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THE TRAFFIC AND TEMPERATURE EFFECT ON THE REFLECTIVE CRACKING

Manuel J. C. Minhoto*; Jorge C. Pais; Paulo A. A. Pereira****

*Instituto Politécnico de Bragança – Escola Superior de Tecnologia e de Gestão
Campus de Santa Apolónia, Apartado 134, 5301-857 Bragança, Portugal
minhoto@ipb.pt

** University of Minho - Department of Civil Engineering
Campus Azurém, 4800-058 Guimarães, Portugal
jpais@civil.uminho.pt
ppereira@civil.uminho.pt

Abstract

This paper presents a study on the influence of the effects of temperature variations, in comparison to the traffic effects, on the reflective cracking behavior. It intends to contribute to the improvement of the pavement overlay design methods which consider reflective cracking as one among distress criteria. The development of this study was based on the numerical simulation of the overlay behavior, through the implementation of numerical thermal and mechanical models based on the finite element, considering the simultaneous action of traffic and temperature variations and their influence on reflective cracking. For overlay design purposes, it is important to consider temperature variations in the evaluation of the overlay behavior produced by the reflective cracking. The expected performance of an asphalt rubber hot mix, produced by the wet process with 20% crumb rubber was compared to a conventional asphalt taking into account the performance of these mixes.

INTRODUCTION

Bituminous overlays have been the most used method to rehabilitate cracked pavements and their service life depends on their performance in different distress modes. When an overlay is placed on a cracked pavement, cracks will develop and propagate to the pavement surface, directly above the cracks of the existing pavement, due to static and repetitive loading, in a few years of service. This phenomenon of distress is traditionally referred as "reflective cracking" and it is a major problem to highway agencies throughout the world (De Bondt, 2000).

Daily and seasonal temperature variations, and associated thermal stresses, maybe a cause for premature overlay cracking, affecting the overlay life of asphalt pavements (Epps, 1997). The binder properties (stiffness, ageing, penetration, among others) are sensitive to temperature variations and the combination of the two most important effects - wheel loads passing above (or near) the crack and the tension increase in the material above the crack (in the overlay) due to a rapid decrease of temperature - have been identified as the most likely causes of high states of stress and strain above the crack and responsible for the reflective cracking phenomena (Sousa et al., 2002).

Thus, due to daily temperature variations, which show an influence in the pavement thermal state a few centimetres below the surface, stresses are induced in the overlay in two different ways: through restrained shrinkage of the overlay and through the movements of the existing blocks resulting of thermal shrinkage (Halim, 1989).

An analytical study about reflective cracking which considered temperature variations was performed throughout a year to evaluate the temperature influence on overlay reflective cracking behaviour. To perform this study, it was necessary to consider temperature variations in all bound layers and the overlay restrained shrinkage phenomenon. For that, a numerical analysis based on 3-D Finite Element methodology was adopted for the numerical simulation of that phenomenon (Minhoto, 2007).

The theoretical modelling of that mechanical mechanism needs the evaluation of material properties, in terms of stiffness modulus, thermal contraction coefficient and viscoelastic response, expressed by relaxation modulus. For the overlay behavior evaluation through a numerical simulation, two hot-mix types were considered: a conventional hot-mix asphalt overlay and an asphalt-rubber hot mix, produced with 20% crumb rubber by the wet process.

STUDY BACKGROUND

This study involves the calculation of the hourly stresses and strains generated by traffic and thermal loading, characterized through the temperature variation in the full-depth of the pavement. The temperature distribution throughout the pavement structure was obtained using field measurements recorded with a datalogger associated with thermocouples, made in a pavement section located at IP4 main road, near Bragança, in the north of Portugal, throughout a year. Traffic data were obtained from field measurements near the temperature measurements location.

Stresses and strains calculations were performed using a 3D Finite Element analysis (FE) for each loading case. For thermal loading, the behavior of bituminous material was considered as viscoelastic, characterized by relaxation modulus, once the overall state of tension in the overlay caused by the temperature variation is time-dependent. For traffic loading, the bituminous material behavior was considered as elastic, characterized by the stiffness modulus. The maximum stresses and strains are concentrated above the existing cracks, creating an active zone of pavement failure or crack propagation. The calculated traffic and thermal stresses and strains were used to verify the influence of the thermal loading in the overlay behavior, through the evaluation of the damage associated to each type of loading.

The overlay damage, during the year, was hourly obtained by comparing the traffic effectively observed with the hourly predicted overlay life that results from each loading case. The evaluation of overlay life for each loading case was made with basis on the mechanistic-empirical methodology proposed by Sousa et al. (2002), which is capable of assembling simultaneously Modes I and II crack opening. In that methodology the influence of pavement characteristics on state of stress and strain was considered by using the Von Mises strain deviator, as expressed in Equation 1:

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

where ε_{VM} is the Von Mises strain, ν is the Poisson's coefficient and ε_1, ε_2, ε_3, are the principal strains. This methodology uses the deviator strain, ε_{VM}, as a "controller", to compare with the results of flexural fatigue tests, in controlled strain, to obtain the predicted overlay life.

SIMULATION PROCEDURES

The simulation procedures involve a multiple 3-D finite-element calculations and each solution was obtained hourly, for each loading case (traffic, temperature variation and both superimposed) and for each axle load type. First, the thermal model, using the steady-state thermal analysis, computes temperatures hourly in all nodes of the mechanical models. These temperatures are needed to set the elements stiffness in traffic models and to calculate the temperature variation, ΔT, in each node, in the thermal model. This temperature variation, ΔT, allows the thermal strain calculation, $\Delta\varepsilon$, given by $\Delta\varepsilon = \alpha * \Delta T$. The thermal strain, when restrained, allows thermal stress calculation as a result of temperature decrease.

The strain and stress states obtained for traffic loading and temperature variations were superimposed (added), to obtain the stress and strain states for superimposed loading. After that operation, the average Von Mises strains in the nodes above the crack zone were computed for each loading case. The Von Mises Strains were used to estimate the overlay life for each studied case.

Equation 1 was used to relate the average Von Mises strain with a fatigue strain concept used on flexural fatigue laws, normally used to evaluate the prediction of pavement life. In this way, the Von Mises strain was related with fatigue laws used in pavement analysis, obtained from four-points flexural fatigue tests, to estimate of the overlay fatigue life. For each hour, the overlay life is obtained for nodal temperature occurred in the zone above the crack.

After overlay life computation, the hourly damage was evaluated. It was obtained as the ratio between observed traffic and overlay life, expressed in number of axles, following the equation:

$$D_{h,e} = \frac{N_{h,e}}{N_{adm,h,e}} \tag{2}$$

where: $D_{h,e}$ = Hourly damage of axle "*e*", at hour "*h*";
$N_{h,e}$ = Number of axles "*e*" observed at hour "*h*" ;
$N_{adm,h,e}$ = Number of predicted axles, for axle "*e*", at hour "*h*".

LOADS

In order to calculate pavement thermal effects and the thermal response of mixes, the temperature distribution in bituminous layers evaluation was made during periods of twenty-four hours along the year of 2004. These temperature distributions allow calculating thermal effects in the zone above the crack. Pavement thermal state variations depend on the climatic conditions, by the thermal diffusivity of used materials (thermal conductivity, specific heat and density) and the depth below the surface (Minhoto et al., 2005).

The temperature distribution throughout the pavement structure, at every hour of the day and night, during a year, was obtained by field measurements, using a temperature-recording equipment (Datalogger with thermocouples). During twelve months (January 2004 to December 2004) pavement temperatures were measured on a new pavement section, located at IP4 main road, near Bragança, in the north of Portugal. At that location, seven thermocouples were installed in the pavement, at seven different depths: at surface, 27.5 mm, 55 mm, 125 mm, 165 mm 220 mm and 340 mm, in a pavement with a 0.125 m overlay layer and a 0.215 m cracked layer. The top one was installed on the pavement surface. The depths for the other six were chosen to provide a good representation of the whole asphalt concrete layers. Figure 1 shows the observed surface temperature where it can be observed the typical temperature variations at summer and at winter periods.

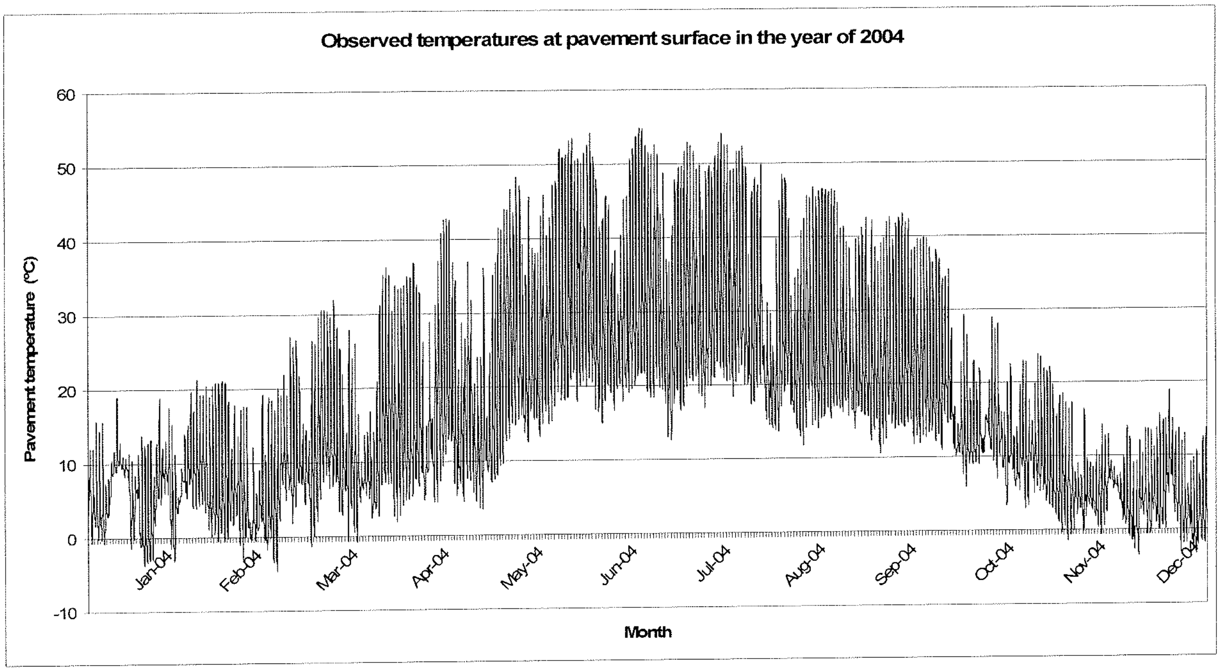

Figure 1 – Observed temperatures at pavement surface

The traffic data were obtained in terms of number of axles, type of axles and wheel load. The number of axles is useful to calculate the damage associated to the traffic. The wheel load configuration, considered in the numerical simulation, is defined as a surface load (pressure) near the vertical location of the crack, simulating the 130 kN standard axle load.

PAVEMENT MODELLING

The pavement structure was idealized as a set of horizontal layers, with constant thickness, resting on the subgrade. For crack reflection analysis, the top layer represents the bituminous overlay and the subjacent layer represents the existing cracked bituminous layer, where a crack is modelled by elements without stiffness. The structural model configuration of the analysed pavement is presented in Figure 2.

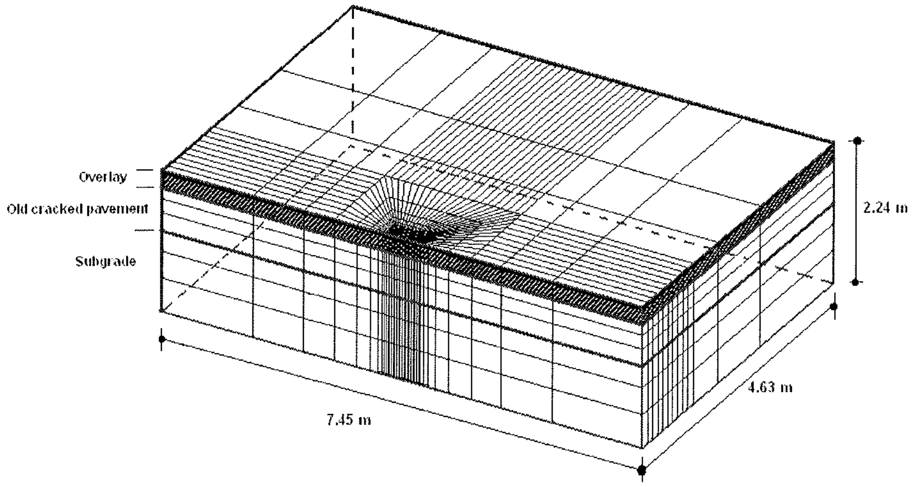

Figure 2 – FE structural model configuration for numerical simulation

The FE model used in numerical analysis was developed by using a ANSYS 7.0 source code and the mechanical model was designed with a three-dimensional finite element mesh, based on a 3-D eight-node structural solid element, that assumes linear approximation of the displacements field and has three degrees of freedom per node.

The analyzed body had a length of 4.63 m, 7.45 m wide and 2.24 m thickness. The total thickness of the model is the result of all pavement layers thicknesses: 0.125 m overlay, 0.215 m cracked layer, 0.30 m aggregate base layer and 1.6 m subgrade. The crack was modelled on the layer just below the overlay, with 10 mm width and longitudinal cracks were simulated.

The processing type of the model depends on the loading case considered in the evaluation of stress and strain states. For thermal loading effects on the overlay, through the evaluation of the mechanical effect of temperature variations, the processing was made as a numerical transient analysis (time-rate dependent), as it is a long term load type, and the material properties must be defined as time-rate dependent, by defining the mechanical behavior through the relaxation modulus. For traffic load the linear elastic analysis was used.

MECHANICAL PROPERTIES

The mechanical properties of the bituminous materials considered in the processing of models were obtained from a set of laboratory tests and are: stiffness modulus, viscoelastic properties (relaxation modulus) and thermal contraction coefficient. In order to estimate the reflective cracking overlay life, fatigue laws were obtained from four-point flexural fatigue tests, for several temperatures.

In this study two types of bituminous mixes were analysed: an asphalt rubber hot mix and a conventional hot mix asphalt. These mixes were extracted from the pavement located on a trial section on Km 197.700 of IP4. In both cases, slabs were obtained from "in situ" pavement, after "in place" operations. For the conventional dense asphalt mix (CM) the binder used was a PG 70-10 (50/70) and the binder content was 5.4 %. The aggregates used were derived from good quality Portuguese granite, extracted near the trial section.

Stiffness modulus

The stiffness modulus, which is temperature-dependent, was evaluated from flexural fatigue tests, conducted according to the AASHTO TP 8-94, performed for 4 different temperatures: -5°C; 5°C, 15 °C and 25°C. In that way, it was considered that the bituminous materials show a linear elastic behavior. The values obtained for the stiffness modulus are presented in Table 1, for both materials modelled, i.e. asphalt rubber hot mix and conventional asphalt mix.

Table 1 – Elastic properties of bituminous mixtures

Temperature (°C)	Stiffness (MPa)	
	Asphalt rubber hot mix	Conventional asphalt mix
-5	4434	16157
5	3221	13563
15	1948	9304
25	1107	4781

Fatigue

The four-point flexural fatigue tests were also performed for several temperatures to obtain the fatigue laws coefficients of temperature-dependent. The fatigue behavior considered for the studied mixtures was evaluated after the stiffness modulus tests for the same test temperatures. For each test temperature (-5°C; 5°C, 15 °C and 25°C) a fatigue life law was achieved and fitted in the following model:

$$N_f = \left(\frac{\varepsilon_t}{(aV_b + b)E^{-c}} \right)^{-d} \qquad (3)$$

where N_f is the fatigue resistance, ε_t is the strain level, E is the stiffness modulus, V_b is the volume of the binder in the mixture and a, b, c and d are constants obtained for each material type, presented in the Table 2. The Equation 3 may be expressed through the following equation, as function of ε_t:

$$\varepsilon_t = ((a \times n) + b) \times E^c \times N^d \qquad (4)$$

Table 2 – Fatigue parameters for asphalt rubber hot mix and for conventional mix

Material type	a	b	c	d
Conventional asphalt mix	1.009	0.928	-0.337	-0.252
Asphalt rubber hot mix	1.957	0.926	-0.434	-0.144

Relaxation Modulus

The viscoelastic material properties are time-and-temperature dependent. A bituminous material behaves as a viscous fluid for high temperatures and as a solid at low temperatures. The temperature influence in the mix behavior may be considered through the adoption of thermal-rheological simplicity principle (WLF function), which considers that the relaxation curve for high temperatures is identical to the low temperature relaxation curve, if loading time is scaled.

Relaxation tests were performed at -5 °C, 5 °C, 15 °C and 25 °C, using bituminous samples representing an asphalt rubber hot mix and a conventional asphalt mix. Each sample is subjected to a constant vertical axial strain, ε_0, applied during loading time, through an induced constant displacement, applied to each sample, with an adopted time loading of 7200 seconds (Figure 3). During each test with controlled constant temperature, in periods of time previously defined, the evolution of the load applied to the sample necessary to keep the sample with a constant length (constant strain) during the loading time, was measured.

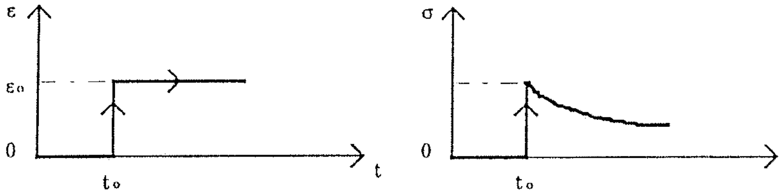

Figure 3 – Relaxation Stresses - strains relationship

With the accomplishment of each test, the values of three controlled parameters are periodically obtained: temperature, sample deformations (displacements) and load. The load is the used parameter for the characterization of the relaxation behaviour of the mixtures. The temperature and the sample deformation are parameters that must be kept constant throughout the test. In Figure 4 a representative graph of the curves obtained for each test (or for each sample) is presented, involving the asphalt rubber hot mix.

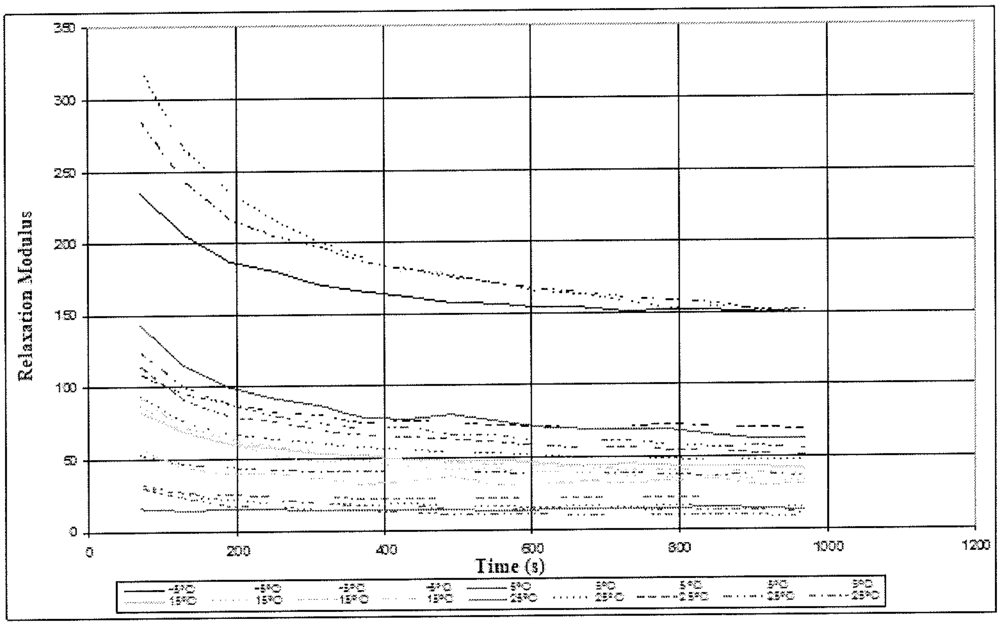

Figure 4 – Relaxation bulk modulus for AR-HMA mix

The characterization of the relaxation behavior of mixtures is made through the determination of the bulk relaxation modulus and the shear relaxation modulus. Representative curves of each type of the observed modulus were obtained and were used as a basis for the adjustment to the functions kernel, in the form of a Prony series. The Prony series must be representative of the viscoelastic behavior of the studied mixtures and include the consideration of thermal-rheological simplicity principle, through the following equations:

$$G = G_{\infty} + \sum_{i=1}^{n_G} G_i \exp\left(-\frac{t}{\tau_i^G}\right) \qquad (5)$$

$$K = K_{\infty} + \sum_{i=1}^{n_K} K_i \exp\left(-\frac{t}{\tau_i^K}\right) \qquad (6)$$

$$\log_{10}\left(A(T(\tau))\right) = \frac{C_1(T - T_r)}{C_2 + T - T_r} \qquad (7)$$

The parameters obtained from this process are presented in Table 3, namely the elastic shear modulus, Gi, elastic volumetric modulus, Ki, relaxation times, τ_i^G, τ_i^K, reference temperature, T_r and C1 and C2 for WLF function.

Table 3 – Relaxation parameters for an asphalt rubber hot mix and for a conventional mix

	Parameters	***AR - HMA***	***Conventional asphalt Mix***		**Parameters**	***AR - HMA***	***Conventional asphalt Mix***
Shear Parameters	G_{∞}	5.11E+00	1.04E+01	**Volimetric Parameters**	K_{∞}	1.38E+01	2.81E+01
	G_1	2.09E+02	2.89E+02		K_1	5.62E+02	7.85E+02
	G_2	4.13E+01	9.45E+01		K_2	1.12E+02	2.60E+02
	G_3	8.85E+00	1.13E+01		K_3	2.39E+01	3.07E+01
	τ_1^G	6.03E-02	5.99E-01		τ_1^K	6.05E-02	5.85E-01
	τ_2^G	1.47E+01	9.49E+00		τ_2^K	1.47E+01	9.16E+00
	τ_3^G	9.86E+03	1.00E+04		τ_3^K	9.86E+03	9.92E+03
				WLF	T_r	1.38E+01	1.31E+01
					C_1	2.23E+07	2.56E+07
					C_2	1.44E+08	1.39E+08

Thermal contraction

Thermal contraction tests were performed using samples of asphalt rubber and conventional mixes. The obtained coefficient of thermal contraction is constant and independent from the temperature. This study adopted the value of $4.3\text{x}10^{-5}$ °C^{-1} for the asphalt rubber hot mix and $3.5\text{x}10^{-5}$ °C^{-1} for the conventional asphalt mix.

DAMAGE EVALUATION

In one-year time-period the main results obtained from this simulation were: i) the Von Mises strains; ii) predicted overlay life; iii) overlay damage. These calculations were performed for traffic loading, temperature variations and the combination of both, traffic and temperature. The Von Mises strain for each loading case was used to predict the pavement life after overlying. Figure 5 shows the hourly predictive overlay life resulting from traffic and traffic+ΔT loading cases for the conventional mix.

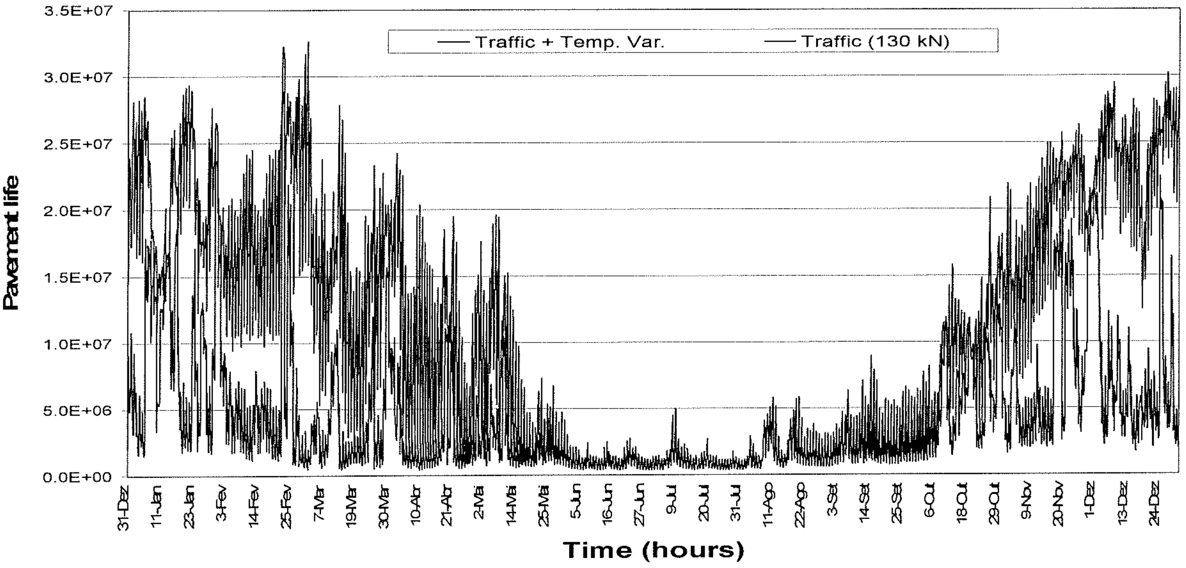

Figure 5 – Predicted overlay life for traffic and temperature variations for the conventional mix

The results show that the overlay life obtained from traffic loading is higher than the overlay life obtained from traffic+ΔT loading, mainly in winter season, when low temperatures occur. In summer, the predicted overlay life is inferior to that of winter. Thus, the effect of traffic+ΔT may have a significant influence on the overlay life, which will justify a special attention.

Knowing the predicted overlay life and the number of axles distribution during the year allows to perform an estimation of the annual damage evolution. The damage evaluation is made in terms of damage distribution and in terms of accumulated damage evolution, measured hourly and monthly. Figure 6 shows the accumulated monthly damage occurred in a conventional mix and in an asphalt-rubber mix overlay for traffic and traffic+ΔT. In this figure the accumulated monthly damage occurred due to the traffic loading is lower than the damage observed for traffic+ΔT. Thus, the traffic+ΔT effect in the overlay damage may have a significant influence when compared with traffic effects that should be considered in a design process. The figure also shows that the asphalt-rubber mix presents a better performance than the conventional mix for traffic+ΔT load case.

CONCLUSIONS

The finite-element analysis was used to simulate the reflective cracking performance of bituminous mixture overlays throughout a year, considering the temperature variations as the main cause for reflective cracking. A thermal response of the pavement structure, made by a thermal analysis, was performed before a mechanical analysis. In the mechanical analysis the transient effect of relaxation was considered, once the overall state of tension in the overlay caused by the temperature variation is also a function of the viscoelastic response of the bituminous materials.

Temperature variations in bituminous layers (overlay and cracked layers), which cause a state of tension in the overlay, are particularly important for estimating the overlay life. The effect of accumulated restrained thermal stresses, as a result of the effect of temperature variations shrinkage, added to the traffic loading effect, will reduce the overlay life. Thus, the effect of temperature variations will support the need for a special attention towards overlay design procedures.

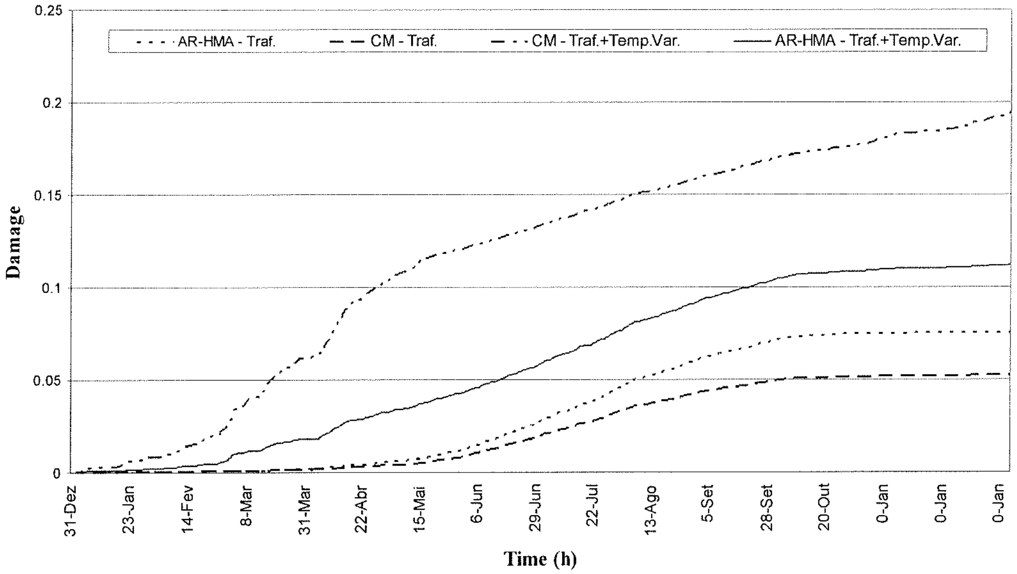

Figure 6 – Accumulated hourly damage

This study allowed concluding that, if the temperature variation is considered, the asphalt rubber mixes show a clear difference in terms of reflective cracking performance, when compared with conventional asphalt mixes. These differences are more expressive during cold seasons. In those seasons the asphalt rubber mixes overlays show a better performance than conventional asphalt mixes overlays.

REFERENCES

Sousa, J.B., Pais, J.C., Saim, R., Way, G. &, Stubstad, R.N. (2002). Development of a Mechanistic-Empirical Based Overlay Design Method for Reflective Cracking. *Journal of the Transportation Research Board.*

Abd el Halim A., (1989). A New Approach Toward Understanding the Problem of Reflective Cracking. *Proceedings of the First International RILEM Conference on Reflective Cracking in Pavements.*

De Bondt A. (2000). Effect of Reinforcements Properties. *4th International RILEM Conference on Reflective Cracking in Pavements – Research in Practice*, Canada.

Epps, Amy L. (1997). Thermal behavior of crumb-rubber modified asphalt concrete mixtures. Dissertation series UCB-ITS-DS-97-2. Institute of Transportation Studies, University of California at Berkeley. ISBN 0192 4109.

Minhoto, M.J.C., Pais, J.C., Pereira, P.A.A. & Picado-Santos, L.G. (2005). Predicting Asphalt Pavement Temperature with a Three-Dimensional Finite Element Model. *Transportation Research Record*: Journal of the Transportation Research Board nº 1919 – Rigid and Flexible Pavement Design 2005. Pps 96-110. TRB. Washington DC.

Minhoto, M.J.C. (2007). The temperature in the reflective cracking of pavement overlays (in Portuguese). Ph. D. Dissertation Thesis. University of Minho. Guimarães, Portugal.