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Influence of Temperature Variation on the Reflective Cracking Behaviour of Asphalt Overlays

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ABSTRACT. *The objective of this paper is to present a study about the influence of temperature on the reflective cracking behaviour through the evaluation of the overlay damage associated to the temperature variation during the year. The development of this study was based on the numerical simulation of the overlay behaviour, based on a three-dimensional finite-element analysis, considering the simultaneous loading of traffic and temperature variation and considering the most predominant type of overlay distress observed in the field: the reflective cracking. A mechanistic-based overlay design method was used to predict the reflective cracking overlay life. The occurrence of temperature variation in the pavements leads to an increase of the reflective cracking phenomenon, due to the stress and strain states created by the temperature, which produce the premature distress of the overlay. Thus, for overlay design purposes, it is important to consider the temperature variation in the evaluation of the overlay behaviour produced by the reflective cracking. Comparisons between expected performance of asphalt rubber hot mix, produced by the wet process with 20% crumb rubber, and conventional asphalt overlays were made, taking into account the performance of these mixes.*

KEYWORDS: *asphalt rubber mix, temperature variation, thermal behaviour of asphalt mixes, numerical analysis*

1. Introduction

Road flexible pavements exhibit a set of distresses on its surface when subjected to the traffic and temperature variation, which are responsible for the discomfort and safety reduction for the users.

Bituminous overlays have been the most used method to rehabilitate cracked pavements. However, the service life of an overlay depends of its performance in different distress modes. An overlay placed on a cracked pavement, the cracks will develop and propagate to the pavement surface, directly above cracks of the existing pavement due to static and repetitive loading, during the first few years of service. This mode of distress is traditionally referred as "reflective cracking" and is a major problem to highway agencies throughout the world. Thus, a concern exists, in road administrations, in the prevention of cracking occurrence, in order to present a good functional and structural performance.

The literature review (Sousa *et al.*, 2002; Halim, 1989; Epps, 1997; de Bondt, 2000), revealed that temperature variations, daily and seasonal, and associated thermal stresses, could be a cause of premature overlay cracking, affecting the overlay life of asphalt pavements. In regions that experience large daily temperature variations or extremely low temperatures, the thermal conditions plays a major role in the reflective cracking response of a pavement. On one hand, binder properties (stiffness, ageing, penetration, etc...) are sensitive to temperature variations. On the other hand 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 rapidly decreasing of temperature - have been identified as the most likely causes of high states of stress and strain above the crack and responsible by the reflective cracking phenomena.

Daily temperature variations have an important influence in the pavement thermal state a few centimetres below the surface. Depending on the level of temperature variation, stress is induced in the overlay in two different ways, which need to be distinguished: through restrained shrinkage of the overlay and through the movements of the existing slabs resulting of thermal shrinkage.

Asphalt mixes with asphalt cement modified by crumb rubber recycled from ground tires, commonly referred as Asphalt Rubber, when properly designed and constructed, can provide a good performance, in terms of cracking resistance, reflective cracking resistance (Minhoto *et al.*, 2003), rutting resistance, optical conditions response and skid resistance, as compared to conventional asphalt mixes, as proved by the field experience (Sousa et al., 2000; Hicks, 1995; Hicks and Epps, 2000; Momm, 2000).

The aim of this paper is to present a study about the influence of temperature variation in the reflective cracking. The development of this study was based on the numerical simulation of the overlay behaviour, based on finite element methodology, considering the simultaneous loading of traffic and temperature variation. Asphalt rubber hot mix, produced by the wet process with 20% crumb rubber, and conventional asphalt overlays were used in this evaluation.

2. Scope of this study

This study involves the calculation of the hourly stresses and strains, during a year (2004), 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, during a year, recorded with a datalogger associated with thermocouples, made in a pavement section, located at IP4 main road, near Bragança, in the north of Portugal. Traffic data was obtained from field measurements near the temperature measurements location.

Stresses and strains calculations were performed using a 3D Finite Element (FE) analysis, 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 and as such as a function of the viscoelastic response of the bituminous materials. 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 traffic and thermal stresses and strains, calculated for each loading case, were used to verify the influence of the thermal loading in the overlay behaviour by the evaluation of the damage associated to each type of loading.

The evaluation of overlay damage during the year was made by hourly evaluation of temperature variation and traffic effects. The evaluation of overlay life was made using the mechanistic-empirical methodology proposed by Sousa *et al.* (2003).

The mechanistic-empirical methodology is capable of assembling simultaneously Modes I and II crack opening. The influence of pavement characteristics on state of stress and strain was considered by defining a deviator strain such as the Von Mises stress. This strain, called "Von Mises strain" was calculated as expressed in Equation [1].

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

Where ε_{VM} is the "Von Mises" strain and ε_1, ε_2, ε_3 are the principal strains.

This mechanistic-empirical methodology is based on the results of flexural fatigue tests, in controlled strain, based on a "Von Mises" deviator strain as the "controller" parameter of the phenomenon. For beam fatigue test conditions subjected to four-point bending, ε_{VM} can also be written as:

$$\varepsilon_{VM} = \varepsilon_{fat}\left(1+\nu\right) \quad [2]$$

Where ε_{fat} is the fatigue strain for beam fatigue test conditions subjected to four-point bending and ν is the coefficient of Poisson.

This parameter can be used to obtain an indication of actual reflective cracking fatigue life. The fatigue behavior of a bituminous mixture could be expressed as a relationship between the number of cycles to failure and the "Von Mises strain".

This research first calculates the stresses and strains above existing cracks through a 3D finite element analysis, for each loading case (traffic loading and thermal loading) and for the combination of both cases, and then calculates the Von Mises strains, ε_{VM}. The Von Mises strains, ε_{VM}, for the traffic loading and for thermal loading, are used to the pavement life prediction. The Equation [2] is used to relate ε_{VM} with ε_{fat}.

3. Loads

In order to calculate pavement thermal effects and mixes thermal response, one needs to evaluate the temperature distribution in bituminous layers during a typical twenty-four hours period. The temperature distribution during the day allows to calculate thermal effects in the zone above the crack. The variation of pavement thermal state is controlled by the climatic conditions, by the thermal diffusivity of used materials, as function of thermal conductivity, specific heat and density, and the depth below the surface (Halim, 1989; Shalaby *et al.*, 1990).

The temperature distribution throughout the pavement structure was obtained by field measurements, using temperature-recording equipment (Datalogger associated with thermocouples). The option of use the field measurement is desirable because actual temperature can be reliably measured. However, this method is relatively slow and only provides information about temperatures in the measurement period (Minhoto *et al.*, 2005).

During twelve months (January 2004 to December 2004) pavement temperatures were measured at 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 just at the pavement surface. The depths for the other six were chosen to give a good representation of the whole asphalt concrete layers. Temperatures were recorded every hour, every day during a year (Minhoto *et al.*, 2005).

In Figure 1 the observed surface temperature is presented and one can see the typical temperature variations of summer and winter periods. Figure 2 and Figure 3 present the temperature annual evolution, at the bottom of overlay and in the bottom of bituminous layers.

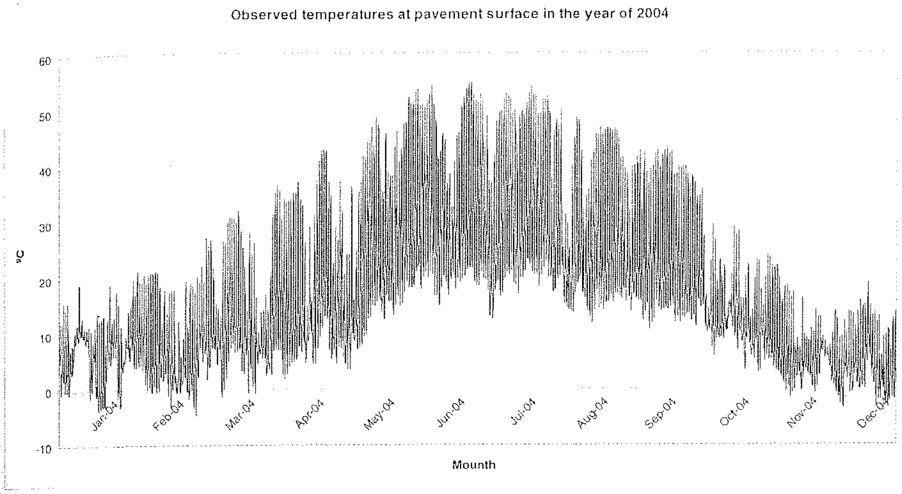

Figure 1. *Observed temperatures at pavement surface*

In the numerical analysis, the thermal effects were expressed through a temperature variation on the bituminous layers. That temperature variation, ΔT, was computed, for each hour and each day, as a difference between a reference temperature, T_{ref}, and the observed temperature.

The thermal response of the bituminous mixes was expressed by a thermal dependence of bituminous stiffness. In the numerical model and at each hour/day, the temperature presents different values and causes different stiffness in the bituminous mixes.

The traffic data was obtained in terms of number of axles, type of axles and wheel load. These values were then converted in 130 kN standard axle 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.

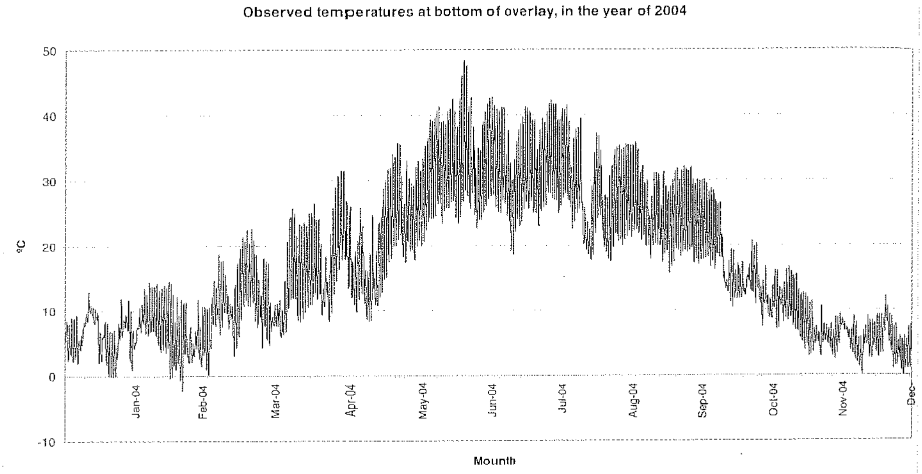

Figure 2. *Observed temperatures at the bottom of the overlay (0.125 m)*

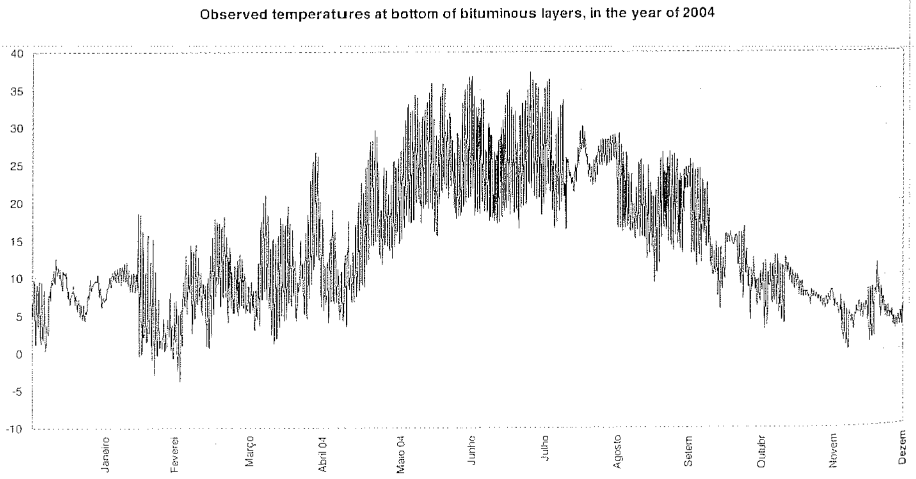

Figure 3. *Observed temperatures at the bottom of the bituminous layers (0.335 m)*

4. Pavement modelling

The pavement structure was idealized as a set of horizontal layers of constant thickness, resting on the subgrade. For the analysis of the crack reflection phenomena, the top layer represents the bituminous overlay and the subjacent layer represents the existing cracked bituminous layer, where a crack is modeled by elements without stiffness. The structural model configuration of analysed pavement is presented in Figure 4.

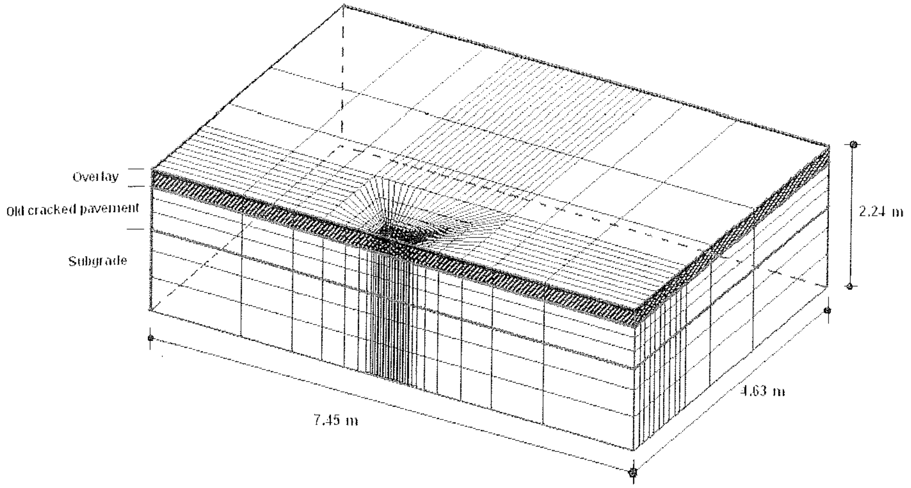

Figure 4. *FEM structural model configuration used in numerical simulation*

4.1. *Model description*

The finite element model used in numerical analysis was developed by using a general Finite Elements Analysis source code, ANSYS 7.0. The design of the mechanical model was based on a finite element mesh definition, oriented for the mechanical analysis, considering the following principles:

– a finer element size is required closer to pavement surface and to wheel load point, where stress gradient is highest;

– a finer element size is required in the overlay above the crack;

– due to the symmetry, only half of the model was modelled.

For three-dimensional analysis, 3-D eight-node structural solid element, SOLID185, was used. This element assumes linear approximation of the displacement's field and has three degrees of freedom per node.

As the problem is symmetric along the wheel axle direction, only half of the geometry is considered in this analysis. 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 modeled on the layer just below the overlay with 10 mm width and longitudinal cracks were simulated.

The first effort to verify and calibrate the purely FEM mechanical analysis of a cracked pavement before and after overlay was accomplished by comparing the vertical crack activity measured in the model with the one measured in the pavement using a crack activity meter.

4.2. *Thermal and load model definition*

The type of model processing depends on the loading case considered in the evaluation of stress and strain states. For thermal loading, the processing was made as a transient process (time-rate dependent), because that load type is a long term load, and the material properties must be defined as time-rate dependent.

For traffic loading, the processing was made as a steady-state process, because that load is considered to be a short-term load, and the material properties associated to the computation must be defined as elastic material without time-dependence.

4.2.1. *Thermal model for temperature distribution*

The pavement temperatures were obtained at seven points in the bituminous layers of the existing pavement. However, to compute the thermal effects in the pavement, one needs to know the nodal temperatures in the full model. Thus, the main objective of this model is to obtain the nodal temperatures for full model (pavement thermal state) for each hour.

The thermal response of a multilayered pavement structure is modeled using a steady-state thermal analysis. The representative flowchart of model procedures is presented in Figure 5, based on five procedures: data input, thermal model definition, thermal loading definition, numerical analysis (running) and post-processing (results output).

4.2.2. *Model for thermal effect*

The Figure 6 presents the representative flowchart of the model for mechanical analysis of traffic loading, based on five main procedures: data input, thermal model definition, traffic loading definition, numerical analysis (running) and post-processing (results output). The numerical analysis is a steady-state analysis based on mechanical response of the material considered as elastic linear behavior.

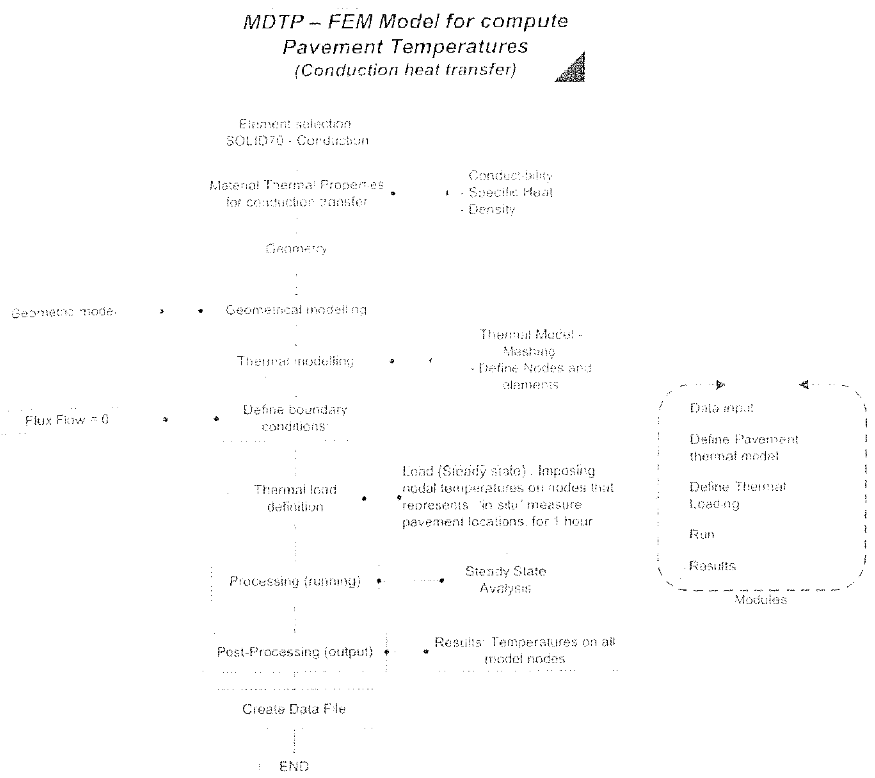

Figure 5. *Thermal model*

4.2.3. *Model for temperature variation effect*

The FEM model to evaluate the temperature variation effect is presented in the Figure 7. Such as other models, this one presents five processing phases: data input, thermal model definition, thermal loading definition (temperature variation), numerical analysis (running) and post-processing (results output). To evaluate the mechanical effect of temperature, this model considers the long-term effect, through a numerical transient analysis. In this context, the material properties must be defined in terms of time-dependent, by defining the mechanical behavior through the relaxation modulus.

The considered load is defined as a difference between a reference temperature and the temperature at each node that occurred in each hour during the analysis. Each analysis is made for 24-hours period and the results are linked to one-year period.

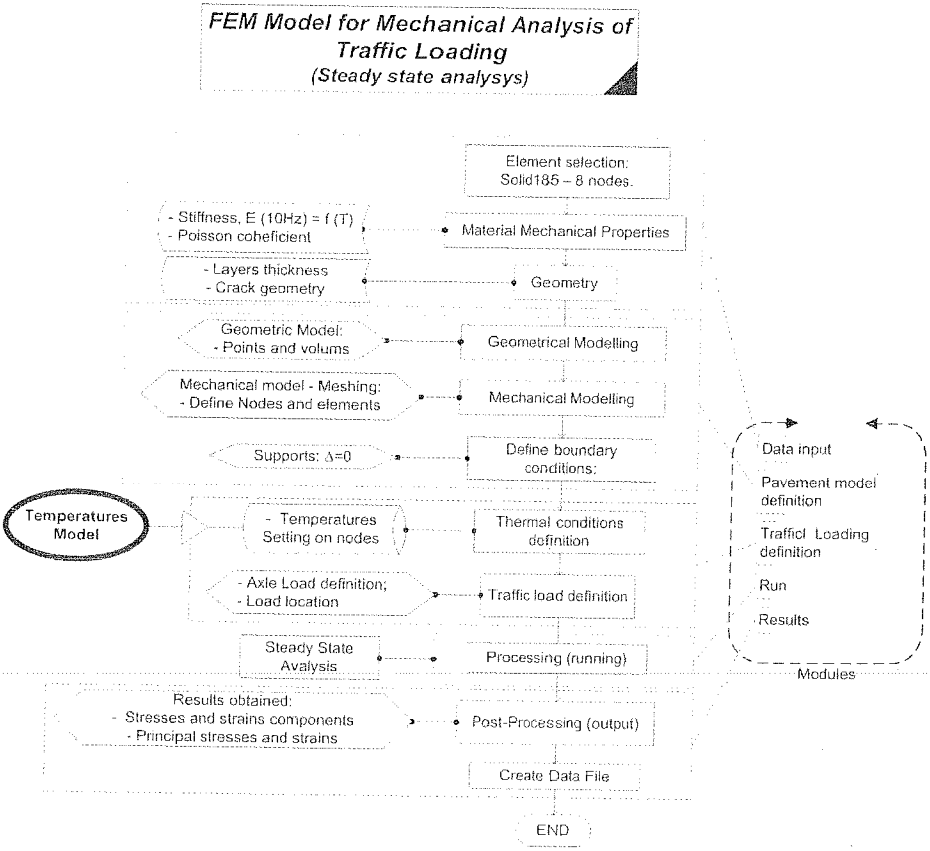

Figure 6. *Traffic loading model*

5. Mechanical properties

The mechanical properties of the material used in this study were defined in two different ways. When the traffic load is applied, it was considered that the bituminous materials show a linear elastic behaviour defined by stiffness modulus, which is temperature-dependent. The stiffness modulus was obtained 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. The values obtained for stiffness modulus are presented in the Table 1, for both materials modelled, ie asphalt rubber hot mix and conventional asphalt mix.

In the pavement analysis, when the temperature variation is applied, it was considered that the bituminous materials show a linear viscoelastic behavior.

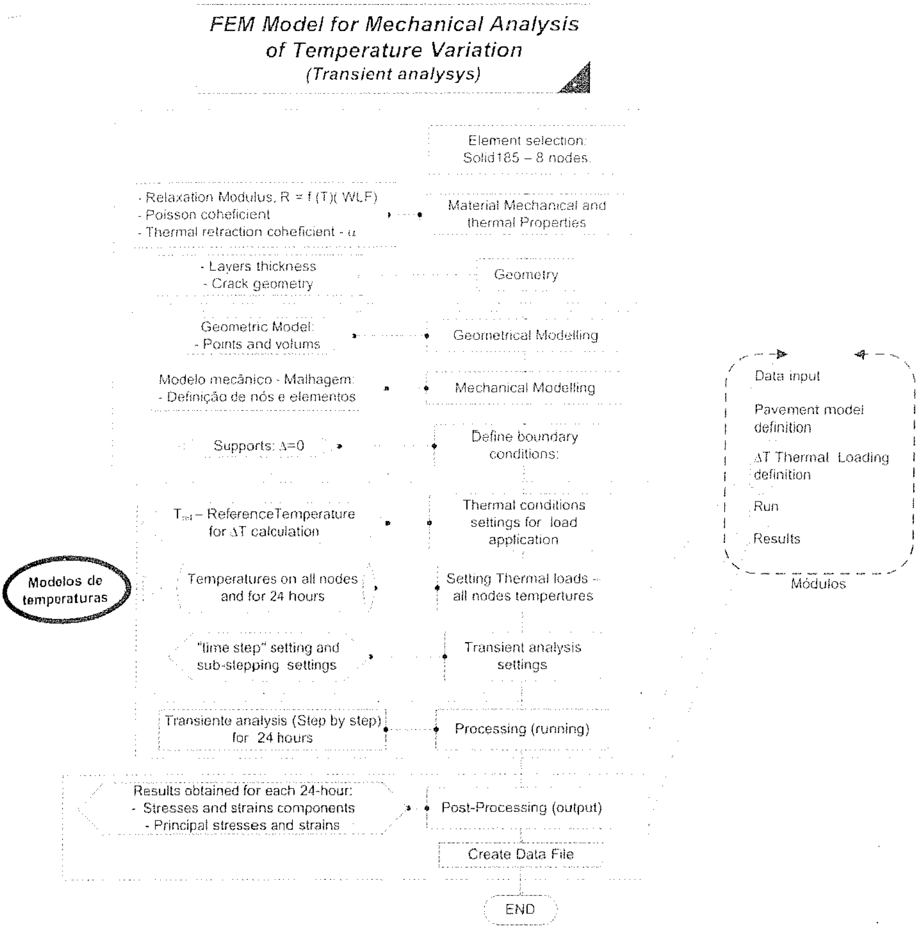

Figure 7. *Model for temperature variation mechanical response*

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. This behaviour may be modelled when thermal-reological simplicity principle is adopted. With this principle, 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 ºC, 5 ºC, 15 ºC and 25 ºC, using bituminous samples representing two mixes: asphalt rubber hot mix and conventional asphalt mix. Tests results were fitted in Kernel functions and considering the thermal-reological simplicity principle, elastic shear modulus, G_i, elastic volumetric modulus, K_i, relaxation times, τ_i^G , τ_i^K , and C_1 and C_2 for WLF function were obtained and the results are presented in Table 2.

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

Table 2. *Prony parameters for asphalt rubber hot mix and for conventional mix*

	Prony Parameters	*AR - HMA*	*Conventional asphalt Mix*
Shear Parameters	K_∞	13.7916	28.06688
	K_1	562.2816	784.52592
	K_2	111.5924	259.80098
	K_3	23.8999	30.709959
	τ_1^K	0.06054	0.5853224
	τ_2^K	14.735537	9.1648282
	τ_3^K	9862.5999	9921.9785
Volumetric Parameters	G_∞	5.1079987	10.388833
	G_1	209.13504	289.38448
	G_2	41.337079	94.452529
	G_3	8.8519824	11.346627
	τ_1^G	0.0603238	0.5990993
	τ_2^G	14.728783	9.4894856
	τ_3^G	9862.342	9998.5339
WLF	T_r	13.838168	13.114544
	C_1	22284918	25574767
	C_2	143777636	139497625

Thermal contraction tests were performed using asphalt rubber and conventional mixes samples. The obtained coefficient of thermal contraction is constant and independent of the temperature and it was adopted for this study the value of 4.3x10-5 °C^{-1} for asphalt rubber hot mix and 3.5x10-5 °C^{-1} for conventional asphalt mix. The Poisson ratio was assumed constant and the used values were:

- for bituminous layers – $\nu = 0.35$;
- for granular layer – $\nu = 0.30$;
- for subgrade – $\nu = 0.35$.

6. Procedures involved in the study simulation

To achieve the main purposes of this study, the simulation procedures involve a multiple 3-D finite-element runs, based on the ANSYS 7.0 software, considering the pavement structure presented. Each solution was obtained for each hour, for each loading case (traffic, temperature variation and both superimposed) and for each axle load type. The main analysis procedure involved in the present study is schematized in the Figure 8.

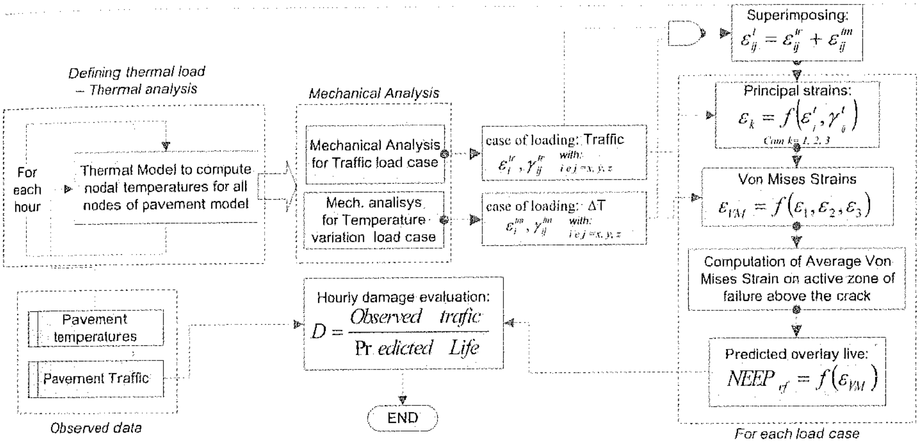

Figure 8. *Procedures involved in the study*

In the first step, for each hour of the year, all nodal pavement temperatures of the finite element model were calculated. This calculation was performed with the thermal model, using the steady-state thermal analysis: The input data of this model were the field pavement temperatures obtained in the seven points of the pavement.

The computed pavement temperatures were applied in all nodes of the traffic model. These temperatures are needed to set the elements stiffness for stress and strain calculation, in the nodes above the crack, for 130 kN traffic loading case. The strain state is used to determinate the superimposed effects in the zone above the crack (Figure 9).

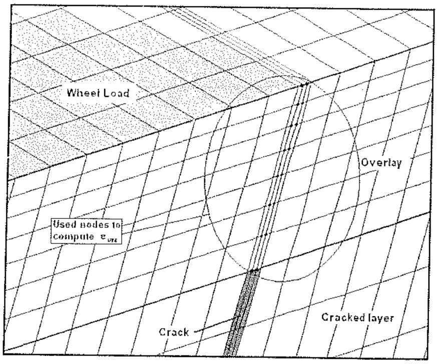

Figure 9. *Nodes used to compute the Von Mises strains in the zone above the crack*

The computed pavement temperatures were also applied in all nodes of thermal mechanical model. These temperatures are needed to calculate the temperature variation, ΔT, in each node. 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 drop down.

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

The equation [2] 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.

The four-points flexural fatigue tests performed to obtain the fatigue laws for using in this study were made for several temperatures. That fatigue laws were developed in terms of temperature-dependent. 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. The hourly damage is obtained as the ratio between observed traffic and overlay life, expressed in number of axles.

7. Von Mises strains and overlay life results

This study was carried out based on a thermal and mechanical FEM simulation, developed to calculate stains state in the overlay and to predict the overlay life. The main results obtained from this simulation, for one year time-period, were the Von Mises strains, predicted overlay life and overlay damage. These calculations were performed for traffic loading, temperature variations and the combination of traffic and temperature.

In Figure 10, the hourly Von Mises strain in the year is plotted against the time, for Asphalt Rubber mix. Figure 11 present these results for the convectional mix.

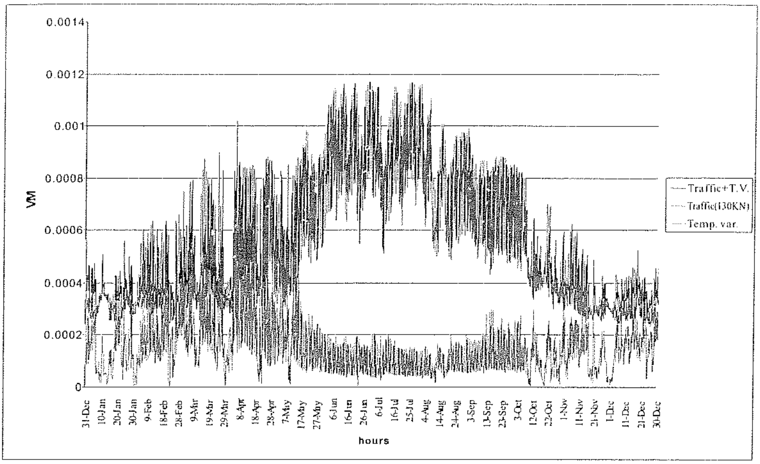

Figure 10. *Von Mises strain for all loading cases for Asphalt Rubber*

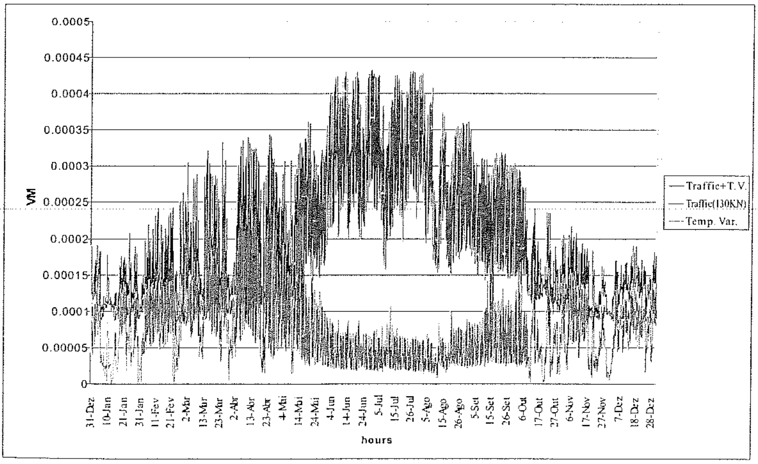

Figure 11. *Von Mises strain for all loading cases for conventional mix*

For traffic and traffic+temperature variantion (ΔT), the results show that the hourly Von Mises strains increases during summer season and decreases during winter season, for both material types (asphalt rubber mix and conventional asphalt mix). In the summer the Von Mises strain for traffic+ΔT presents the same values as for traffic only.

In summer season, the Von Mises strain associated to the temperature variation is less than the hourly Von Mises strain occurred in winter season. On winter season, the traffic+ΔT shows great Von Mises strains than other loading cases. Thus, it can be concluded that the effect of temperature variation is relevant on winter season, when the pavement temperature in the bituminous layers decreases and is less than the temperature in summer season.

Figures 12 and 13 present the Von Mises strain evolution for both materials and respectively for traffic+ΔT and for ΔT loading case. In these figures one can verify that asphalt rubber mix shows greater Von Mises strains than conventional asphalt mix due to the stiffness difference.

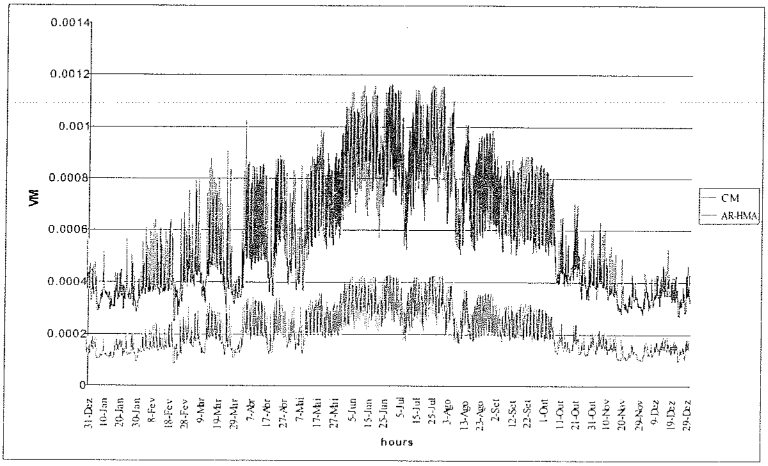

Figure 12. *Von Mises strain for traffic+ΔT combination*

The Von Mises strain for each loading case was used to predict the pavement life after overlay. Figures 14 and 15 show the hourly overlay life, resulted from traffic and traffic+ΔT, for Asphalt Rubber and conventional asphalt mix, respectively.

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

Figure 16 shows the overlay life, for traffic+ΔT for both materials where one can verify that asphalt rubber mix exhibit better behavior than conventional asphalt mix.

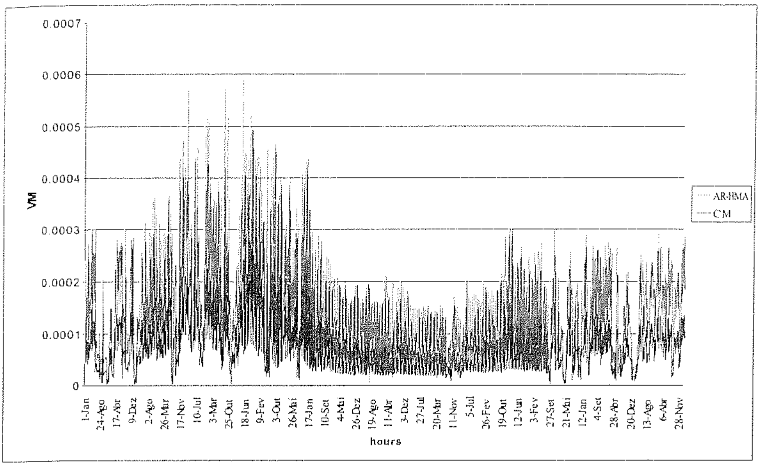

Figure 13. *Von Mises strain for ΔT load case for both materials*

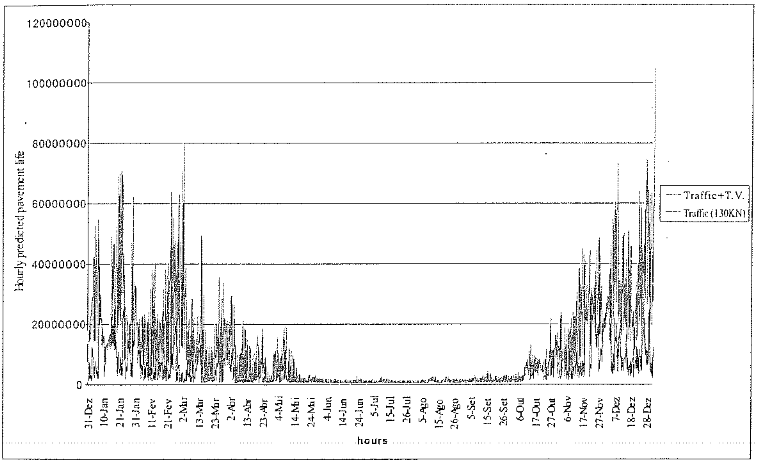

Figure 14. *Predicted overlay life for traffic and traffic+ΔT combination load cases and for Asphalt rubber overlay.*

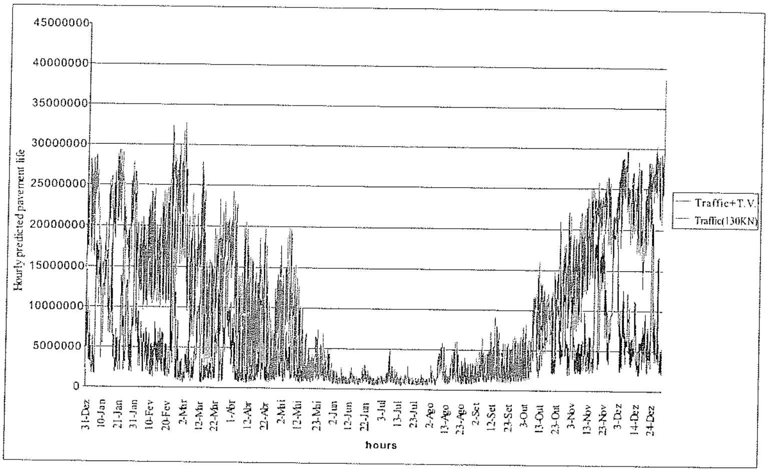

Figure 15. *Predicted overlay life for traffic+ΔT combination load case and for conventional mix overlay.*

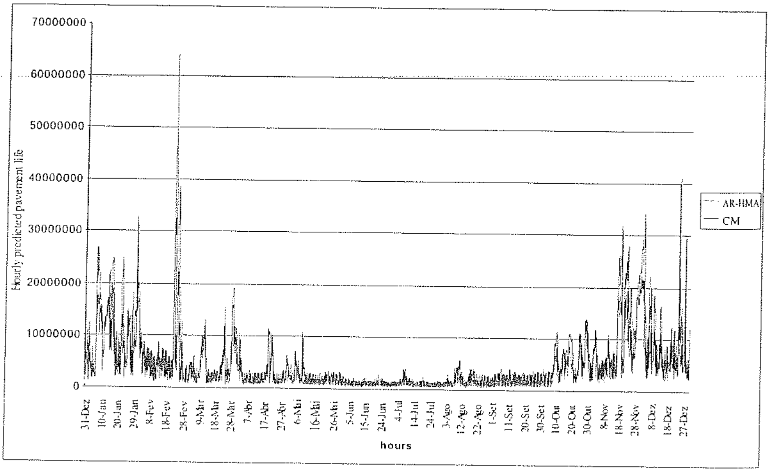

Figure 16. *Predicted overlay life for traffic+ΔT combination load case and for both materials applied on overlay*

8. Damage results

Knowing the predicted overlay life and the distribution of axles during the year, it allows to perform a annual damage evolution. The damage evaluation was made in terms of damage distribution (hourly and monthly) and in terms of accumulated damage (hourly and monthly).

The Figures 17 and 18 shows the accumulated monthly damage calculated for the asphalt rubber overlay and the conventional asphalt mix overlay, for traffic and traffic+ΔT. In these figures, the accumulated monthly damage occurred for traffic loading is less than the damage observed for traffic+ΔT.

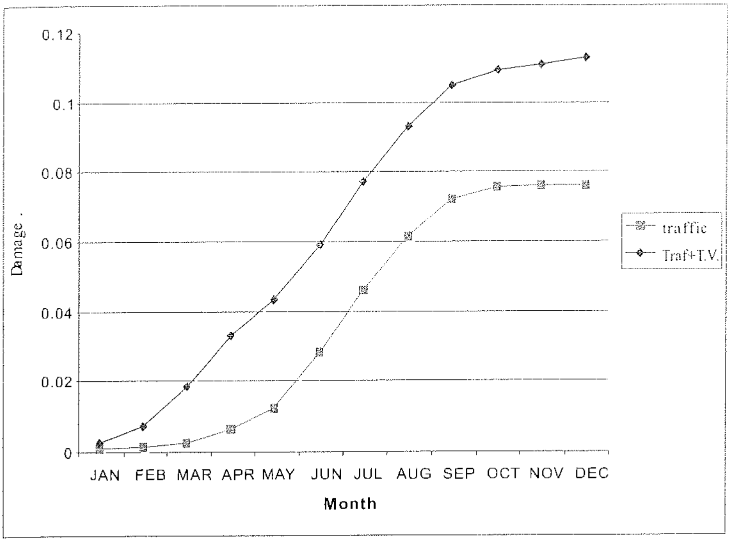

Figure 17. *Accumulated monthly damage evolution in an asphalt rubber overlay*

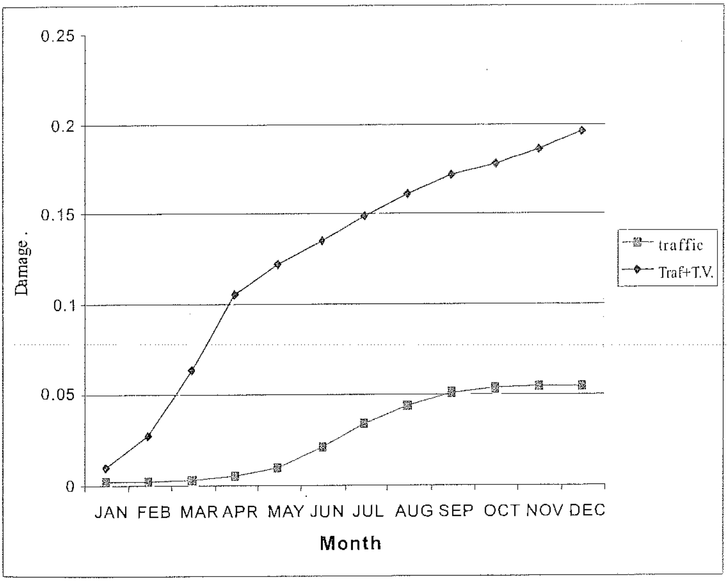

Figure 18. *Accumulated monthly damage occurred in a conventional mix overlay*

Thus, the traffic+ΔT effect in the overlay damage may have a significant influence when compared with the traffic effect, which should be considered in a design process.

In the Figure 19, a comparison between accumulated monthly damage on an asphalt rubber and a conventional asphalt mix overlay is made for traffic+ΔT. In this graph, the conventional asphalt mix overlay exhibit great accumulated monthly damage than the asphalt rubber overlay. In the conventional asphalt mix overlay, the great damage variation occurs during the cold season.

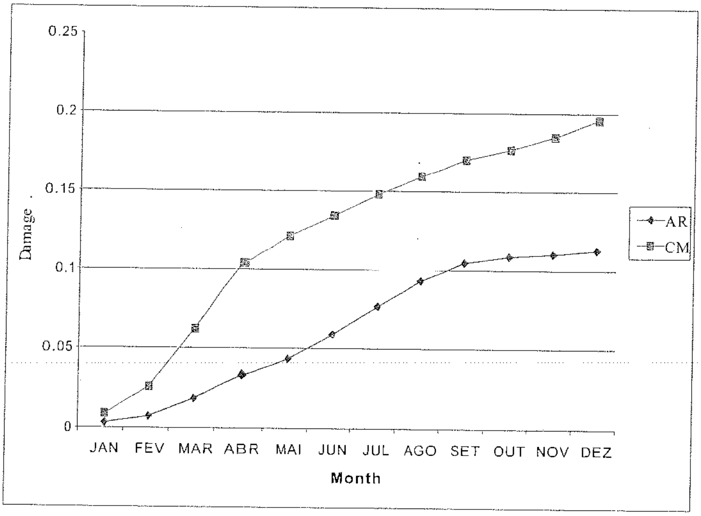

Figure 19. *Accumulated monthly damage for traffic+ΔT and for both overlay materials*

Figure 20 shows monthly damage distribution occurred on both material overlays, for traffic+ΔT loading, and it is observed that the conventional mix overlay exhibit a great monthly damage than the asphalt rubber overlay during the cold season. During warm season, the damage in the asphalt rubber overlay is identical to the conventional asphalt mix overlay damage.

9. Conclusions

The finite-element analysis was used to simulate the reflective cracking performance of asphalt concrete overlays, during a year simulation, considering the temperature variations as the main loading case. A thermal response of the pavement structure, made by a thermal analysis, was performed before the mechanical analysis. In 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.

The temperature variations in bituminous layers (overlay and cracked layers) which cause a state of tension in the overlay, is particularly important for estimate the overlay life. The effect of accumulation of thermal stresses due the effect of temperature variations and traffic loading will reduce the overlay life.

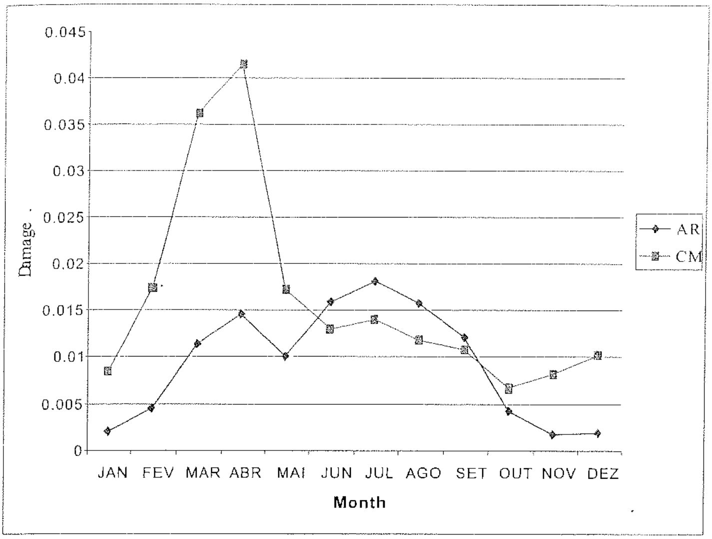

Figure 20. *Monthly damage distribution for traffic+ΔT and for both overlay materials*

This study allowed to conclud 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 shows better performance than conventional asphalt mixes overlays.

Thus, the effect of temperature variation will justify a special attention in overlay design procedures.

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