Universidade do Minho

[CI-34]

Minhoto, M.J.C., **Pais, J.C.**, Pereira, P.A.A., Picado-Santos, L.G.

"Low-temperature influence in the predicted of pavement overlay life"

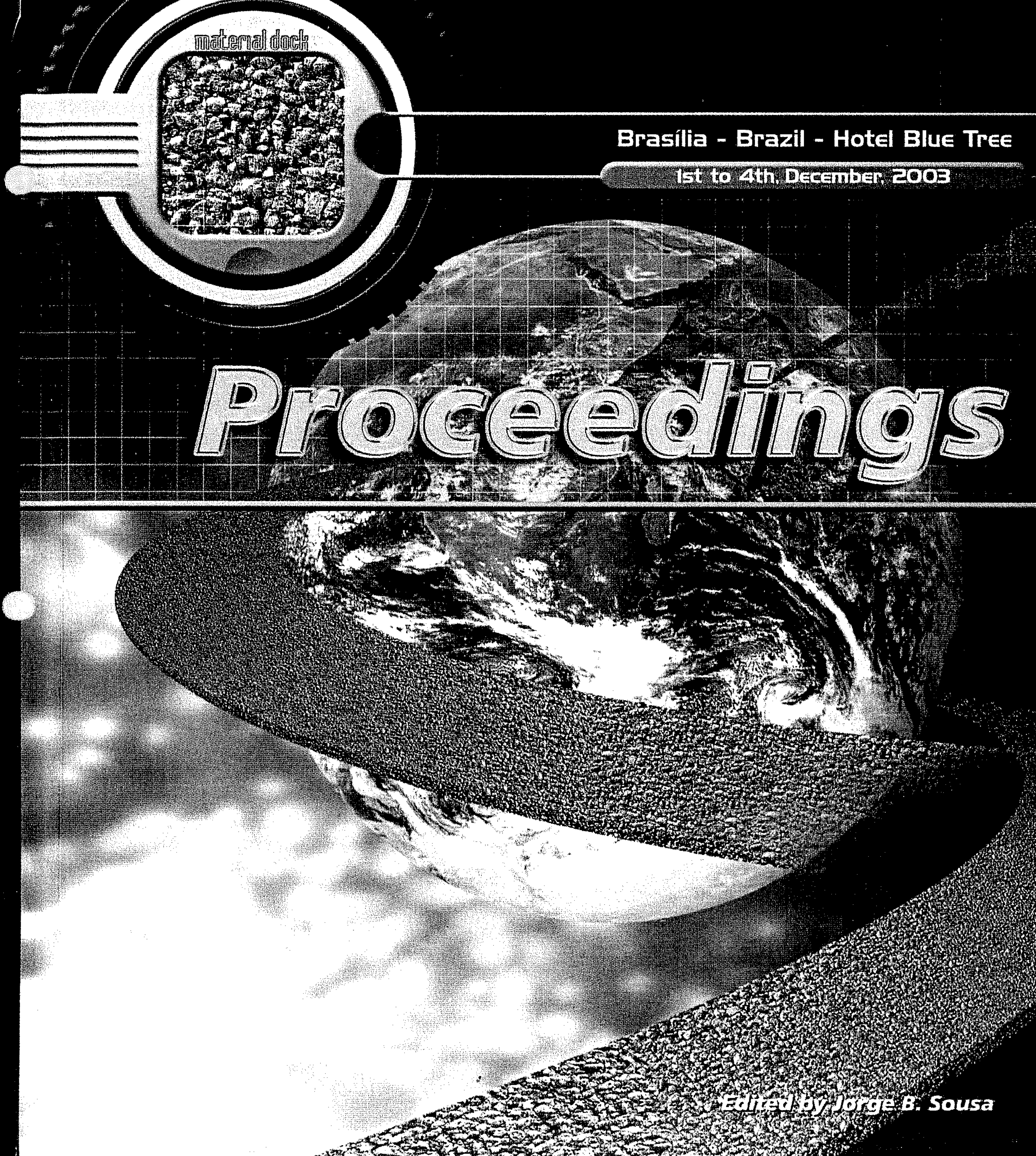
Asphalt Rubber 2003 Conference, Brasilia, Brasil, 2003, p. 167-180

Asphalt rubber 2003

Progress Through Flexibility

Brasília - Brazil - Hotel Blue Tree

1st to 4th, December, 2003



Proceedings

Edited by Jorge B. Sousa

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LOW-TEMPERATURE INFLUENCE IN THE PREDICTED OF PAVEMENT OVERLAY

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ABSTRACT: This paper describes a study of the low-temperature influence in the pavement overlay life, using finite-element methodology that considers the most predominant type of overlay distress observed in the field: the reflective cracking. The temperature drop down has a significant influence on thermally induced stresses which, in turn, impacts on the overlay predictive service life. This paper presents a three dimensional (3D) finite element analysis used to predict the pavement overlay life considering the combining of the thermal conditions with traffic solicitations in a pavement overlay modelled above a cracked pavement.

The results present the influence of initial temperature, decrease in the cracked layer temperature and overlay temperature in the overlay life. Also a comparison between the overlay life due the traffic loading and the temperature decreasing in the overly life is presented. Finally, the overlay life was predicted using asphalt rubber and conventional mix fatigue laws allowing to conclude that the asphalt rubber mixes exhibit more pavement life compared with the conventional mixes even when temperature effects (temperature drop) are considered in the overly design.

KEY WORDS: Low-temperature, reflective cracking, pavement overlay life

1. Introduction

Bituminous overlays have been the most used method in pavements rehabilitation. The service life of one overlay depends on its performance in different distress modes. In the overlay of a cracked pavement, the cracks will develop and propagate to the pavement surface, directly above cracks in the existing pavement under 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 concern to highway agencies throughout the world. Three different mechanisms have been identified as the origin and propagation of cracks in overlays of pavements [SOU 2002]:

1. Thermal stresses from thermal fatigue, which occurs when temperature variations induce cyclic openings and closures of cracks in the pavement, which induce stress concentrations in the overlay.

2. Thermal stresses as a result of rapid cooling down of the top layer, which induces critical tensile stresses on overlay.

3. Repetitive traffic loads induce additional distress in the overlay and increase the rate of crack propagation, whether or not these cracks originate from thermal stresses.

Sousa et al [SOU 2002] concluded that when reflective cracking is caused by traffic loads, complex patterns of distress have been recorded. In these cases, a combination of Modes I and II crack openings are simultaneously present. Differential vertical movements (Δ-vertical) at underlying discontinuities (such as joints or cracks) have been known to be a major cause of reflective cracking in overlays [HAL 1989] [HAL 1990]. However, for cracking caused by thermal movements only Mode I is considered as the main mode of cracking.

In regions that experience large daily temperatures variations or extremely low temperatures, the thermal conditions plays a major role in the reflective cracking response of a multilayered pavement structure. On one hand, binder properties (stiffness, ageing, penetration, etc...) are sensitive to temperature variations. On the other hand, the accumulated restrained thermal stresses as a result of temperature drop down, with, or without, traffic loading effect combination, will accelerate the reflective cracking phenomena.

The combination of the two most important effects: (1) wheel loads passing above (or near) the crack and (2) the material (overlay) above the crack being under tension due to rapidly decreasing or low temperatures, have been identified as the most likely causes of high states of stress and strain above the crack and responsible by the reflective cracking [SHA 1990].

2. Background

Sousa et al [SOU 2002] proposed a mechanistic-empirical methodology capable of assemble simultaneously imposing Modes I and II deflection patterns on asphalt concrete specimens into a coherent procedure. 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 the "Von Mises strain" was calculated as expressed in Equation [1].

Where:

ε_{VM} = "Von Mises" strain

$\varepsilon_1, \varepsilon_2, \varepsilon_3$ = 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 phenomena. For beam fatigue test conditions subjected to four-point bending ε_{VM}can also be written as:

This parameter can been 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 one of the following variables: tensile strain, tensile stress, Von Mises stress, "Von Mises strain", strain energy of distortion or total energy of strain.

This study involves the calculation of the stresses and strains generated by two cases of loading: 130kN heavy axle loading and thermal loading (rapid cooling rate). Such stresses and strains become concentrated above the existing cracks, creating an active zone of pavement overlay failure or crack propagation. Furthermore, and superimposing those stresses and strains calculated for each case of loading one can verify the influence of the thermal loading in the overlay life.

This research first calculates the stresses and strains above existing cracks through a 3D finite element (FE) analysis, for each case of loading (traffic load and thermal load) and for the combination of both cases, and then calculates the Von Mises strains, ε_{VM}. The Von Mises strains, ε_{VM}, for the case of wheel loading and for the case of rapid cooling rate, are used to predict the pavement life for both cases after an overlay, once which considers localized stress concentrations above the simulated crack. The equation [2] is used to evaluate the prediction of pavement life as a result of the combined existing thermal stresses and traffic load stresses. This procedure is based in Shell's laws for calculate the predictive fatigue life.

3. Pavement modelling

Traditionally, the pavement structures are idealized as a set of horizontal layers of constant thickness, homogeneous, continuous and infinite in the horizontal direction, resting on subgrade, semi-infinite in the vertical direction. In the case of crack reflection the top layer represents the bituminous overlay and the subjacent layer represents the old cracked bituminous layer. The structural model configuration of pavement was idealized based in the previous principles and is presented in Figure 1.

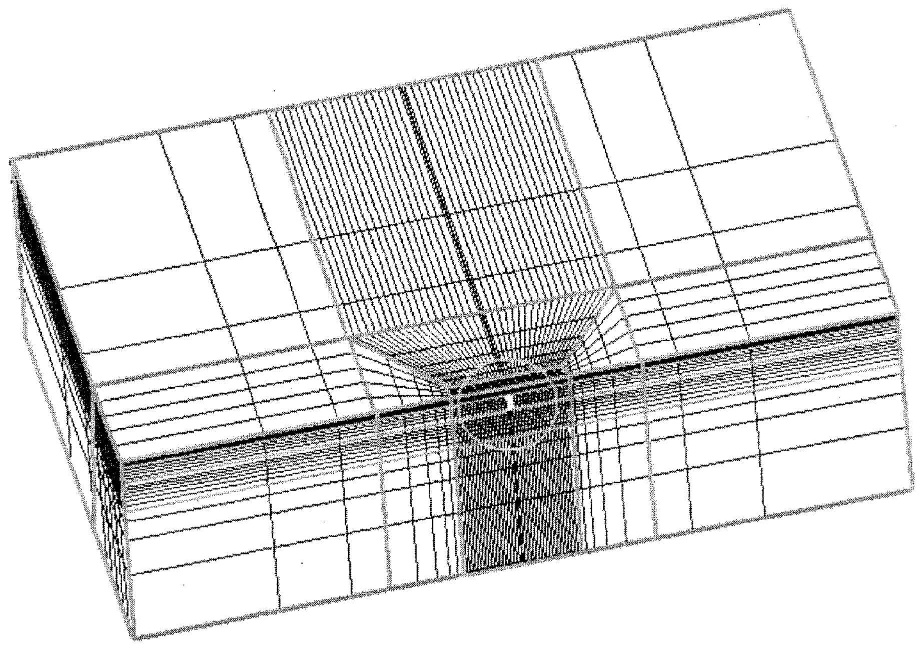

Figure 1. *3D Representation of Finite Element Mesh*

3.1. Finite Element Analysis

The finite element modeling used in numerical analysis was performed using a general Finite Elements Analysis source code, ANSYS 5.6. A linear elastic material model was used. This analysis is a 3D static analysis, a standard finite element discretization in space based, and the calculations at certain thermal condition are based on an instantaneous temperature change from the assumed initial condition. When designing the finite-element mesh for modeling the mechanical analysis, the following factors have been considered:

- 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 needs to be modeled;
- the convergence of results between the FE model and models of crack activity, Von Mises strains, fatigue strains and rutting stains, are achieved;

The 3D mesh model used for the analysis of the dual wheel configuration and thermal loading is given in Figure 2 and Figure 3. The number of elements used was 16330 in both traffic and thermal cases. For three-dimensional analysis, 3-D twenty-node structural solid element, SOLID186, was used. This element assumes quadratic approximation of the displacement's field and has three degrees of freedom per node and is given in Figure 4.

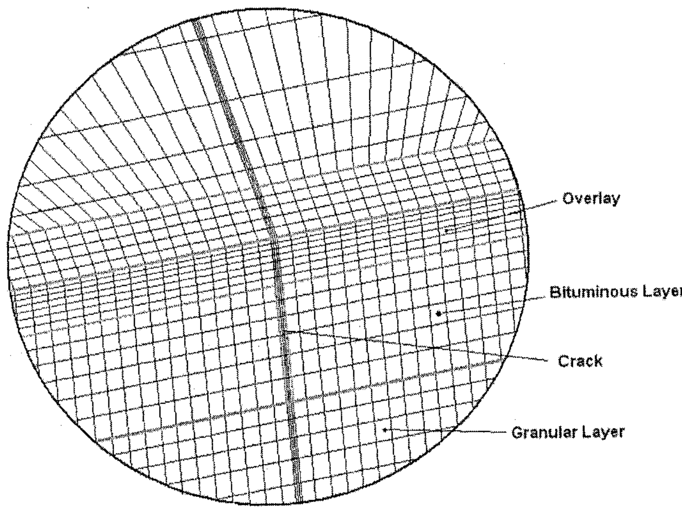

Figure 2. *Crack location*

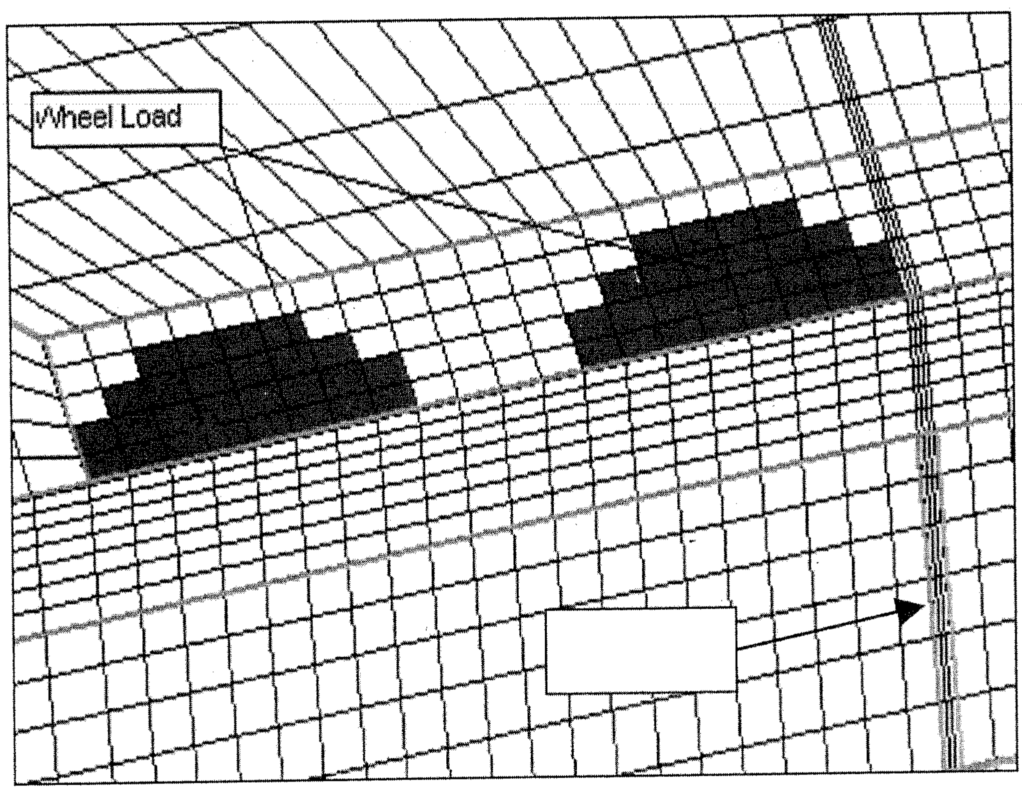

Figure 3. *Wheel load configuration*

As the problem is symmetric along the wheel axle direction, only half of the geometry is needed in this analysis. The analyzed body had a length of 4.5 m and, was 7.45 m wide and variable thickness. The crack was modeled with the extent of the full subjacent layer of the overlay, and the crack with was set to 10 mm. Only longitudinal cracks were simulated. To proceed with this analysis it was necessary to establish the following assumptions:

- The volume changes as a result of the freezing of moisture and thawing are not considered;
- All pavement layers are homogeneous, elastic and isotropic;

Full bond exists between all pavement layers.

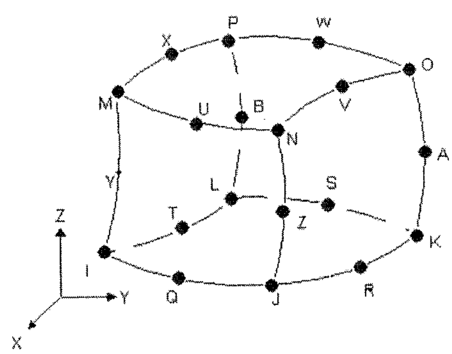

Figure 4. *3-D twenty-node structural solid element*

The vertical boundaries of the body were allowed to move along a plane with the boundaries but no movement was allowed perpendicular to the plane of the walls. Simple supports were applied at the bottom of the body, allowing moving along the horizontal plane and no vertical movement was allowed. 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 calculated vertical crack movements and the Von Mises deviator strain with the values obtained from calibrated statistical expressions developed by Sousa et al [SOU 2002].

3.2. Mechanical properties

In this pavement structural analysis is assumed, that the materials have a linear elastic behavior and they are isotropic and homogeneous, in which the value of the stiffness of bituminous layers are dependent of the temperature.

The influence of the temperature on mixture stiffness was estimated using binder data with Shell relationships, based on the binder stiffness and on volumetric characteristics of the mixture. The binder stiffness, determined from the Van Der Poel nomograph, is dependent on the temperature, penetration index, and the time of loading. In the case of modelling the wheel loading, the adopted frequency of loading was 10 Hz.

In the case of the thermal contraction the mixture stiffness was estimated for 10 seconds loading time, taking into account the relaxation effect [EPP 2000].

In the analysis it is assumed that the coefficient of thermal contraction is constant and independent of the temperature and the typical value of $1.4x10^{-5}$ was adopted. The Poisson ratio is assumed constant in the analysis and the typical values were:

- for bituminous layers – $\nu = 0.35$
- for granular layer – $\nu = 0.3$
- for subgrade – $\nu = 0.35$

In Table 1 is presented the layers thickness and stiffness for base layer and subgrade adopted in this study. The effect of ageing is simulated by affecting the bituminous parameters by adequate factors.

Table 1 – *Study cases conditions*

	Thickness			Stiffness	
Structure Type	Overlay	Cracked layer	Granular Layer	Granular Layer	Subgrade
PAV01	0.02	0.10	0.30	250	100
PAV02	0.07	0.15	0.30	250	100
PAV03	0.10	0.25	0.30	250	100

3.3. Loads

The wheel load configuration is presented in figure 3 and is defined as a surface load (pressure) near the vertical location of the crack, simulating the 130 kN standard axle load.

The thermal loading is characterized by: uniform initial temperature, T_i, of bound layers and the temperature variation, ΔT_i, as result of the rapid cooling down in bound layers (overlay and cracked layer). The initial uniform temperature values, T_i, adopted in this study were: 20ºC, 10ºC and 0ºC. The values adopted for ΔT_i were: -5ºC, -15ºC and –30ºC. The combination of these thermal conditions is considered as thermal loads. Although the –30ºC temperature variation in cracked layer is an unusual situation, this represents an extreme situation of crack opening which may be analyzed.

3.4. FEM Analysis Procedure

The analysis procedure involves a multiple 3-D finite-element runs. Each solution is obtained for each case of loading (traffic load only or thermal load only), for each structure type and for a case resulting of a combination of the initial temperature, Ti, with the temperature variation, ΔT_i. While each stress analysis is performed, the crack width is maintained constant and the crack depth is equal of cracked layer thickness. The crack width variations may occur as results of cracked layer temperature variation only. Each mechanical analysis computes the stresses and strains components for the nodes above the crack.

The results obtained for traffic load and respective thermal load are added. The average Von Mises strains above the crack zone is computed and is used to estimate the overlay life for each case study. The Shell's laws are used to estimate the overlay predictive fatigue life.

3.5. Simulation Analysis Procedure

The study of the temperature influence on pavement life was analysed for 3 pavements (Est01; Est02 and Est03) as defined in Table 1. For each pavement 3 temperatures (20ºC, 10ºC and 0ºC) were selected as initial or reference temperatures. The FE analyses were done decreasing separately the initial temperature of the cracked layer and the temperature of the overlay of 5ºC, 15ºC and 30ºC, resulting 144 combinations for each one of situations studied (wheel load and temperature).

4. FE results

The 3D linear elastic model based on the ANSYS 5.6 software was used to model the development of average shear strains above the crack zone and provides the predicted overlay fatigue life caused by effect of cold temperature shrinkage (thermal loading) and traffic loading.

The overall results are presented in Figure 5, 6 and 7, respectively for each initial temperature (20ºC, 10ºC and 0ºC). In these figures the ΔT_{ovl} represents the temperature decrease in the overlay and the ΔT_{bet} represents the temperature decrease in the cracked layer. The vertical lines (Design life – PAV01, PAV02 and PAV03) represent the pavement life design without any change in the temperature of bituminous layers (design for the initial temperature, respectively 20ºC, 10ºC and 0ºC).

As expected, the results clearly show that the overlay life decreases when the temperature in the bituminous layer decreases. This conclusion can be applied to the 3 initial pavement temperature simulations. Whenever the temperature in the cracked layer is smaller than the temperature in the overlay, the decrease in the temperature in the overlay, increases the overlay life.

The influence of the initial temperature on the overlay life for structure 3 (0.10/0.25) is presented in Figure 8, where one can conclude that increasing the initial temperature the overlay life is also increased. The same conclusion can also be made for the increase of the cracked layer temperature.

The overlay life as function of ΔT_{ovl} for Tinic = 20ºC in structure number 3 is presented in Figure 9, where the overlay life is separate in the overlay life due the traffic loading and the overlay life due the temperature loading. The analysis of this figure allows the conclusion that the overlay life due the traffic load is greater than the overlay life for temperature loading. This difference is clear for large decreases of the bituminous temperature.

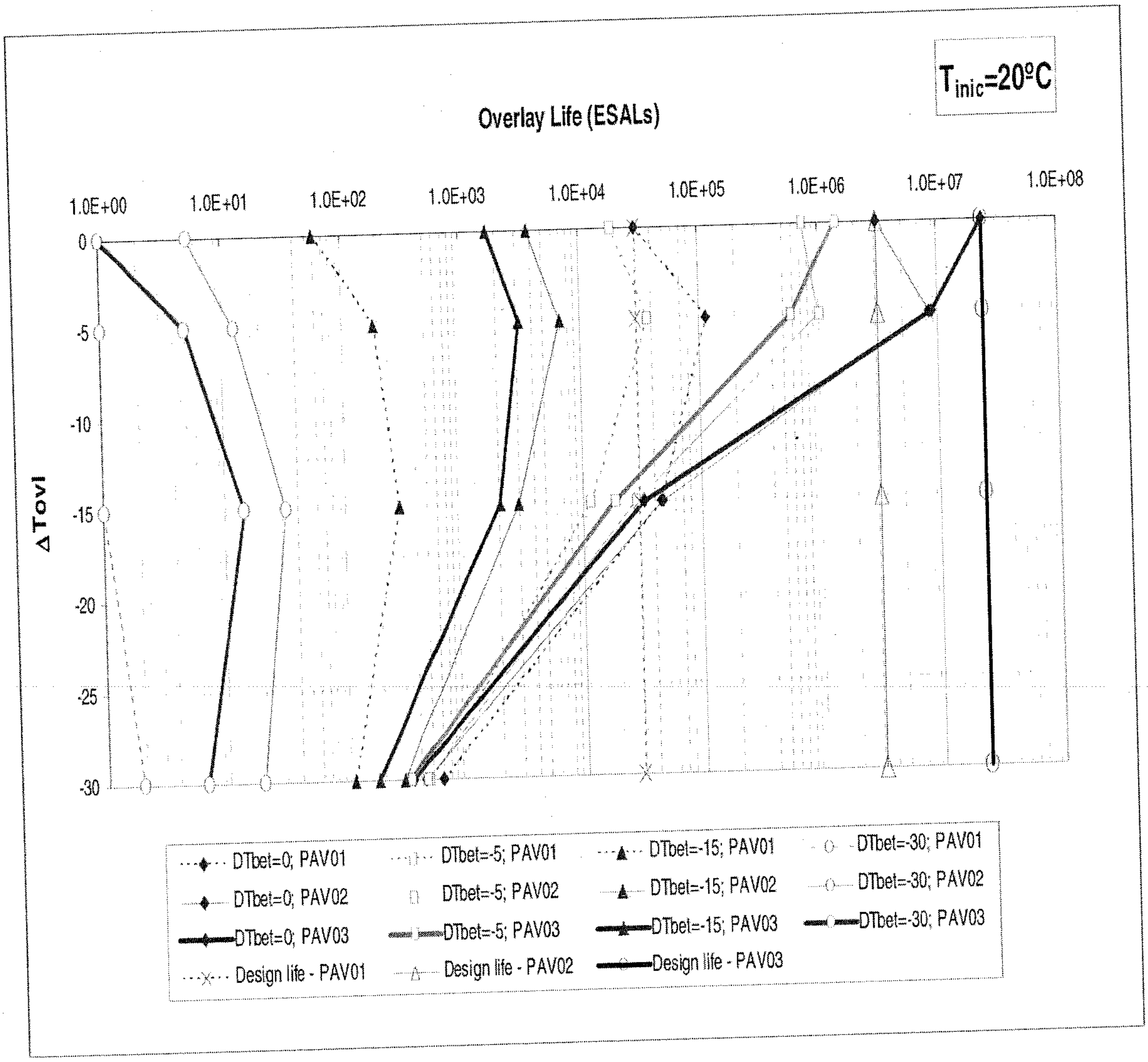

Figure 5. *Overlay life as function as ΔTovl, for initial temperature of 20ºC*

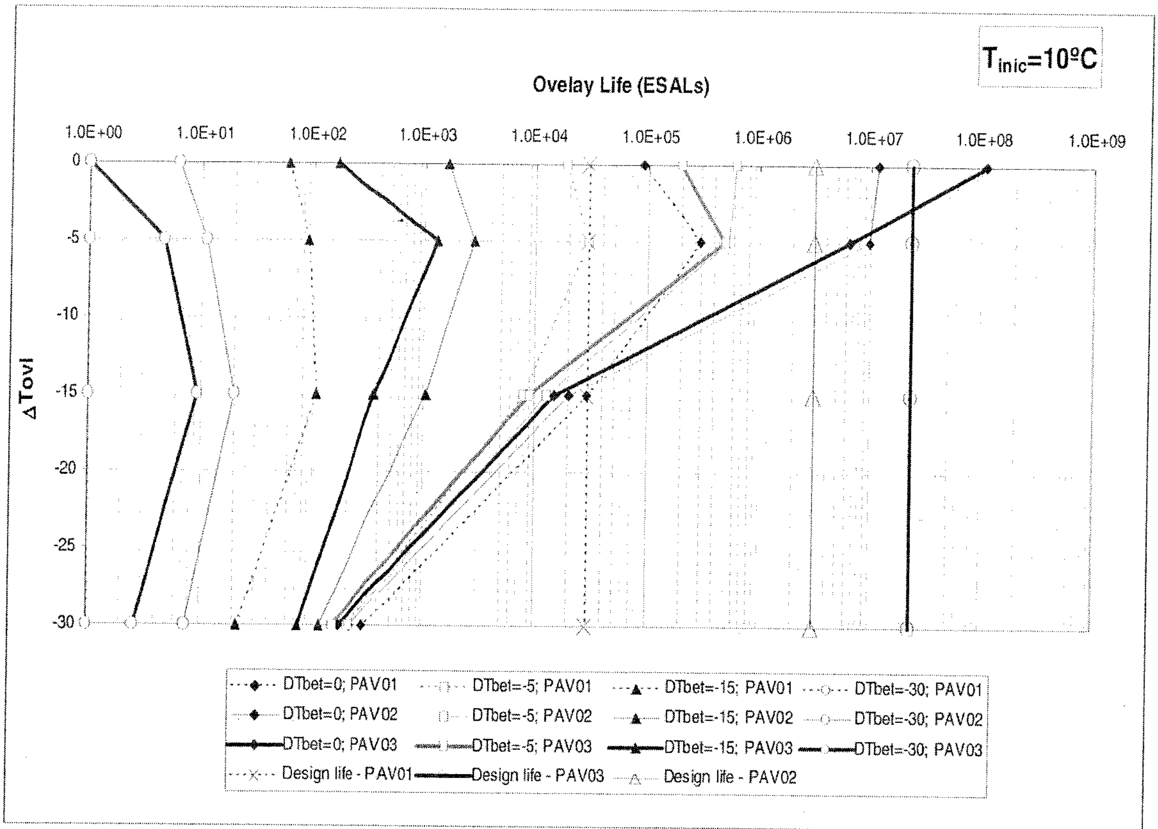

Figure 6. *Overlay life as function as ΔTovl, for initial temperature of 10ºC*

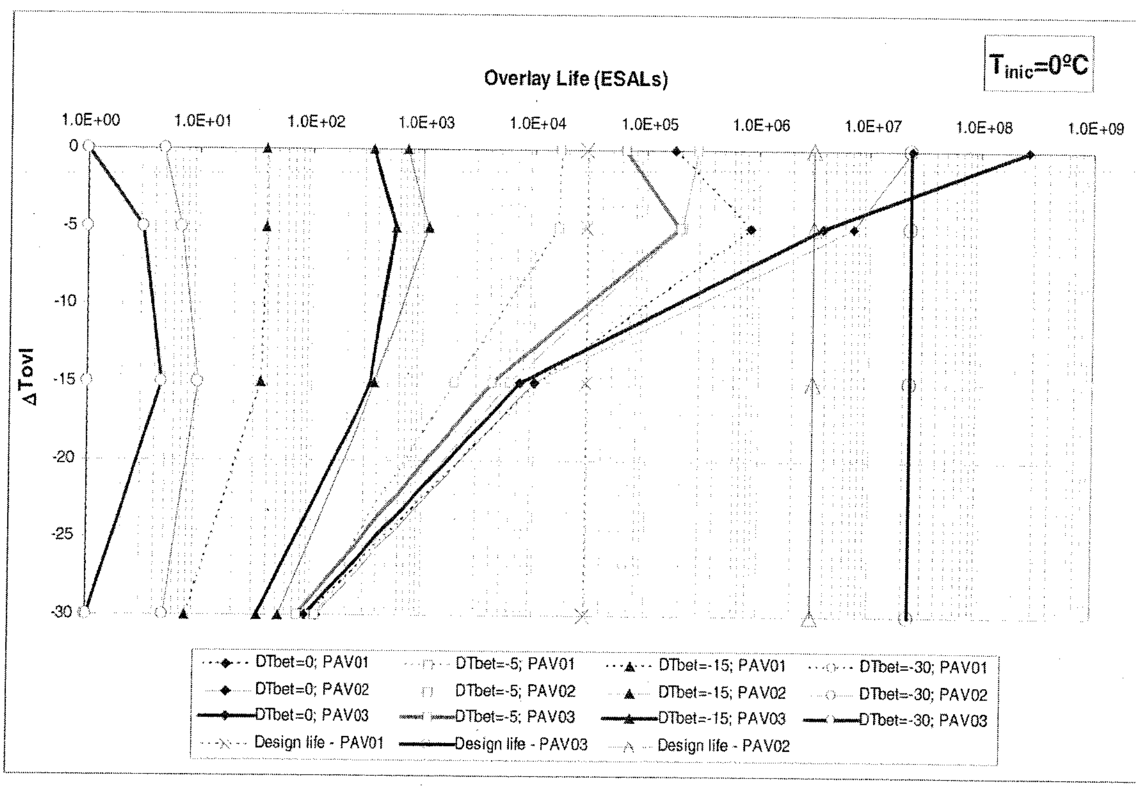

Figure 7. *Overlay life as function as ΔTovl, for initial temperature of 0ºC*

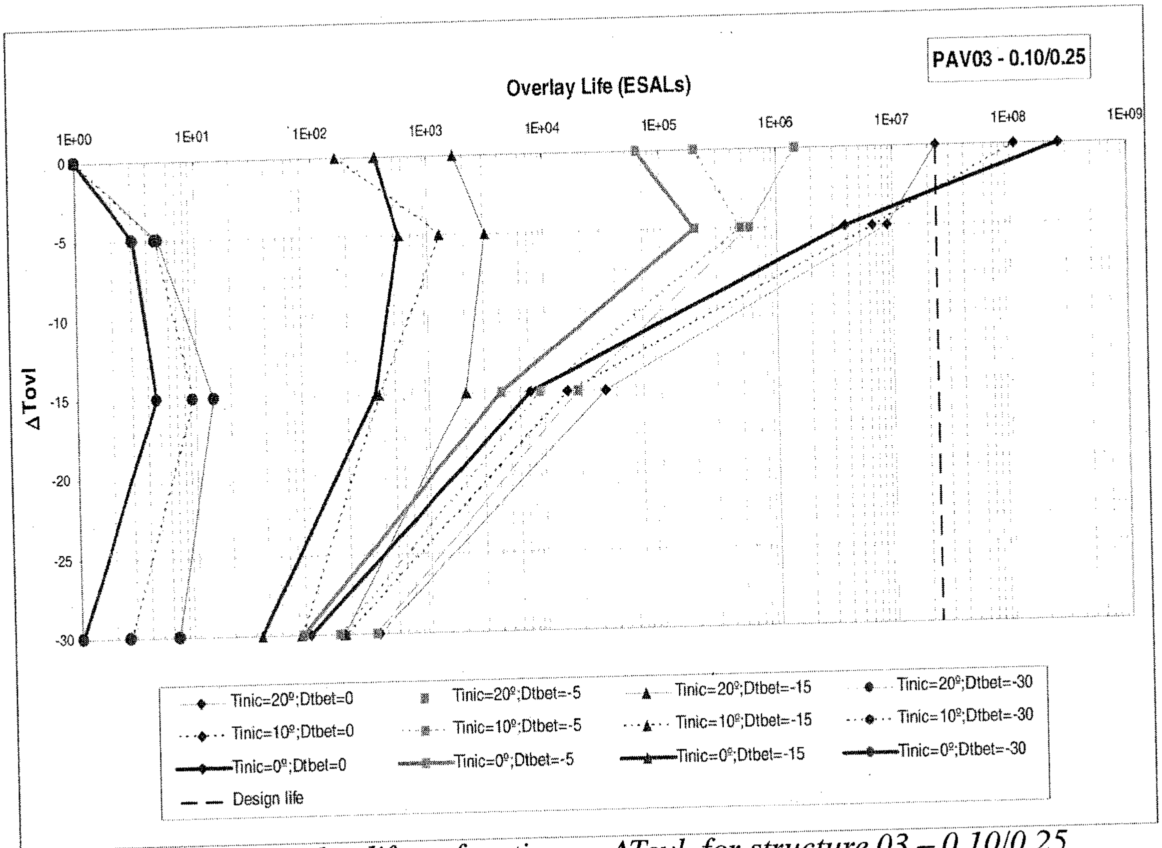

Figure 8. *Overlay life as function as ΔTovl, for structure 03 – 0.10/0.25*

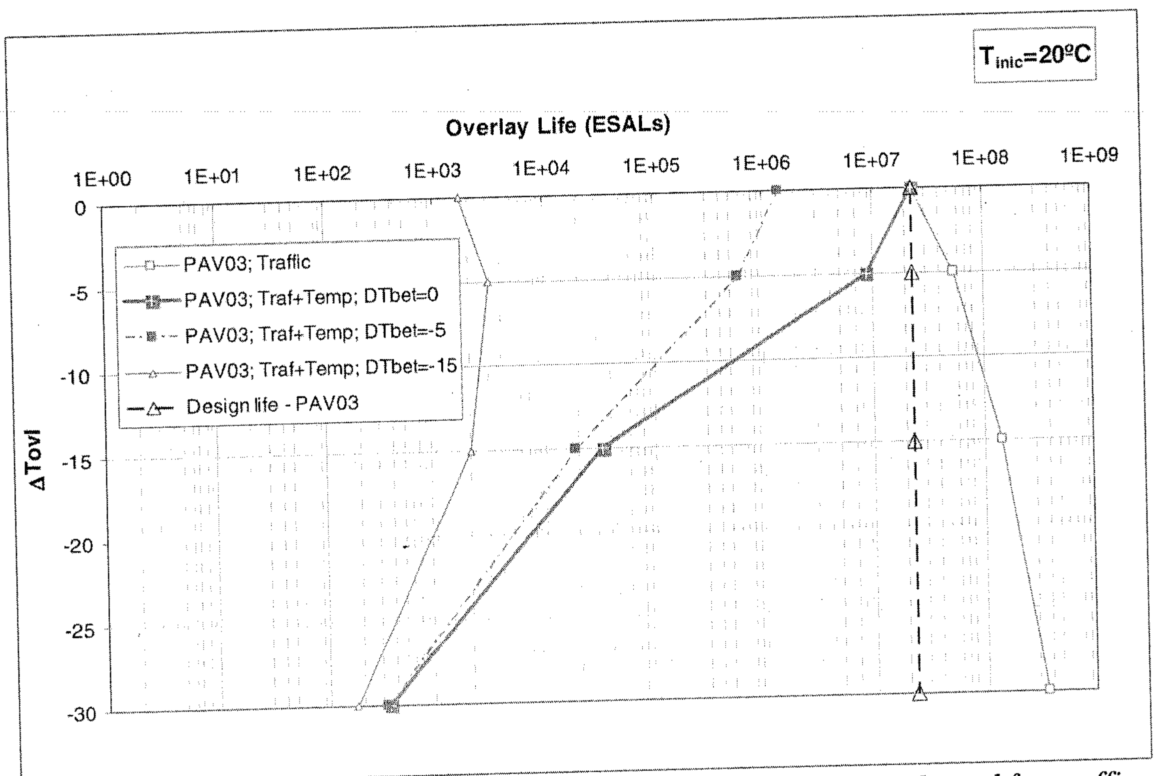

Figure 9. *Overlay life as function as ΔTovl, for traffic loading only and for traffic loading + temperature loading – Tinic=20ºC*

The 3D-FEM model was used also to compute the state of strain and, consequently, the overlay life in the case the temperature drop is equal in all bituminous layers. This simulation represents the usual situation that appears in the pavement and that is considered in the pavement design.

Thus, in Figure 10, the overlay life is plotted against the temperature drop in all bituminous layers. This simulation was made only for an initial temperature of 20ºC and for the above used temperature drops (-5ºC, -15ºC and –30ºC) for all considered structures. The load traffic was included in the state of strain calculation.

Similar results were obtained for the uniform temperature drop in all bituminous layers: the overlay life decreases when the temperature in the bituminous layer decreases and exhibit very low fatigue life for low temperatures.

5. Application to the Asphalt Rubber Hot Mixes

Using the results presented by [SOU 2002], where fatigue test were conducted on laboratory using asphalt rubber hot mixes with the PG 64-16 asphalt cement interacted with 20% crumb rubber from California, generally referred to as the Arizona "Type A" AR Binder. For the California AR binder, AR-4000 asphalt cement was mixed with California crumb rubber, natural rubber, and extender oil in a manner consistent with routine California work (generally called the "Type B" AR binder).

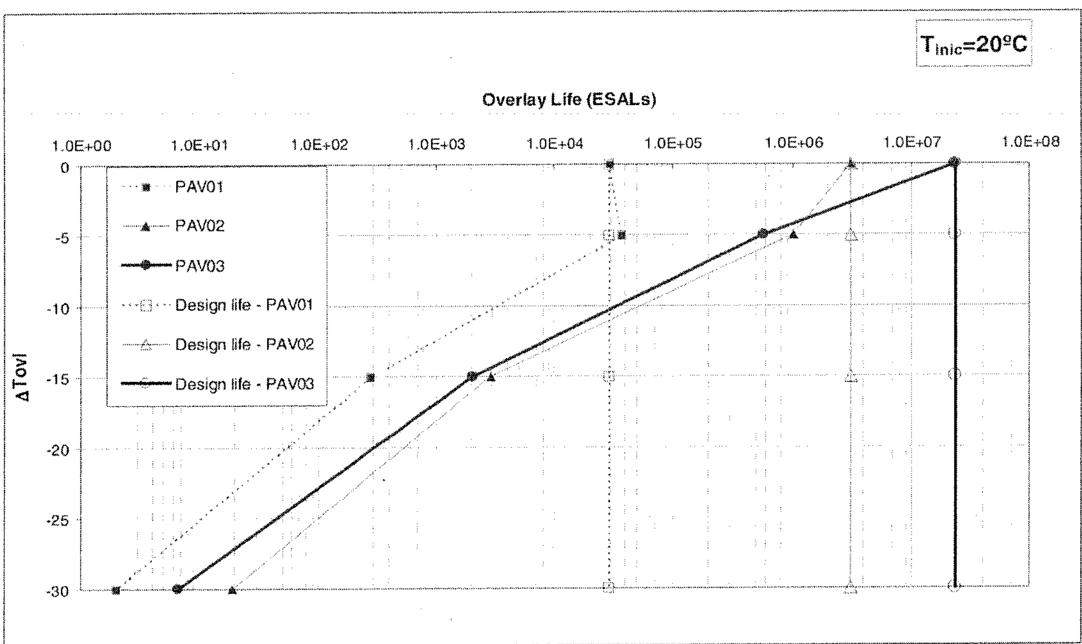

Figure 10. *Overlay life as function as ΔTovl, for traffic + temperature loading for uniform temperature drop in bituminous layers*

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

The flexural fatigue tests conducted in displacement control present the fatigue life

$$ESALs = 4.1245E19 * \left[\varepsilon_{VM} (1x10^{-6})\right]^{-4.9761} \qquad [3]$$

expressed as function of the Von Mises strain as:

Using equation [3] the overlay life was calculated for asphalt rubber mixes and compared with conventional mixes for which the fatigue life was calculated by Shell fatigue law. The results are in Figure 11 where the asphalt rubber mixes present a clear difference in terms of fatigue life when compared with conventional mixes. These differences are more expressive for high temperature drops.

6. Conclusions

The finite-element analysis has proved to be an interesting tool for simulate the performance of asphalt concrete overlays at low temperature under traffic load conditions. In the future, the transient response of the pavement structure by transient thermal analysis is needed (required) before the mechanical analysis. The effect of relaxation must also be considered once the overall state of tension in the overlay caused by the rapid cooling rates is also a function of the creep compliance of the material. These processes need a long time consuming computing process and don't have immediate results.

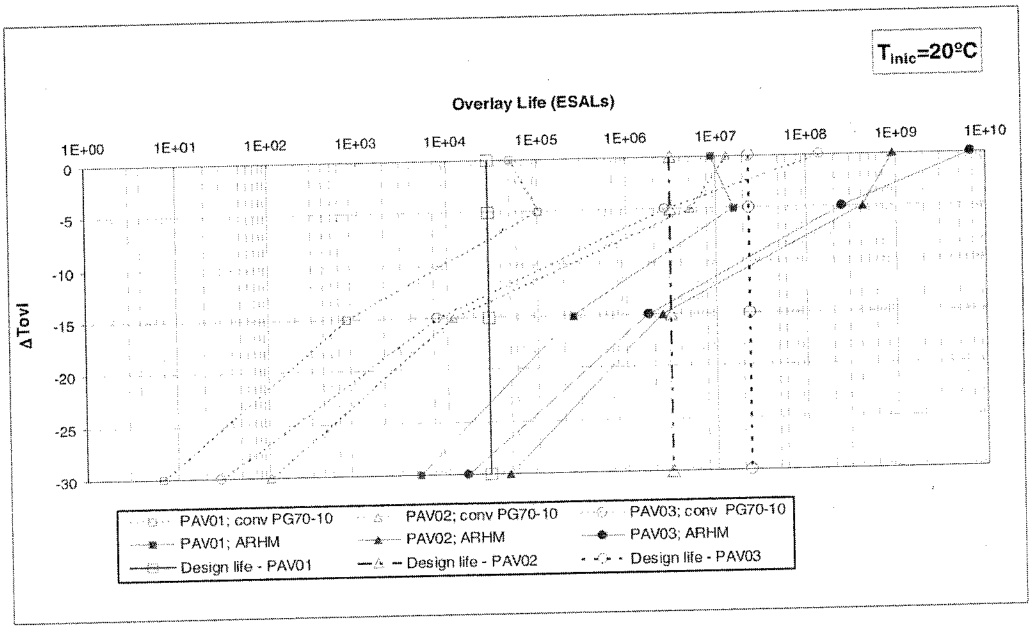

Figure 11. *Comparison between overlay life for conventional and asphalt rubber mixes*

The consideration of rapid cooling rates that cause overall states of tension in the overlay, are particularly important for estimate the overlay predictive life. On one hand, the effect of the temperature in the material properties has a good impact in the overlay predictive life, on the other hand, the effect of accumulated restrained thermal stresses as a result of the effect of cold temperature shrinkage added to traffic loading effect, will reducing the overlay life.

In the scope of this study we have conclude that the asphalt rubber mixes present a clear difference in terms of fatigue life when compared with conventional mixes and these differences are more expressive for high temperature drops

As final conclusion, the effect of cold temperature shrinkage may have a significant influence on overlay life, which in turn will justify a special attention on overlay design procedures.

7. References

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