

# Effect of temperature on asphalt pavement strain responses: APT data and thermo-viscoelastic pavement modelling

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## ABSTRACT

This paper presents data and modelling results of asphalt pavement strain responses for different pavement temperature conditions. The tensile strains developed at the bottom of the structural layers in a thick asphalt pavement are critical to the thickness design.

Measured strain data have been collected during a pavement response to load experiment undertaken using the IFSTTAR's accelerated pavement testing (APT) facility. The effect of the pavement temperature on the tensile strains at the bottom of the asphalt layers is derived from the data in different pavements structures, at different speeds and for different wheel configurations in both the longitudinal and transverse directions.

A thermo-viscoelastic pavement response to load model has also been used to evaluate strains. When comparing measured strains with calculated strains, the viscoelastic model is found to provide a good agreement with the APT strain signals.

**Keywords:** Asphalt Pavements, response to load, pavement testing, viscoelastic modelling, multiple axle loadings.

## 1 INTRODUCTION

The thickness design of asphalt flexible pavements is generally constrained by a fatigue performance criterion of the asphalt base and intermediate layers [1], [2]. The fatigue performance is a function of the material characteristics and the pavement maximum tensile strain developed in the asphalt layers. The calibration of the fatigue performance relationship in a range of temperature conditions requires a good understanding of the effect of climatic conditions on pavement response. This paper focuses on the effect of pavement temperature on the tensile strains in flexible asphalt pavements under a range of truck load configurations.

Bituminous materials are viscoelastic (time dependent) and their properties change with temperature, thus their response is affected by both the loading speed and the temperature of the material. They deform more under a decreasing loading speed (slow ramps, intersections) or increasing temperature (summer weather and warm climate).

The thermo-viscoelastic behaviour of asphalt materials is well known and has been extensively studied in the laboratory [3], [4], [5], [6]. The response of visco-elastic materials is delayed in time with respect to the load application and, for a fixed value of stress the displacement is function of the load frequency and the temperature. Complex modulus testing performed under sinusoidal loading conditions provides a perfect means of assessing the properties of the material in a large spectrum of conditions. Performed under flexural or compression conditions, the (complex) flexural modulus of the material is measured at different temperatures (typically from 0 to 30 or 40°C) and at a range of loading frequencies (typically from 0.1 to 40 Hz) [7].

For a pavement structure which comprises of a range of different materials including the subgrade, granular and asphalt layers, the analysis of the structural response requires the use of a modelling approach in order to take into account the combination of the different layers in the whole response of the structure.

For multi-layered structures, standard linear elastic models are implemented in the pavement design software and are used for routine pavement thickness design [8], [9]. The most commonly used approach is the Burmister multilayer elastic model [10]. By nature, elastic pavement models do not incorporate the effect of material temperature or loading speed. The stresses and strains are calculated for typical material properties and average environmental conditions. For instance, in France, the asphalt design modulus is defined as the complex modulus at 15°C (French average temperature) and a 10 Hz frequency (corresponding to the standard 72 km/h French speed). To cover a wider range of the Australian climatic conditions, the Austroads pavement design approach incorporates adjustments to the asphalt modulus in order to correct for the effect of temperature and speed on the pavement response [1],[11] [12].

More advanced thermo-viscoelastic pavement models have also been developed, which provide advanced theoretical tools for pavement engineering research [13], [14], [15], [16]. These models are built around the materials viscoelastic behaviour for multi-layered structures. The software ViscoRoute used in this paper allows the calculation of the pavement responses for different traffic speeds and different asphalt temperatures using the rheological model of the viscoelastic materials [4], [5]. It provides a tool to examine the effect of loading conditions including different axle configurations [13].

This paper presents data of loading signals measured in an experimental pavement in a range of temperature conditions and analyses the effect of the pavement temperature on the tensile strains. A numerical approach was performed to examine the potential of using thermo-viscoelastic pavement models for the prediction of the effect of climatic conditions on pavement responses.

## 2 APT RESPONSE TO LOAD DATABASE

IFSTTAR's accelerated pavement testing (APT) facility (**FIGURE 1**) simulates traffic loadings on full-scale test pavements. The device applies full truck axle loads in different configurations on an experimental pavement where strain gauges are embedded at different depths. It enables measurements of longitudinal, transverse and vertical strains in the different pavement layers [17]. A large range of traffic speeds can be achieved from static to more than 70 km/h by its design and its circular configuration. However, it can be limited by the type of axle configuration used.

Two pavement structures are considered in this study (**FIGURE 2**): Structure 1 consisting of a 14 mm dense graded asphalt base (200 mm thickness) and a thinner pavement Structure 2 (100 mm thickness) both covered by a 60 mm thick wearing course. The two pavement sections have a total asphalt thickness of 260 mm and 160 mm respectively. They are built with the same materials; a 14 mm nominal maximum aggregate size (NMAS) with 4.6% class 35/50 bitumen dense graded asphalt (GB3) base course material and a 10 mm NMAS with 5.7% class 35/50 bitumen dense graded asphalt for the wearing course.

The longitudinal and transverse strain signals measured at the bottom of the base course when the load is located above the gauges is considered here since they are the critical loading signals for pavement design.

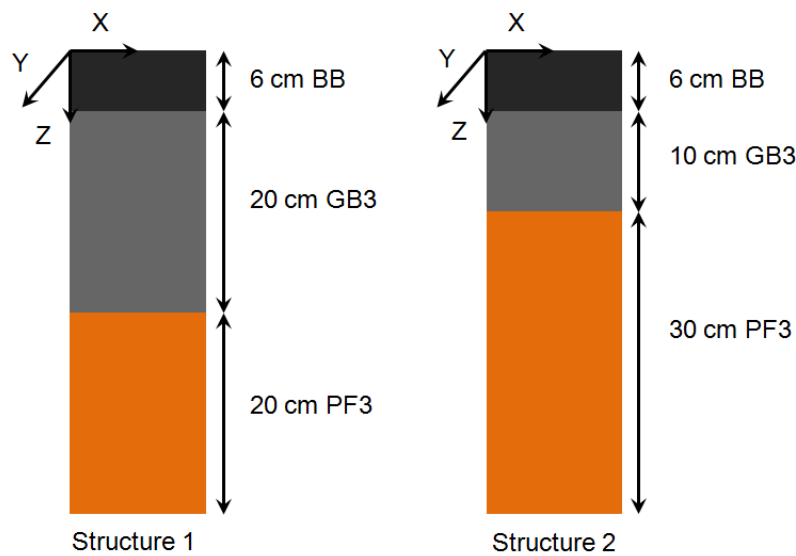
Strain signals are measured under three axle configurations shown in **FIGURE 3**: a single wheel, a tandem and a tridem (triauxle) with 42.5 kN wheel load and speeds between 4 km/h and 50 km/h (upper limit for a loaded tridem configuration). For the duration of the trial, the average temperature of the base course layer varied between 4°C and 38°C.

The traces of both the longitudinal and transverse strain signals at the bottom of the asphalt base layer were recorded. This resulted in 967 longitudinal signals and 1054 transverse signals: 1000 signals per pavement structure and 660 signals per loading configuration. The fatigue life was not available for this database since the testing was not conducted up to pavements failure. The pavements were built with realistic layer thicknesses and would require intensive and unrealistically long testing to approach their fatigue life.

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**FIGURE 1 - Accelerated pavement testing facility of the IFSTTAR**



**FIGURE 2 - IFSTTAR's APT pavements structures**



**(a) Single wheel**

**(b) Tandem**

**(c) Tridem**

**FIGURE 3 – Pavement loading configurations**

In addition to the measurement of the pavement responses, the temperature in the asphalt layers was monitored continuously for the duration of the experiment. Temperature was measured at three depths in both the surface and the base asphalt layers. This data has been used to determine the mean temperature for the two asphalt layers. During the daily temperature variations, temperature gradients developed with depth. The effect of the gradient has not been investigated in this paper and the mean temperature of the base course at the time of testing has been considered for each loading situation.

### 3 THERMO-VISCOELASTIC PAVEMENT MODEL

Analysis of the experimental pavement was undertaken using the ViscoRoute 2.0(c) software [13]. The software package was developed by IFSTTAR (The French institute of science and technology for transport, development and networks) and is composed of a computation kernel and a Graphical User's Interface (GUI). Pavements are modelled by a semi-infinite multilayered medium subjected to one or several moving loads at a constant speed in the x-direction. The load pressure can be a point load or a uniformly distributed load over a rectangular or elliptical area.

The pavement structure is composed of n horizontal homogeneous layers perfectly bonded and piled up in the z direction. However, the model has been further developed to incorporate debonding between the layers.

The behaviour of the material is assumed to be linear thermo-viscoelastic. Each layer 'i' is characterised with its Young's modulus  $E^i$  and its Poisson's ratio  $\nu^i$ . For the viscoelastic asphalt materials, five additional viscoelastic parameters are used:

$E_0^i$ : the static elastic modulus,

$E_\infty^i$ : the instantaneous elastic modulus,

$k_i$  and  $h_i$ : the exponents of the parabolic damper

$\delta_i$ : a positive adimensional coefficient balancing the contribution of the first damper in the global behaviour;

three thermal coefficients  $A_0^i, A_1^i, A_2^i$  of the complex modulus of the Huet-Sayegh model [3], [4], [5]. It consists in two parallel branches: a spring in the first and a spring and two parabolic dampers in the second (FIGURE 4).

The thermo-viscoelastic behaviour is given by the complex modulus at any loading frequency  $\omega$  (rad/s) and temperature  $\theta$  ( $^\circ\text{C}$ ), as shown in Eq. (1).

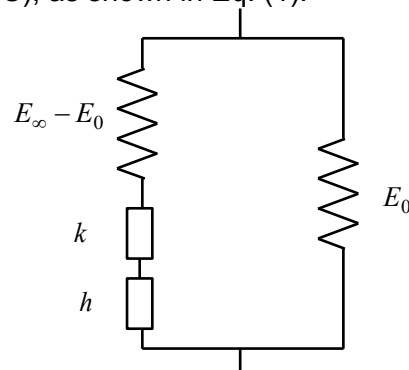


FIGURE 4 - Huet-Sayegh model

$$E^*(\omega, \theta) = E_0 + \frac{E_\infty - E_0}{1 + \delta(i\omega\tau(\theta))^{-k} + (i\omega\tau(\theta))^{-h}} \quad (1)$$

$\tau(\theta) = \exp(A_0 + A_1\theta + A_2\theta^2)$  is a function of the temperature depending on three scalar parameters  $A_0, A_1$  and  $A_2$

For elastic materials which are not time nor temperature dependant the Young's modulus and Poisson's ratio are used similarly to the classic multilayer response to load model used for pavement design [8], [9].

### 4 PAVEMENT MODELLING CONDITIONS

#### 4.1 Pavement configuration and model parameters

The numerical modelling attempted to model the actual conditions of the pavement configurations. The actual mean pavement thicknesses were used in the model. Extracted specimens from the road bed were used to undertake flexural complex modulus testing in the

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**TABLE 1 Huet-Sayegh's model parameters**

Asphalt Type	Thickness (mm)	$E_0$ (MPa) <sup>(1)</sup>	$E_\infty$ (MPa)	$k$	$h$	$\delta$	$A_0$	$A_1$	$A_2$
BB (Structure 1)	70	20	29840	0.2168	0.65821	2.194	3.896	-0.3782	1.582e-03
GB (Structure 1)	170	20	22980	0.1739	0.57757	1.985	4.325	-0.3923	1.960e-03
BB (Structure 2)	70	20	29940	0.1929	0.6250	2.003	3.982	-0.3977	2.239e-03
GB (Structure 2)	90	20	20550	0.1981	0.6029	2.306	6.018	-0.3882	1.507e-03

(1) The minimal moduli  $E_0$  has been removed from the parameter fitting options and assigned as 100 MPa

The subgrade is a 4 mm coarse sand that can be split into two layers. The first subgrade layer (2.2 m) is composed of a sand that has been present in the concrete tank since 2001 with a good bearing capacity (estimated at 120 MPa). The second subgrade layer, about 350 mm, was reworked to achieve the appropriate subgrade height for the pavement layers construction. This layer is of poor quality (35 MPa).

The granular material had a thickness of 230 and 310 mm for pavement structures 1 and 2 respectively. The low bearing capacity of the underlying sand have likely resulted in poor compaction and the resilient modulus of the granular material was estimated at 88 MPa.

Strain sensors (**FIGURE 5**) were embedded in the material at the interface of the layers during the construction of the pavement. They are located at the interface depths between layers and are anchored in the asphalt materials with the measuring element in the middle of the H bar shaped gauges. The gauge has a thickness of 10 mm, therefore it was assumed that the reading was relevant to the strain around 5 mm above the interface. Strain gauges were installed before the placement of the overlaying asphalt in both the longitudinal and transverse direction on the centerline of the trafficked area.

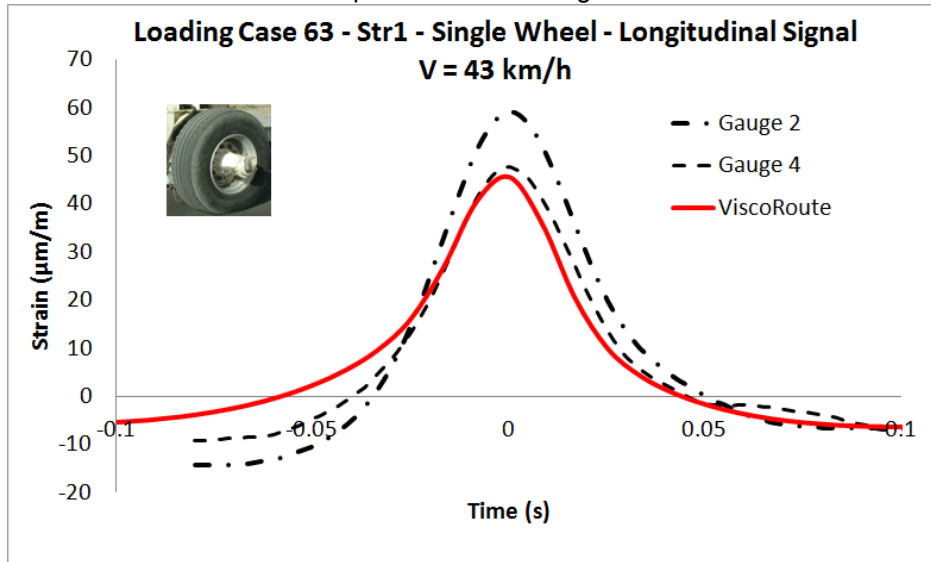


**FIGURE 5 - Strain gauges**

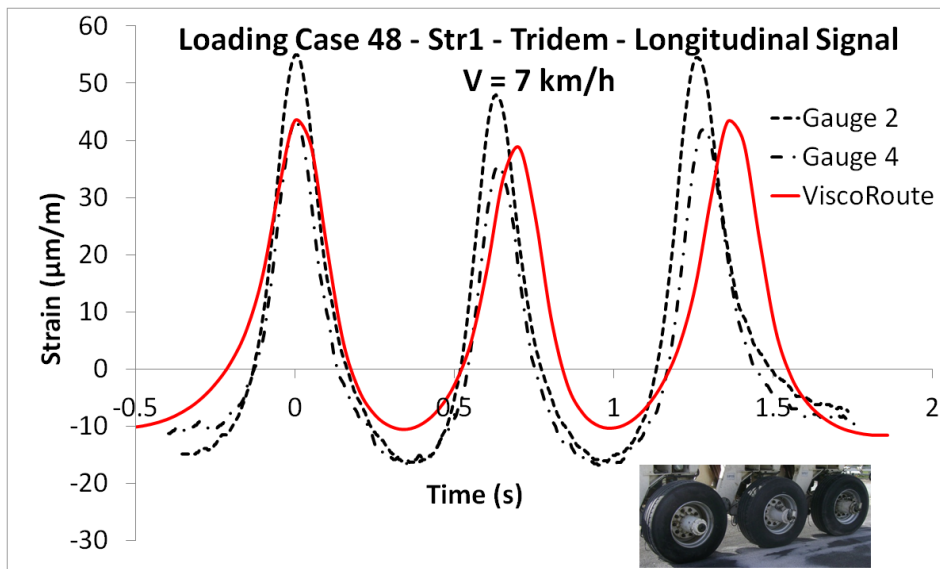
#### 4.2 Strain signals overview

**FIGURE 6**, **FIGURE 7**, **FIGURE 8** and **FIGURE 9** show the superposition of the measured signals using different strain gauges and calculated signals in the longitudinal and transverse directions, at different speeds for both pavement structures. The charts generally show a good agreement of the calculated responses with the measured strain signals. When several gauges were embedded at different longitudinal locations under the wheel-path, the different traces obtained for the measured strains provided an appreciation of the scatter, which can be significant, between different sensors.

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**FIGURE 6 - Superposition of APT signals with ViscoRoute Signal : Longitudinal signal, Single Wheel, V = 43 km/h, Str1 - T = 7°C**



**FIGURE 7 - Superposition of APT signals with ViscoRoute Signal : Longitudinal signal, Tridem, V = 7 km/h, Str1 - T = 7.3°C**

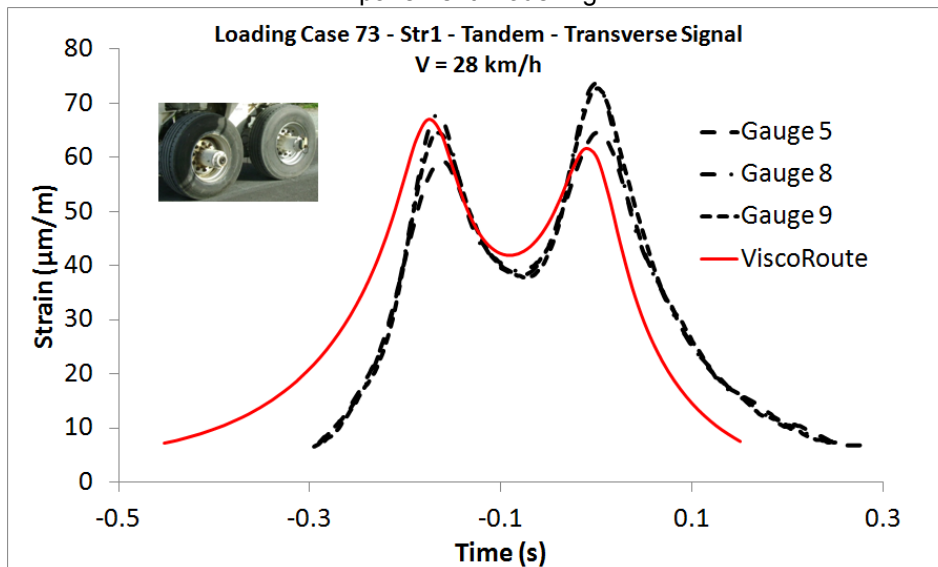


FIGURE 8 - Superposition of APT signals with ViscoRoute Signal : Transverse signal, Tandem, V = 28 km/h, Str1 - T = 9.2°C

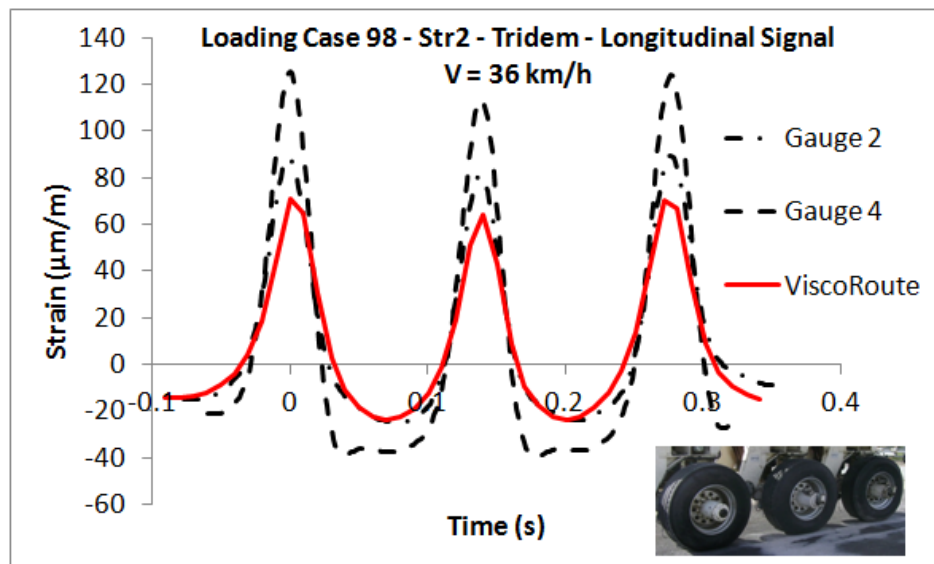


FIGURE 9 - Superposition of APT signals with ViscoRoute Signal : Longitudinal signal, Tridem, V = 36 km/h, Str2 - T = 6.8°C

## 5 APT VS PAVEMENT MODEL COMPARISON

### 5.1 Effect of the asphalt temperature on the peak strains

FIGURE 10, FIGURE 11, FIGURE 12, FIGURE 13 and FIGURE 14 show examples of longitudinal and transverse peak strain data as a function of the mean temperature of the GB3 base layer. They do so for both longitudinal and transverse directions, low and high speeds and the two pavements structures. The strain results exhibit an exponential relationship between the peak strain and the material temperature. Equation (Eq. (2)) provided a reasonable fit for both APT and simulation results, where  $a$  and  $b$  are constants that depend of the pavement structure, the loading configuration and the loading speed.

$$\varepsilon_{max} = e^{(aT_{Asphalt}+b)} \quad (2)$$

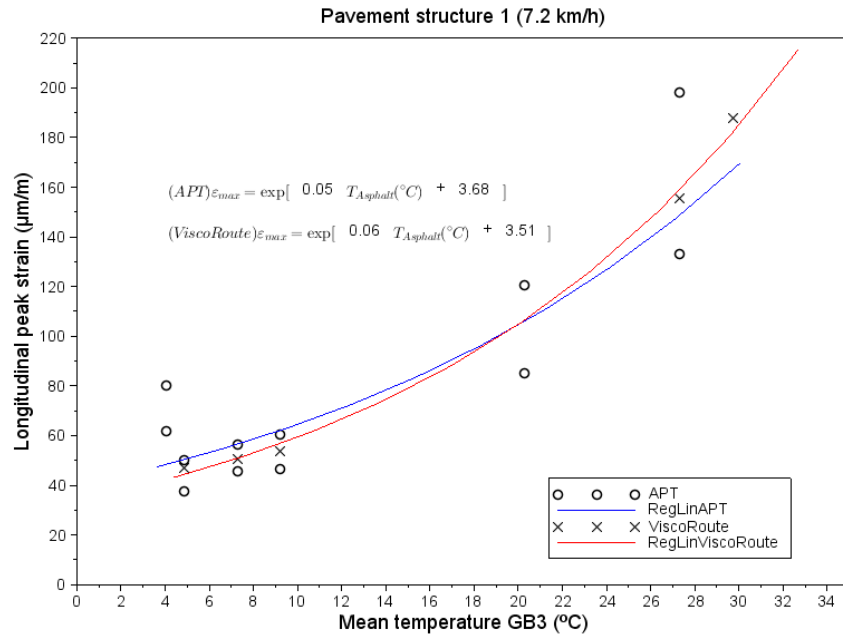
The results presented here follow similar trends to those observed for the measured peak strains at the NCAT test track where a range of asphalt pavements were tested [18]. The NCAT report describes a similar kind of relationship between the temperature ( $T$ ) and the

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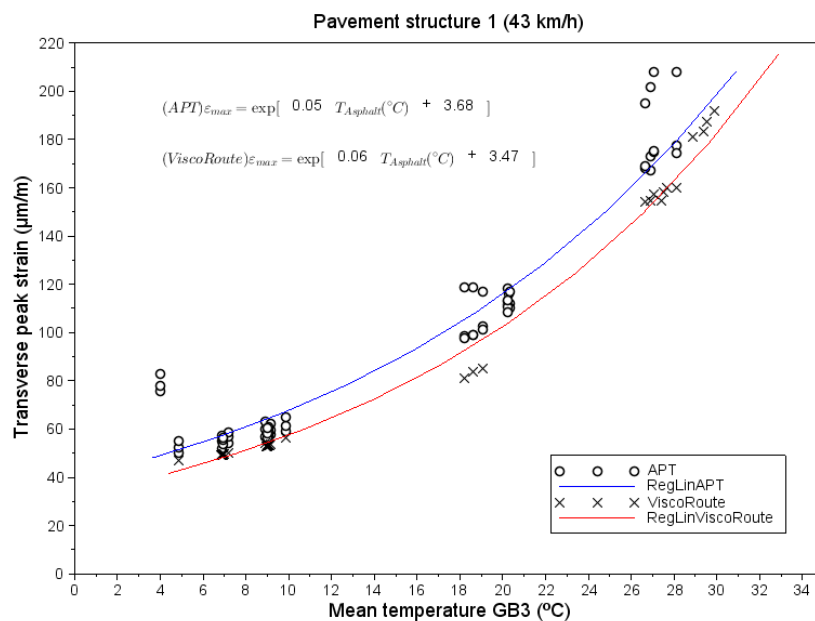
peak strain magnitude at the bottom of the asphalt layer ( $\epsilon$ ): Eq. (3) where  $k_1$  and  $k_2$  are pavement configuration (section) constants.

$$\epsilon = k_1 \exp(k_2 T) \quad (3)$$

**FIGURE 10** and **FIGURE 11** show the effect of temperature on the longitudinal and transverse strains magnitude respectively with the temperature of the base layer of structure 1 for single axle loading. At one temperature, the scatter in the APT data comes from measurements performed using different sensors. The scatter can be significant but it did not alter the qualitative effect of temperature on the measurements from each individual gauge.



**FIGURE 10 - Longitudinal Strain peak as a function of mean temperature of GB3 - Single axle, Structure 1, V = 7.2 km/h**

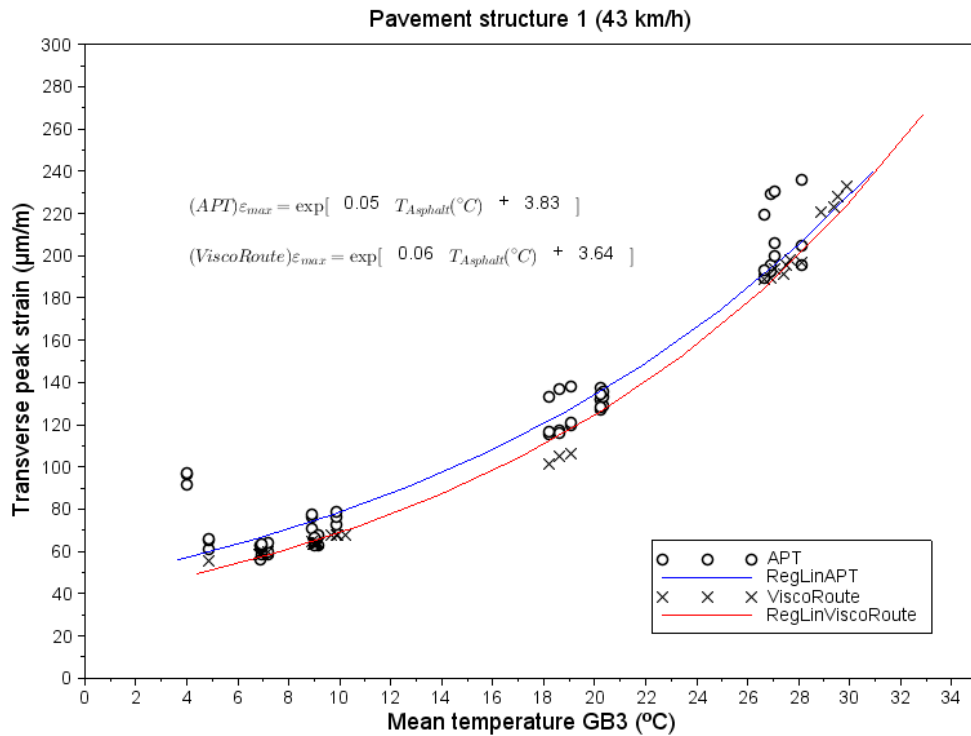


**FIGURE 11 - Transverse Strain peak as a function of mean temperature of GB3 - Single axle, Structure 1, V = 43 km/h**

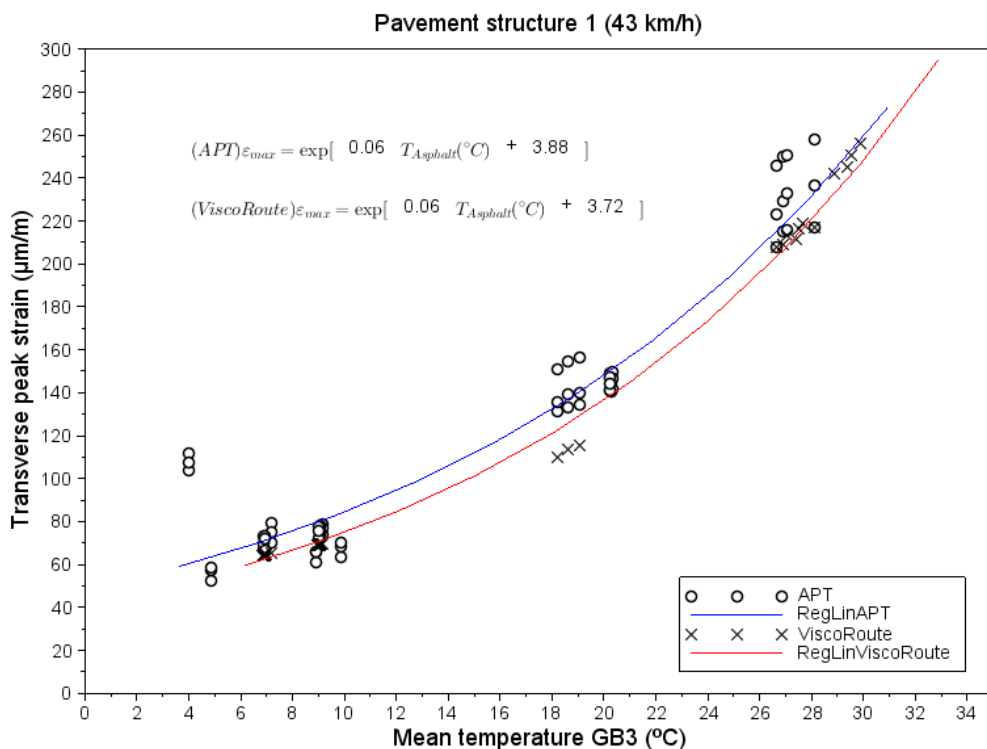
**FIGURE 12** and **FIGURE 13** show the effect of temperature on transverse strains for two and three axle loading configurations respectively on pavement structure 1.



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**FIGURE 12 - Transverse Strain peak as a function of mean temperature of GB3 - Tandem axle, Structure 1, V = 43 km/h**



**FIGURE 13 - Transverse Strain peak as a function of mean temperature of GB3 - Tridem axle, Structure 1, V = 43 km/h**

Similar trends with temperature were observed for the thinner structure (Structure 2). However, as shown in **FIGURE 14**, the predicted strains were offset from measured strains. The pavement model underestimated the strain magnitude in this case.

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Pavement structure 2 (50 km/h)

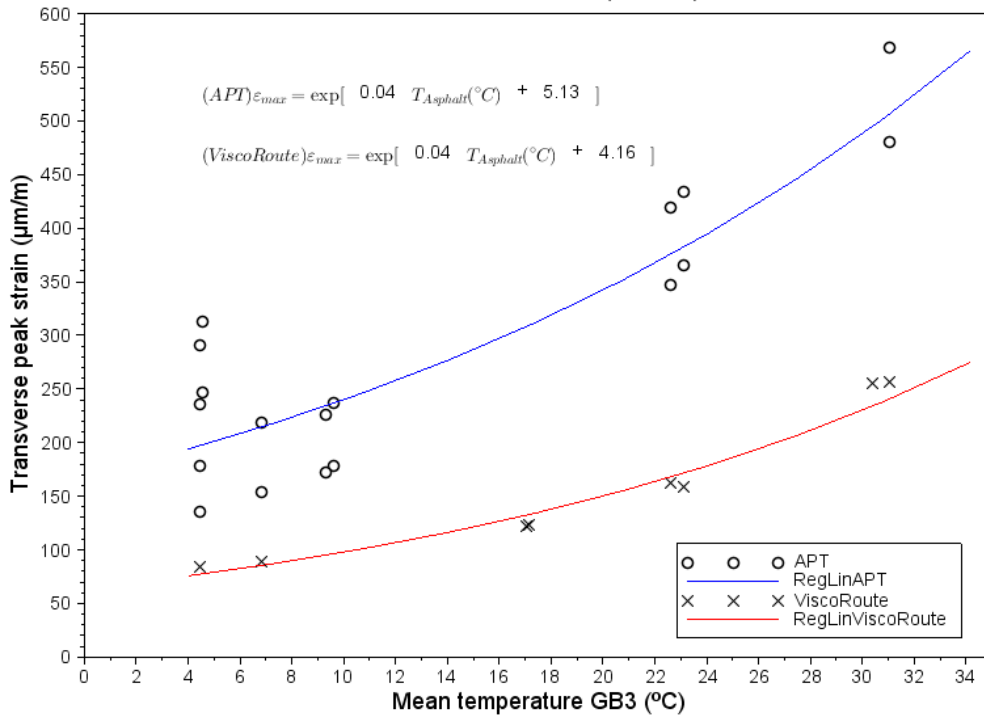


FIGURE 14 - Transverse peak strain vs the mean temperature of GB3 - Single axle, Structure 2, V = 50 km/h

5.2 Comparison of the measured and calculated strains

FIGURE 15 and FIGURE 16, show examples of the strain peaks of calculated signals versus those measured by different strain gauges embedded in pavement structure 1. Taking into account the scatter in the measured responses, the results show that the model predicts the longitudinal peak strains relatively well for the different axle configurations, speeds and temperatures. The longitudinal responses are better predicted than the transverse peak strains which were found to be slightly underestimated.

FIGURE 17 and FIGURE 18 show examples of the strain peaks of calculated signals versus those measured by different strain gauges embedded in pavement structure 2. Results show that the model underestimates the peak of the longitudinal and transverse strain signals for the different axle configurations, speeds and temperatures.

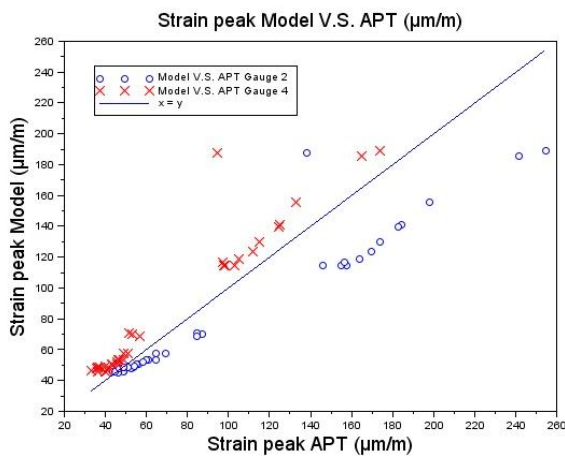


FIGURE 15 - Calculated vs. measured longitudinal peak strain - Single Axle - Str 1

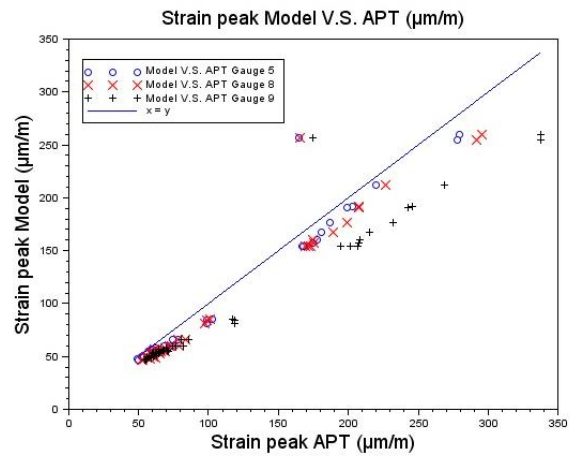
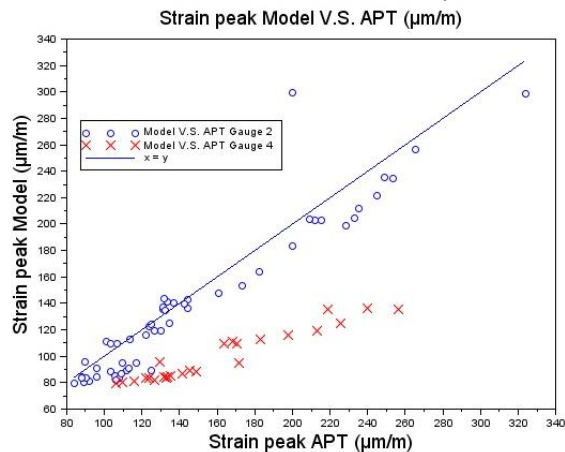
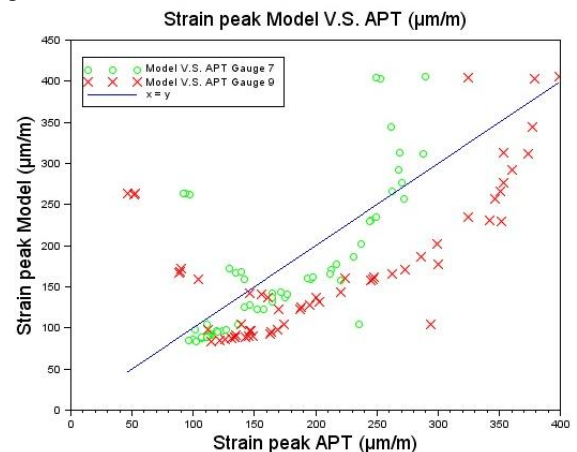


FIGURE 16 - Calculated vs. measured transverse peak strain - Single Axle - Str 1

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**FIGURE 17 - Calculated vs. measured longitudinal peak strain - Single Axle - Str 2**



**FIGURE 18 - Calculated vs. measured transverse peak strain - Single Axle - Str 2**

## 6 CONCLUSIONS

In this paper, a database obtained during an asphalt pavement response to load experiment was used to examine the effect of the asphalt temperature on the critical tensile strains at the bottom of the asphalt layers. The signals measured at the bottom of the base course of experimental pavements of the APT at IFSTTAR showed the same trends as observed at the NCAT test track in the USA. An exponential relationship between the measured strains and the pavement temperature appeared appropriate for the large range of tested conditions (traffic speed and axle configurations).

A parallel modelling approach was undertaken using the thermo-viscoelastic modelling/theory. The simulations were performed with similar loading conditions to those of the full-scale experiment and using the material parameters measured from laboratory testing. The calculated peak strains were compared to the measured strains. Results show that the thermo-viscoelastic pavement model predicted the loading signals on the thick pavement structure for the different loading conditions relatively well. However, the model underestimated the strain peaks in the thin structure. The prediction quality could be improved by further investigations and by developing an enhanced model for the underlying granular layers. The modelling framework provides a means of investigating the relative effect of changes in climatic conditions on the critical response of asphalt pavements. The whole evaluation of the pavement fatigue performance should be complemented by the effect of temperature on the asphalt fatigue and healing performance.

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