Continuous strain monitoring of an instrumented pavement section

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ABSTRACT: Pavement instrumentation has recently become an important aid-tool of pavement monitoring for the assessment of pavement structural behaviour. Classically, measurements on instrumented pavements are performed on site, under known load conditions: the response of the pavement is recorded under the passage of a reference vehicle, with known axle loads. In such conditions, data interpretation and modelling of the pavement are relatively easy. However, on site measurements are time consuming and costly to perform, because they require using a dedicated vehicle, and closing the lane to traffic, which is not easy on a heavily trafficked motorway.

This paper presents an experiment, where an instrumented bituminous pavement motorway section has been followed by remote monitoring, under normal traffic. The section, instrumented with strain gages, temperature probes and geophones, has been monitored continuously during 18 months. Signal sorting procedures have been developed for reducing the quantity of recorded data, and for analysing the structural response of the pavement, under highly variable loading conditions, and are presented and discussed.

The results of the strain gage measurements, made at different depths within the pavement, have shown that the response of the pavement presents large variations with temperature, and in particular, that the degree of bonding between pavement layers can decrease at high temperatures, leading to sliding between pavement layers.

The mechanical response of this instrumented pavement section has been analysed using a classical multi-layer linear elastic pavement model and also a viscoelastic model. The best predictions have been achieved with the viscoelastic model. Different approaches for describing the behaviour of pavement layer interfaces have also been evaluated.

Keywords: pavement monitoring; remote monitoring; strain gage; geophone; data acquisition; pavement modeling; interface

1. Introduction

In pavement research, a considerable amount of effort has been devoted to the study of ageing and evolution of performance of asphalt concrete with time, in order to assess better pavement behaviour and thus improve pavement design. Pavement behaviour, indeed, depends on many factors like environmental conditions, cumulative loading, loading configurations, etc...

To analyse pavement behaviour, destructive and non-destructive test methods can be used (Xue, Wang, Wang, & Druta, 2013). Destructive test methods consist in taking core samples on site to study material performance in the laboratory. Non-destructive methods comprise various pavement surface and pavement structure evaluation methods and in-situ pavement instrumentation.

Pavement surface evaluation methods include distress measurements, longitudinal and transversal profile measurements. Image processing for analysis of pavement surface distresses was first addressed in the literature by Mohajeri and Manning (Jerry, Mohajery, & Manning, 1991), Koutsopoulos and Downey (Koutsopoulos & Downey, 1993)...

For pavement structure evaluation, deflection measurements and wave propagation measurements are complementary approaches, which can be used to assess pavement structural conditions. Deflection measurement methods and back-calculations can be used to determine the elastic moduli of pavement layers, which characterise pavement strength and are important parameters for structural assessment. Wave propagation methods can be used to assess pavement layer properties and pavement interfaces.

Recently, pavement instrumentation has become an important aid-tool of pavement monitoring, for the assessment of pavement structural behaviour. Parameters

measured on site are mainly: strain, stress, temperature, moisture and deflection. Many investigations have been conducted with these parameters to assess pavement performance and predict pavement distress. The study conducted on an experimental pavement section of the Virginia State Route 114 (Xue, Wang, Wang, & Druta, 2013) shows the great potential of a pavement condition monitoring system using different commercial pavement sensors. Finite-element calculations are used to predict the experimental measurements. The ratio of the vertical stress to the longitudinal horizontal strain appears to be related to pavement strength and can be used for the back-calculation of pavement moduli. A condition monitoring system including continuous monitoring and periodic testing in a routine manner is also proposed as component key-factor of pavement management systems. However, the example of monitoring under real traffic presented in the paper is limited to a short period of 45 minutes only.

The study by (Ai, Rahman, Xiao, Yang, & Qiu, 2016) conducted on a section of two lane road investigates the influence of various factors on the dynamic strain response of different asphalt pavement types. These factors include axle configuration, axle load, speed and temperature. The measurements are carried out for specified vehicles only. The results show that the strain increases when axle loading and temperature increase and when speed decreases. The combined effect of high temperatures and heavy loads leads to an increase of the fatigue damage of asphalt surface layers. Some models for predicting strain response at the bottom of the surface layers are also presented. These models combine the application of orthogonal array testing and multivariate regression analysis.

The study proposed by (Al-Qadi, Loulizi, Elseifi, & Lahouar, 2004), which has been conducted on some instrumented sections of the Virginia Smart Road,

demonstrates that, with proper calibration procedures and installation, as well as good data management, instrumentation can be a rational aid-tool to measure pavement response to loading. Measurements have been carried out under the passage of some specified vehicles. The significant influence of speed and temperature on strain measurements is here also demonstrated. The pavement behavior is improved when the calculations take viscoelastic behaviour into account, especially at low temperatures. More theoretical modelling, considering the anisotropic behaviour of the materials and the dynamic nature of the loads is needed to improve the accuracy of the currently available theoretical models. It should be noted that the measurements carried out on all the instrumented sections discussed here are obtained with known loads, moving at known speeds. The position of the load is also known, so that data interpretation and modelling are relatively straightforward. However, for security reasons, conducting such measurements, with a reference vehicle, passing over the instrumented section at known positions and speeds, is difficult to organise on heavily trafficked highways. The other drawback is that the measurements are not continuous, but only performed at fixed dates.

This study presents the instrumentation of a French motorway section, which is subjected to very heavy traffic (around 4,500 trucks/day). For security reasons, closing the slow lane to make measurements with a reference vehicle seemed difficult on this site, and it also appeared more interesting to have a continuous monitoring. The objective of the research was to monitor continuously pavement response and to study pavement evolution under normal traffic and climatic conditions. For this purpose, an instrumentation with remote control has been selected, for several reasons:

- Remote control of instrumentation is particularly appropriate in the context of a heavy traffic motorway, due to difficulties of access to the site.

- Remote monitoring has the advantage of allowing the automatic collection of a large number of data (signals under the passage of all heavy vehicles can be recorded, for example). The main difficulty lies in the absence of precise information on the characteristics of the traffic loads: speed, wandering, axle loads, etc.

The slow lane of the investigated motorway has been reconstructed in 2013. The experimental pavement section has been instrumented during the reconstruction, from 16 to 19 September 2013.

2. Pavement structure and instrumentation

2.1 Pavement structure

The experimental section consists of six different layers (Figure 1). The three upper layers have been rebuilt during the rehabilitation, in 2013. They consist of a wearing course (very thin asphalt concrete, VTAC), a binder course (high modulus bituminous concrete, HMBC) and a base course (high modulus mix HMAC). The cracked GSB layer (Gravel stabilised with bitumen) and cement treated sand layers and the subgrade are older layers, which have been left in place (more than 20 years old).

Figure 1. Structure of the experimental section

2.2 Instrumentation

The experimental section is located on a motorway, in France. The slow lane has been instrumented using temperature probes, strain gages and geophones. The instrumentation layout of the studied section is presented in Figure 2. Instrumentation includes:

- 4 longitudinal and 4 transverse strain gages embedded at the bottom of the high modulus asphalt concrete and bituminous concrete layers. The strain gages used are KM-100HAS gages (Tokyo Sokki Kenkyujo). (Figure 3a)
- 8 temperature probes PT100 installed at the bottom of each bituminous layer (2 probes per layer).
- 8 geophones placed at the bottom of the bituminous layers. The geophones measure the vertical velocity of displacement of the pavement layers. The objective was to try to use the geophones to measure the vertical displacements in the pavement structure, by integrating the displacement velocity measurements.

The geophones used are Geospace GS-11D, with a closing resistance of 47 k Ω (see Figure 3b). They have been placed at different depths (at the bottom of the HMBC, HMAC and GSB layers). In order to evaluate the lateral wander of traffic, three geophones have also been placed at different lateral positions (15 cm apart), at the bottom of the HMAC layer.

Figure 2: Motorway instrumentation layout

Figure 3. TML strain gage (a) and geophone (b)

The strain gages have been embedded in the bituminous pavement layers during construction (Blanc, Trichet , Gouy, Coirier, Nguyen, & Baudru, 2016), using the following procedure:

- First, a thin layer of hot asphalt mix (about 1 cm) is laid.
- The strain gage is positioned on this asphalt layer.
- Then, both gage and cable are covered with hot asphalt mix compacted manually, to protect them
- Finally, the paver and the compactor are used to implement the asphalt concrete layer.

2.3 Description of the remote monitoring system

The sensors are connected to a remote data acquisition system, called PEGASE *Platform*. Developed at IFSTTAR, the PEGASE Platform consists of a “mother board”, which integrates a computation processor (Analog Device Blackfin BF537), data storage, a Wi-Fi communication module and a small and low-power GPS receiver for localization and time synchronization. It also comprises a set of pluggable “daughter boards” including conditioners and analog to digital converters for the different transducers (Le Cam, Cottineau, Lemarchand, & Bourquin, 2008) (Figure 4).

Figure 4. Wireless data acquisition system PEGASE developed at IFSTTAR

The PEGASE system is very compact, modular, and consumes little energy. It has been used for various applications like bridge inspection, cable monitoring, pavement monitoring... (Sohm, et al., 2012b) (Duong, Blanc, & Hornych, 2016) (Hug, Blanchard, Hornych, Blanc, & Kerzreho, 2015).

On the site, the PEGASE boards have been installed in a weatherproof cabinet, installed behind the safety barrier. All the recorded measurements are transferred continuously via 3G network (within a few hours maximum) to a remote server, and stored in a database, for further analysis. Data from the instrumented motorway section have been recorded and analyzed since March 2014 for the temperature probes and since May 2015 for the strain gages and geophones.

3. On site measurement results and modelling

In order to control that the sensors are operating correctly and to determine an initial model for the pavement structure, a specific on-site measurement campaign has been conducted at the beginning of the study, in March 2014. During this campaign, the slow lane remained open to traffic. The measurements were performed with a 5 axle semi-trailer truck, with known axle loads and dimensions (with a total load of 43 tons). This reference truck passed 10 times over the instrumented section, at a speed of 90 km/h.

The on-site measurements have been modelled with a linear elastic model, and using the following approach:

- For the new pavement layers (VTAC, HMBC and HMA), standard values of elastic moduli, defined according to the French standard NF P 98-086, have been used for the calculations. Their values at 15°C and 10 Hz are displayed in Table 1. For the modelling, these values have been corrected to take into account measurement frequencies and temperatures.

- The elastic moduli of the old pavement layers have been adjusted in order to fit the in-situ strain measurements.

The elastic calculations have been made using the French pavement design software ALIZE (<http://media.lcpc.fr/ext/pdf/prod/alize.pdf>). This software is based on the multi-layer linear elastic model of Burmister (Burmister, 1943) in compliance with the French pavement design guide (LCPC-SETRA, 1994). The pavement layers are assumed to be isotropic and infinite in the horizontal plane.

Figures 5 and 6 present a comparison between measured and calculated horizontal strains at the bottom of the HMAC layer (at 16°C, 13 Hz). L2 and L3 are the longitudinal strain gages and T2 and T3 the transverse strain gages located at the bottom of the HMAC.

Figure 5. Measured and predicted longitudinal strains at the bottom of the HMAC layer (16°C, 13 Hz)

Figure 6. Measured and predicted transverse strains at the bottom of the HMAC layer (16°C, 13 Hz)

It was concluded that the linear elastic calculations predict well longitudinal strain amplitudes, and less accurately transversal strains. In particular, the measured transversal strains increase progressively under the 3 rear axles, and don't return to zero between the loads. This is due to the viscoelastic behaviour of the bituminous materials, and cannot be reproduced with the elastic model. The structure of the experimental section and the moduli of the different pavement layers, fitted with the elastic model are presented in Table 1.

Table 1. Tested pavement structure and fitted pavement layer moduli (corrected to 15 °C, 10 Hz)

Material	Elastic Modulus (MPa)	Thickness (cm)

Very thin asphalt concrete (VTAC)	3000	2.5
High modulus bituminous concrete (HMBC)	11000	6
High modulus asphalt concrete (HMAC)	14000	7
Gravel stabilized with bitumen (GSB)	5000	8
Cement-treated sand	14000	30
Subgrade	150	50

The objective of this first study was to define initial moduli of the different pavement layers, in order to follow subsequently their evolution under the effects of traffic and climatic conditions.

4. Measurements obtained using remote monitoring

4.1 Examples of strain measurements

As explained in detail below, the monitoring procedure consists in recording only strain signals under heavy vehicles (based on a threshold level), and analyzing only the signals corresponding to one category of trucks, 5-axle semi-trailers. This leads to about 100 to 300 heavy vehicle signals per day.

Some examples of strain gage measurements recorded under 5-axle semi-trailer trucks at low and high temperature using the remote monitoring, are presented in Figures 7 and 8. Positive values correspond to strains in extension. Six strain gage signals are presented:

- 2 longitudinal strain signals at the bottom of the HMAC (at 15cm depth): gages L2 and L3.

- 2 transverse strain signals at the bottom of the HMAC (at 15cm depth): gages T2 and T3.
- 2 transverse strain signals at the bottom of the HMBC (at 8cm depth): gages T5 and T8.

The longitudinal strain gages at the bottom of the HMBC have been damaged during construction.

As regards the signals recorded under real traffic, the precise characteristics of the trucks (speed, axle loads) are not known. However, speeds are generally close to 80 km/h.

Figure 7. Strain signals recorded at low temperature (15°C, at 9h55min, November 4th, 2015).

Figure 8. Strain signals recorded at high temperature (35°C, at 13h03min, July 2nd, 2015).

The results show that, at low temperatures, the strains in the HMAC layer are in extension in both longitudinal and transversal directions. The strains in the HMBC layer are in extension in the transversal direction.

At high temperatures, the strain signals change significantly: The strain amplitudes are much higher, with transversal strains reaching values of approximately 160 μstrains at the bottom of the HMBC layer. The shape of the transverse strain signals at the bottom of the bituminous layers is also modified, with a slow return to zero after loading. This delayed response is due to the viscoelastic behaviour of the bituminous layers, and is more pronounced under the three rear axles of the vehicle and at high temperatures.

Similar results have been previously observed in a study conducted at IFSTTAR using the accelerated pavement testing facility (Grellet, Doré, Chupin, & Piau, 2016). In this study, high extension strains (more than 250 μstrain) have been measured at the

bottom of the bituminous wearing course of a thin pavement structure at high temperature (30°C), and similarly, a slow return to zero of the strains after loading was observed.

4.2 Remote monitoring: Data sorting process

Data acquisition is carried out on the motorway experimental section under real traffic. Temperature measurements are recorded continuously, every 15 minutes. Strain gage and geophone measurements are recorded only when the level of displacement velocity measured by the geophones exceeds a triggering threshold. Thus, only the signals corresponding to heavy trucks are recorded and not those corresponding to passenger cars. The geophone G1 placed in the center of the HMAC layer is used to define the threshold, and when this threshold is exceeded, the measurements of all the geophones and strain gages are recorded.

All the sensor measurements are transferred to a server through the wireless data acquisition system. With the threshold that has been selected, the system records approximately between 5,000 and 10 000 files (corresponding to heavy vehicle passages) per month, as shown in Figure 9. For the last two months (December 2015, and January 2016), the number of files is lower because the data acquisition was interrupted during part of this period.

Figure 9. Number of strain signal files recorded each month using the PEGASE system.

All the signals recorded correspond to different types of heavy vehicles, passing at different lateral positions on the pavement. In order to be able to use this data for modelling, and to evaluate the properties of the pavement layers, a sorting procedure has been defined. The idea was to select only the signals of the trucks passing at a constant lateral position, with their wheels centered above the strain gages, because this situation is simple to model. To perform this selection, it was decided to use the measurements of the 3 geophones G1, G3 and G4, placed at different lateral positions (15 cm apart) at the bottom of the HMAC layer. The embedded strain gages are aligned with the geophone G1 (Figure 10). Therefore, when the measurement of geophone G1 is maximum (higher than that of geophones G3 and G4), it means that the wheel loads are centered on this geophone, and also on the strain gages (with a precision of about ± 10 cm).

Figure 10. Lateral position of geophones G1, G3, G4, and position of the strain gages

To illustrate the effect of the lateral position of the vehicle wheels on pavement response, three transverse strain signals corresponding to vehicles passing with their wheels centered above geophones G1, G3 and G4 respectively, are presented in Figure 11. The results indicate that the measured strain signals are very different, depending on the lateral position of the wheels.

Figure 11. Transverse strain signals recorded when a vehicle passes with its wheels centered above geophone G1 (1), G3 (2) or G4 (3).

To verify the experimental observations, calculations have been carried out with different positions of the applied vehicle loads using the design software ALIZE. The calculations show that the transverse strain is very sensitive to the position of the vehicles. The transverse strain can even change its sign (extension or contraction) when a vehicle passes at different lateral positions relative to the sensors (Figure 12).

Figure 12. Three strain signals obtained at the bottom of the HMBC layer with different positions of the vehicle wheels above the strain sensors. (distance from the sensor line: 6.5 cm (green line), 11.5 cm (red line), and 16.5 cm (blue line)).

Another difficulty, with the present analysis of strain measurements, made under real traffic, is the lack of information about heavy vehicle loads (no axle load measurement system is installed on the test site). To overcome this difficulty, a solution, also exploited on weight in motion systems, has been used. It is based on the observation that on regular European 5 axle semi-trailer trucks (with two axles on the tractor and 3 axles on the trailer), the tractors always present similar characteristics (similar dimensions, and axle loads). Due to this, even when the payload in the trailer varies, the load of the first axle (the steering axle) remains always very similar, whatever the semi-trailer brand, and is generally close to 65 kN (Schmidt, Jacob, &

Domprobst, 2016). For this reason, for the modelling of the response of the pavement, it was decided to use only signals obtained for 5-axle semi-trailer trucks (T2S3), and to analyse only the strains measured under the first axle.

Therefore, for the analysis of the response of the pavement, the following sorting procedure, taking into account the type of truck, and its lateral position, has been proposed (Figure 13) :

- First, the signals corresponding to the vehicle wheels passing directly above the gages are selected, based on the information given by the geophones G1, G3 and G4, placed at different lateral positions.
- Then, the number of peaks of each signal is computed and only the signals corresponding to 5-axle semi-trailer trucks are selected.
- Finally, the shape of the signals is analysed, and only the files where the amplitude of the first peak is sufficient, compared with the noise level, are retained.

Figure 13. Strain signals sorting method.

The number of files selected after each step is presented in Figure 14. The highest number of data is recorded during the summer. The ratio of the final to the initial number of files for each month is almost constant, around 9%. The final number of selected files is about 400 files per month for the winter period and 800 files per

month for the summer period. This number of files seemed sufficient, statistically, to analyse and model the response of the pavement, on a monthly basis.

Figure 14. Number of strain signal files selected after the sorting process

4.3 Evolution of longitudinal and transverse strains

After the selection of the signals, the longitudinal and transverse strains corresponding to the first peak (first axle) have been computed for each signal. As an example, the monthly average values of the “first peak” horizontal strains measured at the bottom of the HMBC layer (at 8cm depth) and at the bottom of the HMAC layer (at 15cm depth) are presented in Figures 15 and 16.

Figure 15. Monthly average values of transverse horizontal strains under the first axle at the bottom of the HMBC layer.

Figure 16. Monthly average values of longitudinal and transverse strains under the first axle at the bottom of the HMAC layer

The results of Figure 15 show that the longitudinal strains in the HMBC layer are in extension. The strain and pavement temperature evolutions are clearly correlated: longitudinal strains increase when the temperature increases. The largest average strain (about 100 μ strain) is recorded in July 2015, with values decreasing to about 20 μ strain in January 2016. The results confirm that strain amplitudes in the bituminous layers increase significantly in the summer. The strain measurements of both gages are consistent, with a maximum difference between the two strain gages of approximately 20 μ strain in the summer.

The longitudinal and transversal strains in the HMAC layer are both in extension. Like for the HMBC layer, strain and pavement temperature evolutions are similar: strain increases with temperature. The largest strain is approximately 40 μ strain in the longitudinal direction and 70 μ strain in the transverse direction. These values have both been obtained in July 2015, when the average monthly pavement temperature reached 30°C. The longitudinal and transverse strains fall to about 20 μ strain and 30 μ strain respectively, in January 2016. The strain measurements of the two gages with the same orientation are consistent (maximum difference of about 10 μ strain)

The results obtained in the two bituminous layers indicate that the seasonal variations of the horizontal strain measurements (from winter to summer) at the bottom of the HMBC layer (binder course) are much higher than those measured at the bottom of the HMAC layer (base course). The variation of the bituminous layer moduli with temperature does not seem sufficient to explain these large variations.

Figure 17 summarizes the variations of the average monthly strain values, calculated with the procedure described above, with the average monthly temperatures measured in each pavement layer, for the two years of monitoring (2015 and 2016). The results show that:

- The variations of strains at the bottom of the bituminous layers with temperature are consistent, and present a non-linear trend. Measurement scatter increases at high temperature.
- Very similar strain variations with temperature are observed during the two years of measurements (2015 and 2016), indicating that there is no significant evolution of the material properties during this period (in particular no fatigue damage), which is not surprising, because the pavement has been reconstructed recently, in 2013.

Figure 17. Monthly average horizontal strains under the first axle at the bottom of HMAC and HMBC layers as a function of temperature, during the monitoring period.

5. Mechanical pavement modeling

5.1 Different modeling scenarios using Alizé and Viscoroute

To analyze the behavior of the instrumented pavement section, calculations have been carried out using both elastic and viscoelastic models. The elastic calculations have

been performed using the French pavement design software ALIZE (<http://media.lcpc.fr/ext/pdf/prod/alize.pdf>) whereas the viscoelastic calculations have been performed using the Viscoroute© software (Chabot, Chupin, Deloffre, & Duhamel, 2010). Viscoroute© is an analytical, multilayer pavement modelling software developed at IFSTTAR, for modelling of pavements with viscoelastic materials, under moving wheel loads. Viscoroute© is based on the viscoelastic model of Huet-Sayegh (Huet, 1965) (Sayegh, 1966), and can also take in to account linear elastic behaviour.

5.2 Modeling results

Linear elastic modelling with the Alizé Software

The objective of the modelling was to compare experimental strain signals obtained in the two instrumented pavement layers (HMAC and HMBC) at different temperatures, with the predictions of the pavement models (first elastic, then viscoelastic models).

In the French pavement design method, as in many other methods, simplified pavement layer interface conditions are considered: the interfaces are assumed either fully bonded or fully sliding. In a first step, calculations have been made with ALIZE, with these two assumptions, and with pavement layer moduli corresponding to those determined from the initial on site measurements (see §3), adjusted for temperature. The calculations have been carried for a 5 axle semi-trailer truck, with axle loads corresponding to those used for the on-site tests, and a total load of 43 tons.

Figures 18 and 19 compare the experimental and calculated horizontal strain signals obtained at the bottom of the HMBC and HMAC layers at low (15°C) and high temperature (35°C). Tables 2 and 3 also compare the maximum experimental and calculated tensile strains obtained at 15 °C and 35 °C respectively.

Table 2: Comparison of maximum measured and calculated horizontal tensile strains at the bottom of HMBC and HMAC layers at 15°C (ALIZE calculations).

	Transverse strain HMAC layer (μ strain)	Longitudinal strain HMAC layer (μ strain)	Transverse strain HMBC layer (μ strain)
Measured	40	28	35
Calculated Bonded interfaces	15	18	5
Calculated Sliding interfaces	32	30	46
Calculated 2mm thick elastic layer interface	35	36	41

Table 3: Comparison of maximum measured and calculated horizontal tensile strains at the bottom of HMBC and HMAC layers at 35°C (ALIZE calculations).

	Transverse strain HMAC layer (μ strain)	Longitudinal strain HMAC layer (μ strain)	Transverse strain HMBC layer (μ strain)
Measured	105	85	100
Calculated Bonded interfaces	65	80	23
Calculated Sliding interfaces	98	96	155
Calculated 2mm thick elastic layer interface	98	100	108

The results show that:

- When the two interfaces at the bottom of the HMBC and HMAC layers are considered bonded, the calculated strains are much lower than the measured strains, in particular for the transversal strains. This is observed both at low temperature (15 °C), and high temperature (35 °C).

- When the two pavement interfaces are considered fully debonded, the calculated horizontal strains are closer to the measured strains, but sometimes even higher than the measured strains, especially at the bottom of the HMBC layer, at both low and high temperature.
- At high temperature, the strain signals also clearly indicate a viscoelastic response of the bituminous layers. This is particularly evident for the transverse strain signals, at the bottom of both layers, which show that the strains gradually increase under the three rear axles, and return slowly to zero after the passing of the vehicle. This delayed response is typical of viscoelastic effects, and cannot be reproduced with the linear elastic model.

Due to the difficulty to predict correctly all the strain measurements with simple interface conditions (fully bonded or fully debonded interfaces), a third assumption was made with ALIZE: the interfaces were modeled as thin intermediate elastic layers (2mm thick) with a low elastic modulus. The values of elastic moduli of the interfaces were then adjusted to fit the measured strains. The values obtained were:

- 85 MPa for the HMBC /HMAC interface
- 25 MPa for the HMAC / GSB interface

The strains calculated with this third assumption are also represented on Figure 18 and Figure 19. With the thin elastic layers, a good prediction of the maximum longitudinal and transverse strains is obtained. However, with the elastic model, the shape of the strain signals, and in particular the slow return of the strains to zero cannot be accurately predicted. For this reason, it was decided to perform additional calculations with Viscoroute©.

Figure 18. Experimental and theoretical horizontal strain signals calculated using Alizé, at the bottom of the HMAC layer (1 and 2) and the HMBC layer (3) at 15°C

Figure 19. Experimental and theoretical horizontal strain signals calculated using Alizé, at the bottom of the HMAC layer (1 and 2) and the HMBC layer (3) at 35°C

Viscoelastic modelling with Viscoroute©

With Viscoroute©, the pavement is described as a multi-layer structure, and the layers are considered homogeneous and infinite in plane. Each layer can be described by a linear elastic model, or by the Huet-Sayegh viscoelastic model. The calculation is performed under a moving wheel load. The load / pavement contact area can be punctual, circular, elliptical or rectangular, and can be loaded by a uniform vertical or horizontal stress.

The Huet-Sayegh model is a linear thermo-visco-elastic model, used in France to describe the behaviour of asphalt mixes in the small strain domain. This model describes the variations of the complex modulus with frequency and temperature $E^*(\omega, \theta)$. The model is described by the following equations:

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

The parameters of the model are:

- E_0, E_∞ are limits of the complex modulus for $\omega=0$ or $\omega=\infty$;
- h, k are exponents such that $1 > h > k > 0$, related respectively to the ratio $E_{\text{imag}} / E_{\text{real}}$ when ω tends to 0 (respectively to infinity);
- δ is dimensionless constant.
- $\tau(\theta)$ is a function of the temperature θ , which has the following expression :

$$\tau(\theta) = \exp(A_0 + A_1\theta + A_2\theta^2) \quad (2)$$

In view of the results obtained with ALIZE, 3 different assumptions have been made for the interfaces at the bottom of the HMBC and HMAC layers : The interfaces have been considered fully bonded, or described by a thin layer (2mm) with elastic or viscoelastic behaviour. The characteristics of the pavement structure used for the Viscoroute© calculations are summarized in table 4. Figures 20 and 21 compare the experimental and calculated horizontal strain signals obtained at the bottom of the HMBC and HMAC layers at low temperature (15°C) and high temperature (35°C).

Table 4: Pavement structure characteristics used for the Viscoroute calculations

Material	Behavior	Lower Interface condition	Thickness (m)	E_∞ (MPa)	Poisson ratio	E_0 (MPa)	k	h	δ	A_0	A_1	A_2
VTAC	viscoelastic	bonded	0.025	19644	0.35	18.934	0.213	0.628	2.535	3.072	-0.382	0.0017
HMBC	viscoelastic	3 cases	0.06	11000	0.35	11	0.19	0.59	2.24	2.943	-0.397	0.002
HMAC	viscoelastic	3 cases	0.07	31008	0.35	21.779	0.186	0.599	2.064	5.865	-0.388	0.002
GSB	Elastic	bonded	0.08	5000	0.35	-	-	-	-	-	-	-
Sand cement	Elastic	bonded	0.3	14000	0.35	-	-	-	-	-	-	-
Soil	Elastic	bonded	0.5	150	0.35	-	-	-	-	-	-	-
bedrock	Elastic	-	Infinite	10000	0.35	-	-	-	-	-	-	-

For the viscoelastic interface, in the absence of measured parameters, typical values of Huet-Sayegh parameters obtained for a bitumen emulsion have been used in the calculations. Their values are summarized in table 5.

Table 5: Interface tack coat characteristics used for the Viscoroute calculations.

E_{∞} (MPa)	Poisson ratio	E_0 (MPa)	k	h	δ	A_0	A_1	A_2
1968.21	0.35	0	0.27242	0.88316	9.0483	-1.6296	-0.39118	0.0024648

Figure 20. Experimental horizontal strain signals and signals computed using Viscoroute, at the bottom of the HMAC layer (1 and 2) and of the HMBC layer (3) at 15°C.

Figure 21. Experimental horizontal strain signals and signals computed using Viscoroute, at the bottom of the HMAC layer (1 and 2) and of the HMBC layer (3) at 35°C.

Tables 6 and 7 also compare the maximum experimental and calculated tensile strains obtained at 15 °C and 35 °C respectively.

Table 6: Comparison of maximum measured and calculated horizontal tensile strains at the bottom of HMBC and HMAC layers at 15°C (ALIZE calculations).

	Transverse strain HMAC layer (μstrain)	Longitudinal strain HMAC layer (μstrain)	Transverse strain HMBC layer (μstrain)
Measured	40	28	35
Calculated Bonded interfaces	8	15	15
Calculated 2mm thick elastic layer interface	37.5	35	42

Calculated 2mm thick viscoelastic layer interface	41	25	35

Table 7: Comparison of maximum measured and calculated horizontal tensile strains at the bottom of HMBC and HMAC layers at 35°C (ALIZE calculations).

	Transverse strain HMAC layer (μ strain)	Longitudinal strain HMAC layer (μ strain)	Transverse strain HMBC layer (μ strain)
Measured	105	85	100
Calculated Bonded interfaces	100	55	70
Calculated 2mm thick elastic layer interface	120	86	167
Calculated 2mm thick viscoelastic layer interface	108	60	123

The results obtained with Viscoroute show that:

- For the calculations with the linear elastic interfaces, the longitudinal strains are relatively well predicted, but the predictions are less satisfactory for the transversal strains, in particular under the tridem axles.
- The calculations with the viscoelastic interfaces lead to better predictions. In particular, when the temperatures are high, the slow return of the strains to zero after loading is well reproduced with the assumption of the viscoelastic tack coat.

Modelling of interface behaviour at different temperatures.

In the different modeling scenarios with Alizé and Viscoroute, it was found that the assumption of bonded interfaces is not realistic, and leads to much lower tensile strains than the experimental results, especially at high temperatures. It was also found that the

high tensile strains can be much better predicted when the interface is described as a thin “intermediate layer” (elastic, or viscoelastic), with a lower stiffness than the HMBC and HMAC layers. Comparing the calculations made for 15 °C and 35 °C, it was also found that the stiffness of this “intermediate layer” decreases when temperature increases.

All these results suggest that some sliding occurs at the interfaces, and that their degree of bonding changes with temperature. This can probably be explained by the fact that the tack coat (bitumen emulsion) is very sensitive to temperature, and presents a low stiffness at high temperature. This observation is consistent with the results of laboratory studies, based on interface shear tests, such as those performed by (Bae, Mohammad, Elseifi, Button, & Patel, 2010), which also confirm the strong influence of temperature on interface resistance.

Modelling of interface behaviour with Alizé

In order to characterize better the variation of interface stiffness with temperature, detailed calculations have been carried out, first with the linear elastic software ALIZE.

For these calculations, as explained in §4.2, we used only the first peak of the strain signals (corresponding to the first axle), because the load of the front axle can be estimated (it is generally close to 65 kN, for 5 axle semi-trailers). In the calculations, the load was modelled as a single wheel loaded at 32.5 kN (representing half of the first axle). A loading speed of 70 km/h (corresponding to a frequency of about 10 Hz) was chosen for modeling. The moduli of the different pavement materials were those corresponding to table 1, but adjusted to the real average monthly measured temperatures. The modeling results were then compared with the monthly average strain values measured on site. Again, the calculations were performed with several interface conditions: fully bonded, fully debonded, and interfaces represented by a thin elastic

layer; in this last case, the modulus of each interface layer was adjusted, for each monthly average temperature, to fit the in-situ measurements.

Figure 22 presents the results of these calculations. It compares the maximum horizontal strains measured at the bottom of the bituminous layers, for different average temperatures, and those calculated using Alizé with the different interface conditions.

Figure 22. Comparison between the experimental maximum horizontal strains and those calculated using Alizé at the bottom of the HMAC layer (1 and 2) and of the HMBC layer (3) for different interface conditions.

The results show that the strain values calculated with bonded interfaces are lower than the experimental ones. This approach based on the classical assumption of the French design method, clearly underestimates horizontal strains, in particular transverse strains, at the bottom of the HMBC and HMAC layers. The strains calculated with the other assumptions (fully debonded interfaces and elastic interface layers) are

similar, and close to the measured values. The strains vary exponentially with temperature, which is consistent with the on-site measurements.

The moduli obtained at different temperatures for the elastic interface layers are presented in Figure 23. The moduli of both interface layers are low (typically between 20 and 100 MPa), and decrease when the temperature increases. The decrease is particularly important between 25°C and 30°C. These results are interesting because they suggest that even in relatively new pavements, the layer interfaces are not perfectly bonded. Relative sliding between the layers can occur, especially at high temperatures, when the tack coat stiffness at the interface is low. This reduced bonding between the pavement layers generates an increase in the tensile strains at the bottom of the upper pavement layers (here, HMBC and HMAC layers), which may affect their fatigue life.

Figure 23. Alizé-predicted interface layer moduli between HMBC/HMAC and HMAC/GSB layers

Viscoroute© modeling results

Similar calculations, with different interface conditions, and different pavement temperatures, have been performed with Viscoroute©, using the same material

characteristics as in table 4. Again three conditions have been used for the modelling of the interfaces: fully bonded interfaces, thin elastic layers, and thin viscoelastic layers. Figure 24 presents the measured and calculated horizontal strains at the bottom of the bituminous layers for the different scenarios. As with Alizé, the Viscoroute© calculations seriously underestimate horizontal strains in the case of bonded interfaces. The best predictions are achieved when the pavement interfaces are described as thin viscoelastic layers.

Figure 24. Comparison between measured maximum horizontal strains at the bottom of the HMAC and HMBC layers and those calculated using Viscoroute, for different interface conditions.

Figure 25 presents the moduli obtained with the assumption of a linear elastic interface, at different temperatures. Here again, the tack coat moduli are low and decrease when the temperature increases. Like with ALIZE, a significant drop in the modulus values is observed between 25°C and 30°C. The results obtained using

Viscoroute© confirm those obtained with ALIZE. The low moduli of the interface layers prove that the degree of bonding between the pavement layers is low, especially at high temperatures. The modulus of the interface between the HMBC and HMAC layers is here slightly higher than in the ALIZE calculations (80 MPa at 30°C, instead of 40 MPa), however, the general trend is the same: the moduli of the thin interface layers are much lower than those of the HMAC and HMBC bituminous materials. (approximately between 20 and 160 MPa for the different conditions)

Figure 25. Visoroute-predicted tack coat moduli between HMBC/HMAC and HMAC/GSB layers

Conclusion

This paper presents results of the monitoring of an instrumented test section located on a recently reconstructed French motorway. The slow lane of the section is instrumented with strain gages, temperature probes and geophones. The acquisition and the wireless transfer of the measurements are performed using the PEGASE system, developed at IFSTTAR. Large amounts of data are continuously recorded since 18 months under real traffic. These measurements made under real traffic are affected by the variability of the

traffic loads (type of trucks, axle loads, truck lateral positions on the road). To be able to analyse the mechanical response of the pavement, a sorting procedure has been proposed, to reduce this variability, while also limiting the quantity of data. This procedure includes two steps:

- The first step consists in selecting only signals corresponding to 5-axle semi-trailer trucks, and in using geophones placed at different transversal positions in the wheel path to select only trucks whose wheels are centered above the gages.
- The second step consists in treating only the signals measured under the front axle of the semi-trailers, taking advantage of the fact that the load on this front axle is relatively constant (and close to 65 kN), whatever the total weight of the truck.

After selecting the appropriate signals, the strain variations at the bottom of the binder course (HMBC) and at the bottom of the base course (HMAC) have been analyzed. The results show a large increase of strains with temperature in the two layers, with maximum tensile strain levels at high temperature (35 °C) reaching 160 μ strain. They also show that transverse strains are significantly higher than longitudinal strains. A clearly viscoelastic response is also observed at high temperatures, with strain accumulations under successive loads, and delayed response to loading.

Calculations have been performed, in order to evaluate the mechanical properties of the different pavement layers, first with a linear elastic model (ALIZE software), and then with a viscoelastic model (Viscoroute software). To try to explain the high tensile strains measured at the bottom of the HMBC and HMAC layers, different interface conditions have been considered in the calculations : fully bonded,

fully debonded, and interface described as a thin layer (2 mm), with mechanical properties similar to those of a tack coat. It was concluded that :

- The viscoelastic model describes better the shape of the strain signals.
- With bonded interfaces, the measured tensile strains were largely underestimated, especially at high temperatures.
- The best results were obtained with the interfaces described by a thin elastic layer, with a low modulus, varying with temperature (for the elastic model) and by a thin viscoelastic layer (for the viscoelastic model) .

These results indicate that even in relatively new pavements, layer interfaces are not necessarily perfectly bonded, as supposed in the French design method. Relative sliding can occur between the layers, especially at high temperature. This Sliding may lead to an increase of tensile stresses at the bottom of bituminous pavement layers, and thus reduce their fatigue life. This sliding of pavement layer interfaces has also been observed in full scale tests on the IFSTTAR accelerated pavement testing facility, and in laboratory studies

In conclusion, the monitoring of this experimental pavement has shown that to predict strain levels in pavement layers, under different temperature conditions, and pavement damage mechanisms, it is important to take into account viscoelastic behaviour of bituminous materials, and to describe accurately the behaviour of pavement layer interfaces. With multi-layer linear elastic or viscoelastic models, describing the interfaces as thin layers, with temperature-dependent elastic or visco-elastic properties, represents a possible solution.

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