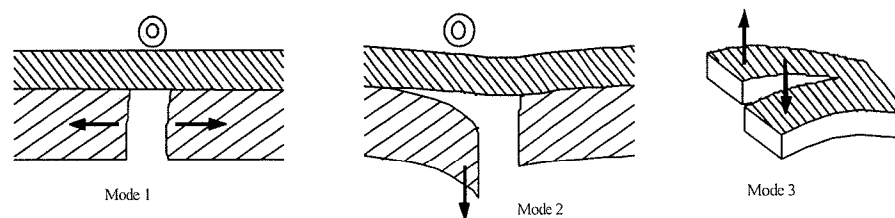

Figure 1. Crack Movements (Colombier, 1989)

Due traffic loads, these movements occur in pavement cracks depending on the position of a wheel load. The first mode is usually observed when a wheel load passes over a transverse or longitudinal crack. The second mode is observed when a wheel load approaches a transverse crack or when the load passes by the edge of a longitudinal crack. The third mode only appears in longitudinal cracks when the wheel load passes near the end of the crack. Figure 2 represents these modes, as proposed by Pais (1999).

Longitudinal cracks   Transverse cracks

Crack   Load
-----------[——→]-----------
                        Mode 1   Crack
                                        --------------[↑]--------------
Crack   Mode 1

          [——→]   Load
       Load   Mode 2
                                        Crack

Crack
-------------------------------   [↑]   Mode 2
              [——→]
     Mode 3   Load
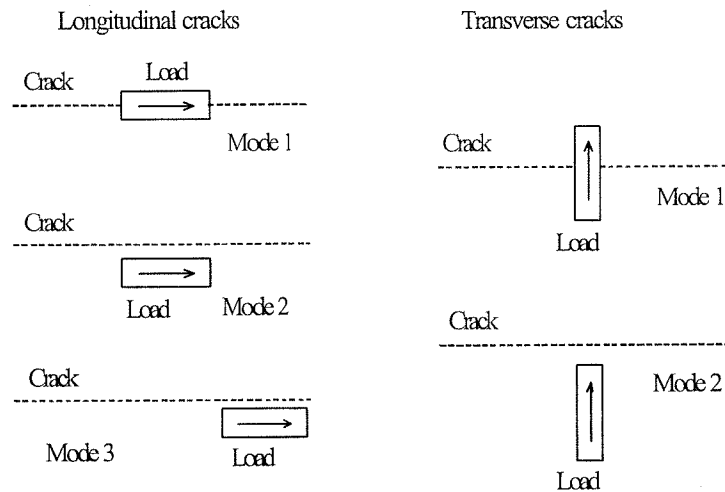   Load

Figure 2. Crack Activity Modes as a Function of Location of Load (Pais, 1999)

From this analysis, it can be concluded that the most frequently observed modes of cracking in flexible pavements are Modes 1 and 2, representing the horizontal and vertical movements between the two edges of a crack. These movements are commonly called "crack activity", and they can be evaluated directly in an existing pavement using a crack activity meter (CAM).

4. Numerical simulation to estimate crack activity after overlay

In general multi-layered, elastic layered theory techniques have been used to evaluate the distribution of stresses and strains in pavement structures. Multi-layer methods are based on the theory of continuum mechanics and do not take into account the physical discontinuities such as cracks that exist in pavements.

Finite element model techniques are currently the most comprehensive way of modelling the pavement and are considered to be the most appropriate tool for improving the understanding of the behaviour of flexible pavement structures. Such a finite element model would consider the effects of flexible layer thicknesses and material properties. The material properties and behaviour are essential in this analysis, as with any form of theoretical pavement assessment. It is also possible to describe the interface between layers and cracks.

A simple finite element mesh can be developed to carry out a basic analysis. However, to adequately model the characteristics of the pavement structure in order to fully understand its behaviour, a 3D FEM is required.

Thus, the SAP2000 finite element software was chosen which incorporates these features and allows easy and fast analysis. The 3D FEM to simulate an overlaid cracked pavement was made in two parts. In the first part, 3D FEM represented the cracked pavement and validated the results of the

CAM testing before overlay. Only after this validation the full 3D FEM was made and validated with FWD results obtained after overlay.

3D FEM solid mesh in Figure 3 represents the cracked pavement with which a linear elastic analysis was performed. The pavement has 4 layers, an overlay layer, a bituminous cracked layer, a granular layer and a subgrade layer. A longitudinal crack is also represented in a model with 4.70 m * 2.4 m (due symmetrical pavement configuration) * pavement thickness. If the pavement has more than 4 layers, usual situation in flexible pavements, layers of identical materials must be included in one layer.
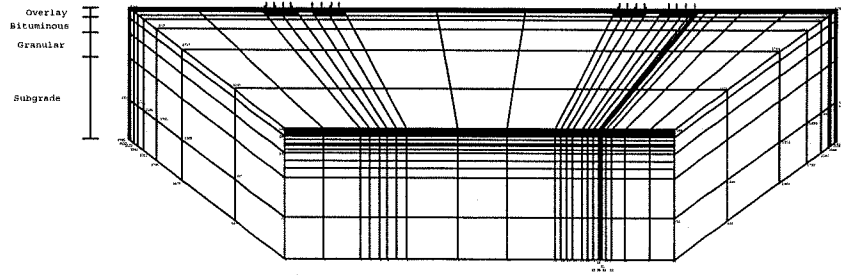

Figure 3. 3D representation of finite element mesh

Using the 3D finite element model, the crack activity after overlay was calculated to fit in a statistical model given by Equation [1].

$$Crack\ Activity(1x10^{-6}m) = a * \left[Overlay\ thickness\ (m)\right]^b \qquad [1]$$

Where:

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

$$b = \prod_{i=1}^{6}\left[b_{1i} * \ln(X_i) + b_{2i}\right] \qquad [3]$$

and a_{ij} and b_{ij} coefficients are given by the Table 1 and 2.

Table 1. *Statistical coefficients for <u>vertical</u> crack activity after overlay*

i	X_i	a_{1i}	a_{2i}	b_{1i}	b_{2i}
1	Cracked thickness (m)	-1.190E-01	-1.286E+00	6.065E-02	-8.820E-01
2	Granular thickness (m)	4.940E-01	-3.279E+00	4.751E-03	2.967E-01
3	Overlay modulus (MPa)	-2.885E-01	2.945E+00	-8.227E-03	1.457E+00
4	Cracked modulus (MPa)	1.734E-01	-6.342E-01	-1.826E-01	3.036E+00
5	Granular modulus (MPa)	-9.188E-03	6.512E-01	-1.051E-01	1.465E+00

| 6 | Subgrade modulus (MPa) | -5.246E-01 | 4.856E+00 | 3.770E-02 | 9.037E-01 |

Table 2. *Statistical coefficients for <u>horizontal</u> crack activity after overlay*

i	X_i	a_{1i}	a_{2i}	b_{1i}	b_{2i}
1	Cracked thickness (m)	-1.242E+00	-2.904E+00	-2.082E+00	-4.655E-01
2	Granular thickness (m)	-1.112E-02	-1.012E-01	4.879E-02	-1.137E+00
3	Overlay modulus (MPa)	-2.900E-01	2.757E+00	-4.130E-02	7.856E-01
4	Cracked modulus (MPa)	2.428E+00	-1.194E+01	1.076E-03	1.115E+00
5	Granular modulus (MPa)	2.872E-02	6.844E-01	3.153E-03	8.584E-01
6	Subgrade modulus (MPa)	-1.446E-01	1.643E+00	-1.324E-02	7.453E-01

The validation of this 3D finite element model was made using the FWD measurements of the crack activity after overlay in trial section on Portugal.

This crack activity after overlay measured in pavement requires access to the top of the cracked layer. This can be accomplished in two ways. In the first way a piece of wood with the overlay thickness is placed over the crack and the bituminous mixture is placed around it just prior to overlay compaction. After the pavement cools down the wood can be taken off providing access to the existing crack. In the other way a double aluminum foil sheet is be placed on the crack and the overlay is place. After pavement cools down the overlay is cored until the existing pavement at a location given by topography.

These methods, to access old pavement, change considerably pavement the stress and strain field round the crack which have an important effect on crack activity after overlay. Thus, the 3D FEM validation was be made changing the model mesh by modeling the hole of the overlay.

At the time this paper was written validation was only made for three test sections in IP5 road way in Portugal where crack activity was measured before and after and 11 to 13 cm overlay. The measured values ranged between 40 and 70 micro-meter while the predicted values ranges between 40 and 50.

This validation taking into account the size of the hole and the distance of the FWD loading plate to the crack indicate that the crack activity phenomena can be modeled as a linear elastic model and that it is particularly sensitive to the conditions existing around the crack. As such tire foot print and tire inflation pressures will be important factor in crack activity prediction.

5. Proposal to perform RCD tests

Reflective cracking test developed by Sousa et al (1996), represented in Figure 4, in the standard shape can be executed with cylindrical or rectangular specimens up to 150 mm (5.9 inches) long and

thickness up to 50 mm (2 inches). The crack width set in the RCD must be 10 mm (0.4 inches) allowing a free movement of the zone over crack.
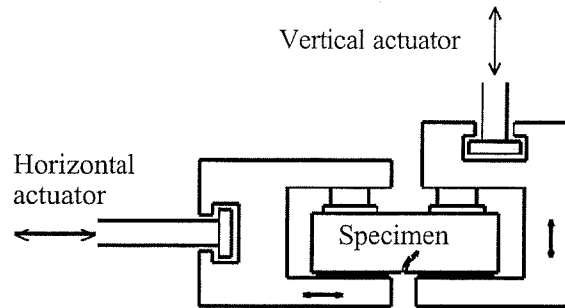

Figure 4. Representation of the reflective cracking device

Using the concept of crack activity, RCD tests must be executed in displacement control mode. Vertical and horizontal displacements are given by Equation [1].

To simulate overlay thickness greater than 50 mm, fatigue laws must be obtain, performing RCD tests at 20, 35 and 50 mm, and extrapolate the results to the desired thickness. This limitation has been set due to the size of the device used. More reliable results (for thickness higher then 50 mm) may be obtained if a larger device is to be built.

6. Proposed empirical-mechanistic design method

Based in this study, an empirical-mechanistic method for overlay design, including a criterion to taking in account the reflective cracking is proposed. This iterative method is presented in Figure 5.

This method begins after the thickness overlay is defined using the actual design methods, which include only the flexural fatigue and permanent deformation criteria.

The iterative process includes three main parts:
1. The evaluation of the crack activity after overlay;
2. The evaluation of reflective cracking fatigue life;
3. Comparison between cracking resistance and number of standard axles.

The evaluation of the crack activity after overlay must be made knowing the properties (thickness and stiffness) of existing pavement layers, the overlay thickness and stiffness. These parameters can be used either based on existing predictive empirical models or based on numerical models.

In the second part of this method the reflective cracking resistance of bituminous mixture is evaluated using either laboratory tests or by the application of existing reflective cracking fatigue laws.

The laboratory tests must be performed using the Reflective Cracking Device and applying the vertical and horizontal crack activity after overlay.

The last part of the method is the comparison between the reflective cracking fatigue life and the number of equivalent standard axles. If the reflective cracking fatigue life is greater than the number of equivalent standard axles the overlay design is concluded and the overlay thickness resist to the flexural fatigue, permanent deformation and reflective cracking. If the comparison fails the iterative process goes to the beginning by either increasing the overlay thickness or changing the overlay material.
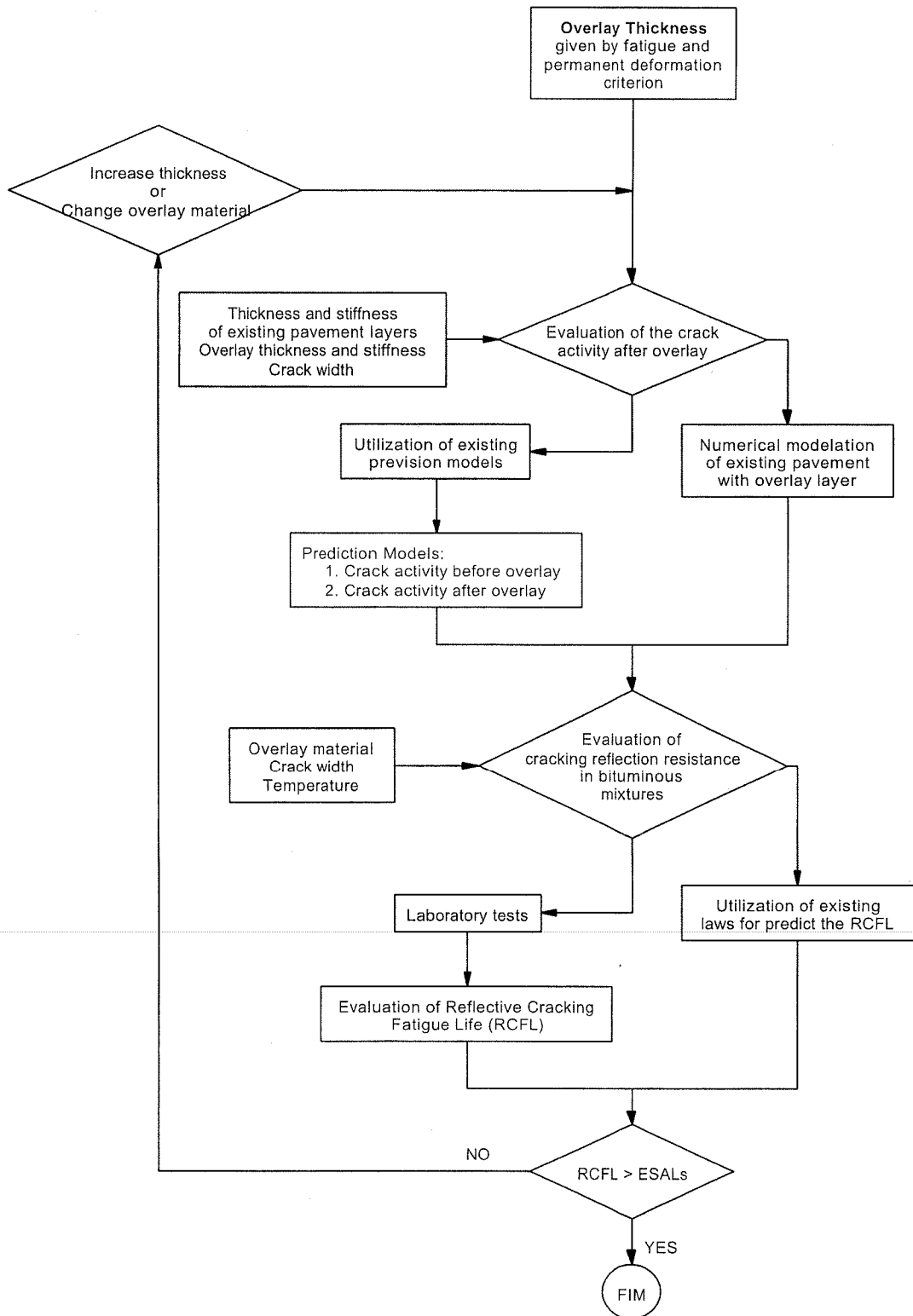
Figure 5. Proposed empirical-mechanistic method to design overlay layers

7. Conclusions

The basic framework and most of the key aspects of the development of an overlay methodology that directly takes into consideration the reflective cracking mode is presented.
The 3D linear elastic model based on the SAP2000 software was used to model the crack activity after overlay.

Field validation showed excellent correlation between the values of the crack activity measured and predicted thus offering a high level of reliability to use the crack activity in reflective cracking tests.

An empirical-mechanistic method for overlay design, including a criterion to taking in account the reflective cracking was proposed.

8. References

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