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Reflective cracking behavior for traffic and temperature effects

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ABSTRACT: This paper presents a study on the influence of the effects of temperature variations, in comparison with traffic effects, on the reflective cracking overlay behavior. It is intended 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.

1 INTRODUCTION

The aim of the paper is to present a study on the influence of temperature variations on the reflective cracking overlay. With the obtained knowledge, emphasis will be placed on the improvement of the pavement overlay design methods, by demonstrating the possibility to develop relationships that consider temperature variation effects in relation to the reflective cracking phenomena in the pavement overlay design methodologies. The developments of this study were supported on the numerical simulation of the overlay behavior, based on the finite element methodology and considering the simultaneous loading of traffic and temperature variations on a conventional asphalt overlay.

This study also involves an evaluation of the hourly stresses and strains, generated by traffic and thermal loading characterized through temperature variation in the full-depth of the pavement during a year. That temperature distribution throughout the pavement structure was obtained by field measurements in a pavement section located along IP4 main road, near Bragança (northeast of Portugal), for a period of a year, using a temperature-recording equipment. Traffic data were obtained in field near the temperature measurements location.

The 3D finite element methodology was used to model the reflective cracking phenomena, in order to calculate the stresses and strains associated to each single case of loading: traffic (130 kN axle load) and observed full-depth pavement temperatures. Based on those strains results, the strain state of the combination of both cases was evaluated.

In the case of thermal loading strain evaluation, the bituminous material behavior was considered as viscoelastic, characterized by the relaxation modulus, as the overall state of tension in the overlay caused by the temperature variation is time-dependent and thus function of the viscoelastic response of the bituminous materials. In the case of traffic loading the bituminous material behavior was considered as "elastic" material, characterized by the stiffness modulus.

Those computed stresses and strains became concentrated above the existing cracks, creating an active zone of pavement overlay failure or crack propagation. The traffic and thermal stresses and strains, calculated for each case of loading, were used to verify the influence of the thermal loading in the overlay behavior through the evaluation of the hourly damage associated to each type of load.

The overlay damage evaluation was made hourly along the year was made through the ratio between the hourly observed traffic and the hourly predictive overlay life. The overlay life evaluation was made using the mechanistic-empirical methodology proposed by Sousa et al (2005).

This methodology is capable of assembling Modes I and II deflection patterns simultaneously on asphalt concrete specimens into a coherent procedure. The influence of pavement characteristics on state of stress and strain was considered by applying the Von Mises strain deviator, expressed by Equation 1.

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

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 the Von Mises 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:

$$\varepsilon_{VM} = \varepsilon_{fat}(1+\upsilon) \tag{2}$$

where ε_{fat} is the fatigue strain for beam fatigue test conditions subjected to four-point bending.

2 THERMAL LOADING

The full-depth pavement structure temperature distribution was obtained through field measurements, using temperature-recording equipment – a Datalogger associated with thermocouples – because, by this means, actual temperature can be reliably measured. However, this method is relatively slow and it only provides information about temperature 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 (north of Portugal). At that location, seven thermocouples were installed in the pavement at seven different depths: at surface, 0.028 m, 0.055 m, 0.125 m, 0.165 m 0.220 m and 0.340 m.

The depths were chosen to offer a proper representation of the whole asphalt concrete layers (0.340 m). The temperatures were recorded at every hour, every day, allowing to produce the visualization of the annual temperature evolution, such as the observed temperatures at the bottom of the overlay, as presented in Figure 1. In that figure the typical temperature variations of summer and winter periods are clearly identified.

3 PAVEMENT MODELLING

The pavement structure was modeled as presented in Figure 2. For crack reflection analysis the top layer represents the bituminous overlay and the subjacent layer represents the old cracked bituminous layer, where a crack is modeled by elements without stiffness.

The finite element model used in three-dimensional numerical analysis was developed by using a general finite elements code, ANSYS 7.0. The design of a mechanical model is based on a finite element mesh definition, oriented to mechanical analysis, considering a finer element mesh closer to the pavement surface, nearer the wheel load point and in the overlay above the crack. An eight-node structural solid element was used assuming linear approximation of the displacement field and three degrees of freedom per node.

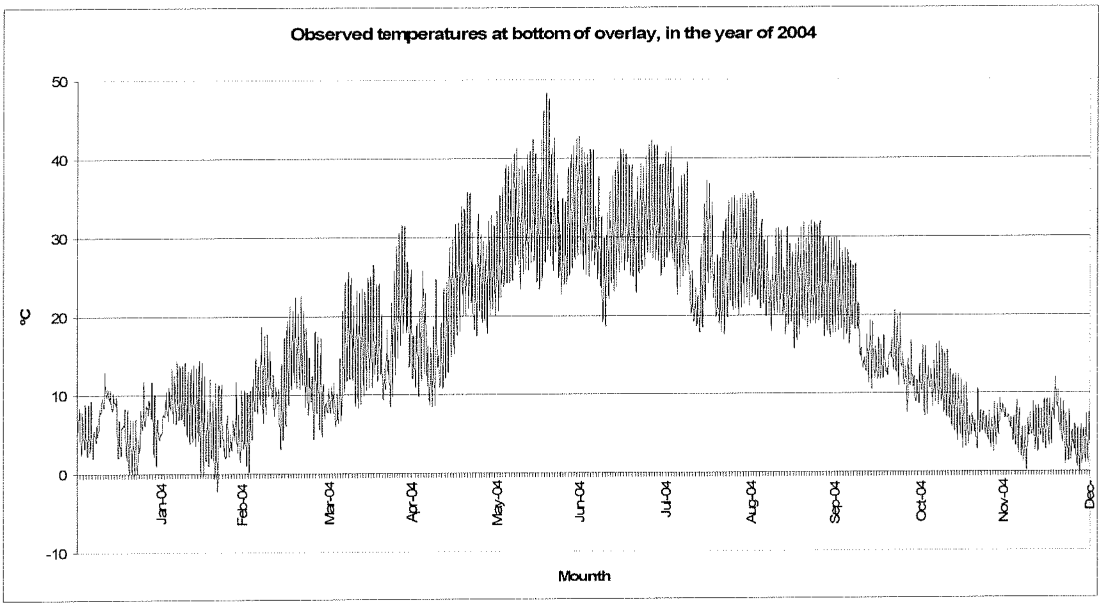

Figure 1. Observed temperatures at overlay bottom.

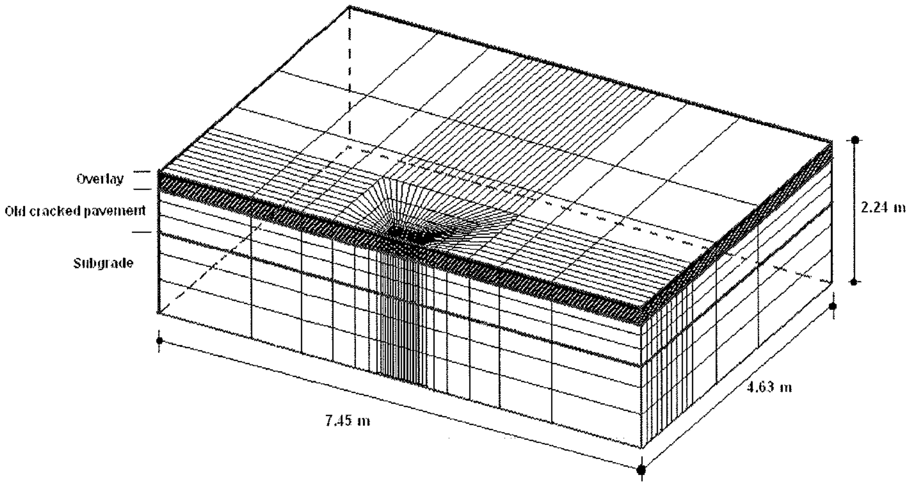

Figure 2. Structural model configuration used in numerical simulation.

The model is 4.63 m long, 7.45 m wide and 2.24 m thick. The model total thickness 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. A longitudinal crack was modeled on the layer which is just below the overlay with 10 mm width. The resulting number of elements was 13538, in both traffic and thermal cases.

The first effort in order to verify and calibrate the purely FEM mechanical analysis of a cracked pavement before and after the 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, according to the model developed by Pais et al (2002). The calibration was accomplished by comparing the crack movements in a pavement and in the FEM model for two different conditions: before and after the pavement overlay.

Once the type of processing depends on the loading case considered, for thermal loading, the model processing was carried out as a transient process (time-rate dependent), because that load type is a long term load, and the material properties are time-rate dependent. For the traffic loading case, the model processing was based on a steady-state process, as that load is considered to be a short-term load, and the material properties were defined as elastic material, or non-time-dependent.

4 MECHANICAL PROPERTIES

The stiffness modulus for modeling 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 stiffness modulus values obtained for the conventional mix used in this work are presented in Table 1.

Table 1. Elastic properties of the bituminous mixture used in this study.

Temperature (°C)	**Stiffness (MPa)**
-5	16157
5	13563
15	9304
25	478

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:

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

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, $a = 1.009;\ b = 0.9283,\ c = -0.3772$ *and* $d = 3.961$

For the temperature variation modeling, it was considered that the bituminous material shows a linear viscoelastic behavior, time-and-temperature dependent, modeled through thermal-reological simplicity principle. With this principle, the relaxation curve for high temperatures is identical to the low temperature relaxation curve, when loading time is scaled.

Relaxation tests were also performed at -5 °C, 5 °C, 15 °C and 25 °C, using bituminous samples of the conventional 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 modulus, τ_i, and C_1 and C_2 for WLF function were obtained and presented in Table 2.

Table 2. Prony parameters of the bituminous mixture used in this study.

	Parameters	**Value**		**Parameters**	**Value**
Volumetric Parameters	K_∞	2.81E+01	**Shear Parameters**	G_∞	1.04E+01
	K_1	7.85E+02		G_1	2.89E+02
	K_2	2.60E+02		G_2	9.45E+01
	K_3	3.07E+01		G_3	1.13E+01
	τ_1^K	5.85E-01		τ_1^G	5.99E-01
	τ_2^K	9.16E+00		τ_2^G	9.49E+00
	τ_3^K	9.92E+03		τ_3^G	1.00E+04
			WLF	T_r	1.31E+01
				C_1	2.56E+07
				C_2	1.39E+08

Thermal contraction tests were performed and the coefficient of thermal contraction, constant and independent from temperature, obtained for this study was 3.54x10-5 /°C. The Poisson's ratio was assumed to be constant and the value adopted was 0.35 for bituminous layers and subgrade and 0.30 for granular layers.

5 SIMULATION PROCEDURES

The simulation procedures to achieve the purposes of this study involved a multiple 3-D finite-element runs considering the pavement structure referred above. Each solution was obtained for each hour and for each loading case (traffic, temperature variation and both superimposed). The main analysis procedure involved in the present study is schematized in Figure 3.

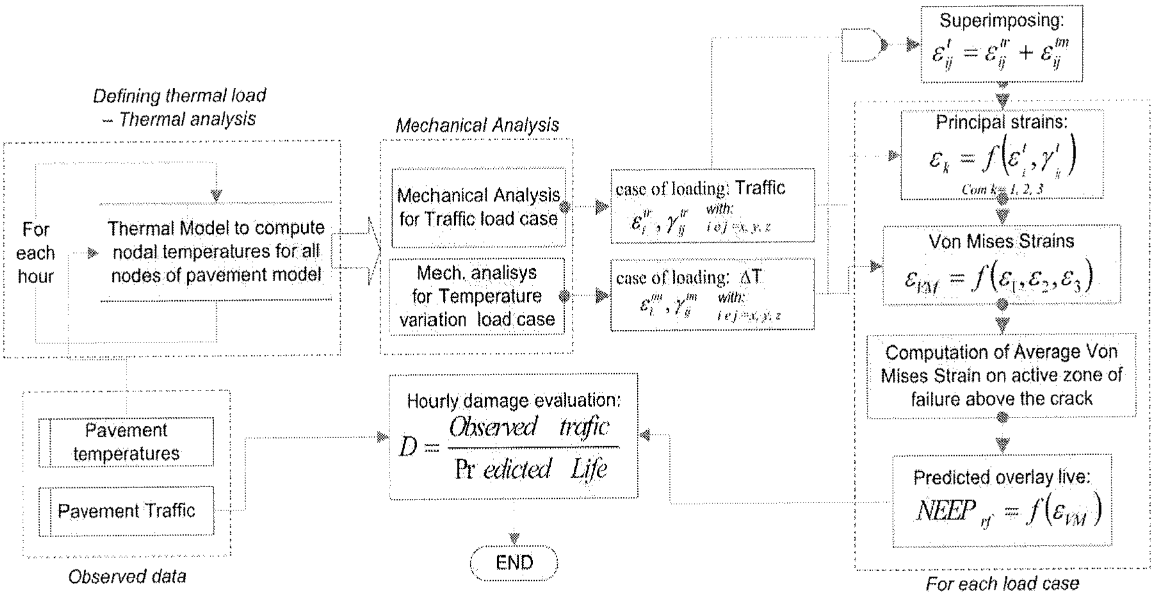

Figure 3. Procedures involved in the study.

In the first stage, for each hour of the day along a year, all nodal pavement temperatures of the finite element model were calculated by using the thermal model, a steady-state thermal analysis based, and applied in all nodes of traffic and temperature variation models. The input data of the thermal 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 to set the elements stiffness for stress and strain calculation for 130 kN traffic loading case. The computed pavement temperatures were also applied in all nodes of thermal mechanical model.

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

Equation 2 was used to relate the average Von Mises strain with a fatigue strain concept used on flexural fatigue laws, obtained from four-point flexural fatigue tests, normally used to evaluate the prediction of pavement life. In this way, fatigue life was estimated considering the Von Mises strain of the overlay. The four-point flexural fatigue tests performed to obtain the fatigue laws to be used in this study were carried out at different temperatures. Those fatigue laws were developed in terms of temperature-dependency.

The overlay life was obtained from nodal temperature occurred in the zone above the crack at every hour. After that, the hourly damage was evaluated.

6 VON MISES STRAIN AND OVERLAY LIFE RESULTS

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. In Figure 4, the hourly means Von Mises strain evolution along the year is plotted against the time.

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.

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.

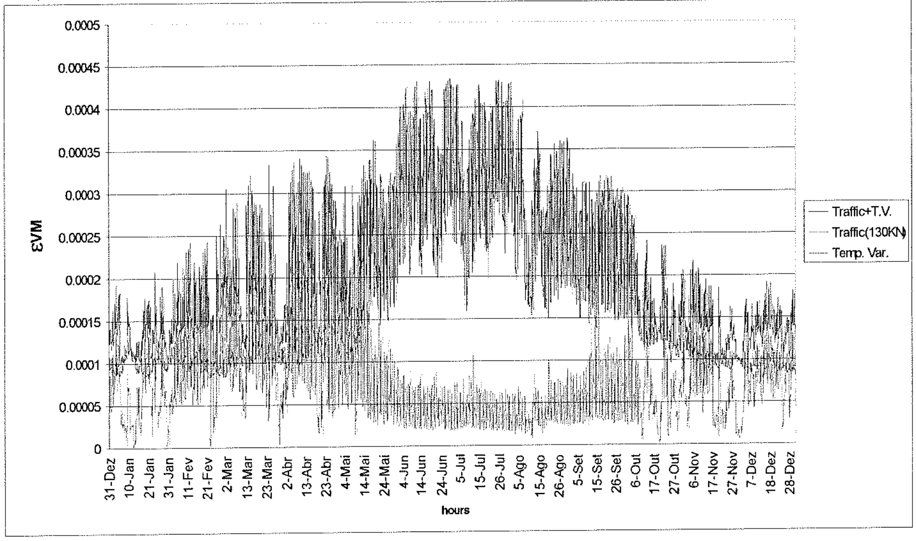

Figure 4. Von Mises strain for all loading cases.

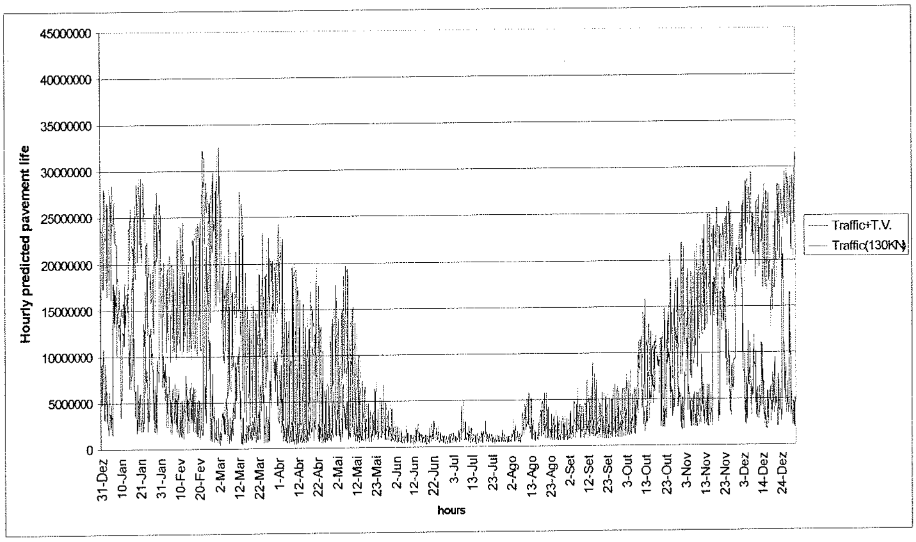

Figure 5. Predicted overlay life for traffic+temperature variations.

7 DAMAGE RESULTS

Knowing the predicted overlay life and the number of axles distribution during the year allows to perform an annual damage evolution estimation. 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 overlay for traffic and traffic+ΔT. In this figure the accumulated monthly damage occurred in relation to 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..

Monthly and annual damage for the real loading conditions (traffic and temperature variations) was obtained from the previously presented results, as shown in Table 3.

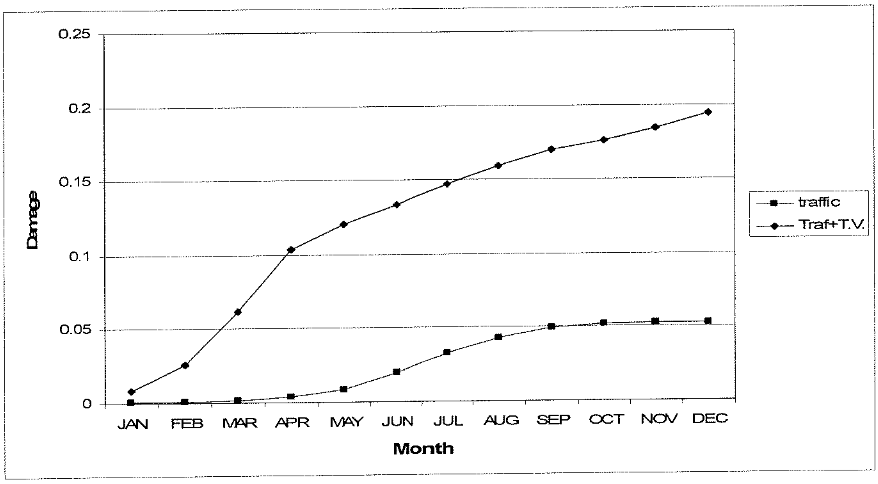

Figure 6. Accumulated monthly damage occurred in a conventional mix overlay.

Table 3. Real monthly and annually damage for real loading conditions.

Period	Air temperature				Real damage
	T_{ref}	ΔT	T_{min}	T_{mean}	
January-04	10.14	8.06	2.08	5.96	0.008340
February-04	11.02	10.67	0.36	5.06	0.017382
March-04	11.69	9.95	1.73	6.65	0.036154
April-04	15.69	13.13	2.56	9.41	0.041459
May-04	19.68	12.29	7.39	13.68	0.017202
June-04	28.13	15.22	12.91	20.99	0.012995
July-04	27.68	15.17	12.51	20.58	0.013910
August-04	25.78	11.49	14.29	20.30	0.011692
September-04	25.16	16.46	8.70	16.62	0.010663
October-04	16.75	9.12	7.63	11.98	0.006598
November-04	10.09	9.13	0.97	4.95	0.008147
December-04	9.08	9.45	-0.37	3.81	0.010155
Annual	20.80	13.15	7.65	14.27	0.194697

8 THEORETICAL SIMULATION

The reflective cracking evaluation presented needs time investment in terms of computing processes and does not provide immediate results. Thus, the development of procedures that allow a rapid evaluation of the damage associated to each loading condition is important for this study, mainly for the development or improvement of the pavement overlay design methodologies in order to consider the temperature variations effect in the reflective cracking phenomena.

Thus, the development of relationships between the thermal loading parameters and the corresponding pavement damage and the development of shift factors between that theoretical damage and the damage for real loading conditions are some of the purposes of the present research.

For a large number of "theoretical standard situations" of temperature variations loading, the hourly damage was calculated in order to establish a direct relationship between those two variables (loading conditions and associated damage). The standard situations of temperature variations are characterized, for a period of twenty four hours, by means of two parameters: reference temperature, T_{ref} (the maximum daily air temperature), and the maximum daily temperature variation, ΔT. Those situations were considered theoretical and it was assumed that these conditions happened during the analysis period. The theoretical damage was calculated for the observed traffic.

First, for each theoretical loading situation, an hourly distribution was adopted, for twenty-four hours, for the main atmospheric parameters that influence the pavement thermal state, specifically the air temperature evolution, the solar radiation evolution, the mean wind speed and the full-depth pavement temperature distribution for the initial thermal state. Those parameters were established through an exhaustive analysis of temperature measurements.

After that, the evaluation of the theoretical stress/strain states in the pavement overlay associated to each standard situation was carried out. This procedure involved the use of simulation thermal models for full-depth pavement temperature determination. Considering these temperatures, mechanical models were applied to determinate the stress/strain states in the pavement overlay.

A set of damage curves between (T_{ref}, ΔT) and the obtained damage were deduced. Each damage curve represents the variation of the damage during any period, as a function of the temperature variation, ΔT, for a specific reference temperature, T_{ref}. Figure 7 presents the curves of the annual damage for a reference temperature, T_{ref}, respectively.

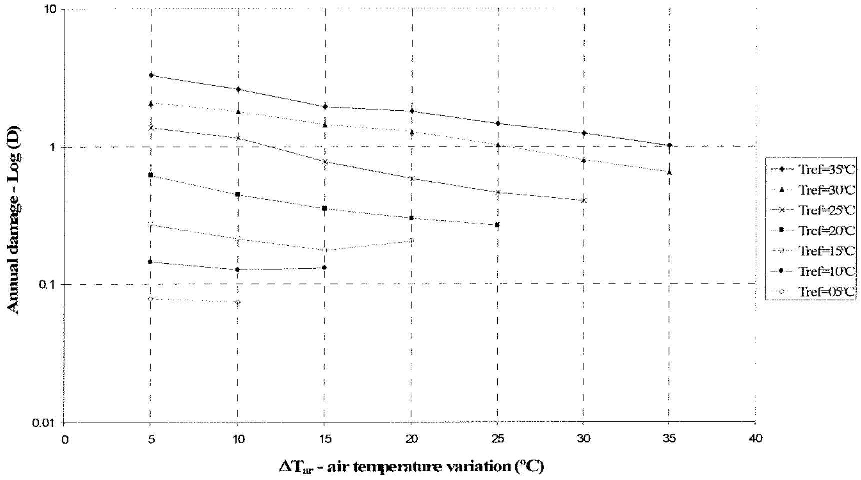

Figure 7. Overlay damage for theoretical simulations.

The establishment of a reasonable number of damage curves allowed developing a statistical study for fitting the results within a generalized law. These results provide evidence that monthly damage variation against reference temperature, T_{ref}, and temperature variations, ΔT, for each month, show an exponential trend, and the best-fit relationship obtained follows Equation 4.

$$damage = a \times T_{ref}^{b} \times e^{c \times \Delta T} \tag{4}$$

where: a, b and c = monthly damage fitting constants, for each month; T_{ref} = reference temperature; ΔT = temperature variation.

The a, b and c generalized constants were obtained statistically for each month, through the monthly damage evolution analysis, by fitting Equation 4 to damage values associated to the (T_{ref}, ΔT) standard cases. The constants obtained for the statistical analysis are presented in Table 4 and are function of the reference temperature.

With the real and theoretical damage values, obtained for each considered period, a representative factor between the theoretical damage and the real damage can be established for each standard situation. This factor, called "damage shift factor", is expressed by Equation 4.

Table 4. Generalized constant values for monthly damage evaluation

Validation range	Constant values			R^2
	a	b	c	
35°C<T_{ref}<15°C	1.770E-06	2.617E+00	-5.653E-02	8.618E-01
15°C<T_{ref}< 5°C	8.388E-04	1.199E+00	-1.598E-02	7.814E-01

$$r = \frac{D^{real}_{monthly}}{D^{theoretical}_{monthly}} \tag{4}$$

where r = damage shift factor between theoretical and real damage; D_{real} = total monthly damage resulting from real traffic and temperature variations; $D_{theoretical}$ = total monthly damage resulting from theoretical situations of traffic and temperature variations.

Table 5 shows the "damage shift factor" values for each analysis period. The fitting statistical study for obtaining *a, b* and *c* constants was carried out monthly and during the global analysis period.

The analysis of Table 5 allows concluding that, during cold months, the values of the damage shift factor are values near 1. During warm months that parameter presents dispersion and, in the majority of cases, shows values higher than 1.

Table 5. Real damage, theoretical damage and damage shift factor.

Period	Air temperature				Real damage	Theoretical damage	Shift factor (Dr/Dt)
	T_{ref}	ΔT	T_{min}	T_{mean}			
January-04	10.14	8.06	2.08	5.96	0.008340	0.011862	0.703097
February-04	11.02	10.67	0.36	5.06	0.017382	0.012580	1.381666
March-04	11.69	9.95	1.73	6.65	0.036154	0.013649	2.648738
April-04	15.69	13.13	2.56	9.41	0.041459	0.018468	2.244931
May-04	19.68	12.29	7.39	13.68	0.017202	0.002151	7.995755
June-04	28.13	15.22	12.91	20.99	0.012995	0.004643	2.798691
July-04	27.68	15.17	12.51	20.58	0.013910	0.004463	3.116920
August-04	25.78	11.49	14.29	20.30	0.011692	0.004562	2.563000
September-04	25.16	16.46	8.70	16.62	0.010663	0.003232	3.298987
October-04	16.75	9.12	7.63	11.98	0.006598	0.001688	3.907951
November-04	10.09	9.13	0.97	4.95	0.008147	0.011599	0.702369
December-04	9.08	9.45	-0.37	3.81	0.010155	0.010169	0.998642
Annual	20.80	13.15	7.65	14.27	0.194697	0.524624	0.371117

9 DESIGN PROCEDURES

The purpose of the present study is to develop a generalized overlay design methodology. It three phases: a) data definition; b) daily damage evaluation and c) performance evaluation.

Data definition and damage evaluation phases must have the same treatment as the procedure for the establishment of damage relationships previously presented.

In the future the proposed methodology must develop the process of evaluation of the hourly damage for 24 hours, which will consist in the application of relationships that produce the results obtained for traffic and thermal effects observed during the year. The establishment of relationships to obtain these objectives will have to observe the following aspects:

- the relationships for standard (theoretical) loading situations must be established with basis on the acceptance of two values of air temperature (T_{ref}, ΔT) as adopted in the second part of this paper.
- the relationships will have to be developed for several overlay structure types, characterized for diverse thicknesses of the pavement and several values of the stiffness of the existing layers, including that of the subgrade foundation.

The process of development of the relationship proposed must generally follow the procedures adopted in this paper. The resulting relationships will have to allow:

- the establishment of a pair of values (T_{ref}, ΔT) which must guarantee the calculation of a daily profile of Von Mises strains associated to the combination of traffic and variations of temperature loading;
- the establishment of a pair of values (T_{ref}, ΔT) which must allow the calculation of a daily profile that makes possible to obtain a permissible hourly traffic, as an alternative to the profile considered in the previous point;
- the establishment of a pair of values (T_{ref}, ΔT) which must guarantee the calculation of a daily profile of hourly damages associated to the combination of traffic loading and temperature variation.

10 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 variation will support the need for a special attention towards overlay design procedures.

This study has demonstrated that it is possible to include the effects of temperature variations in a design process of pavement overlays. For that, it is necessary to develop a methodology that includes relationships, such as the ones presented in this paper, for evaluating damage and shift factors to adjust the results to the real behavior of overlays.

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