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Evaluation of Pavement Damage through the Analysis of Asphalt Layer Modulus and Strain Evolutions during an Accelerated Pavement Test

Xuan Quy Le^{1,2}, Mai Lan Nguyen¹, Pierre Hornych¹, Quang Tuan Nguyen²

¹ Gustave Eiffel University, Nantes Campus, France

² University of Transport and Communications, Hanoi, Vietnam

xuan-quy.le@univ-eiffel.fr

Abstract. Accelerated Pavement Tests (APT) have been proved as a reliable methodology to evaluate pavement performance within a short period. However, the evolution of damage of such full-scale pavements, which are similar to actual pavements, is still not fully understood. In this paper, deflection measurements, asphalt strains and surface cracking measurements are used to evaluate the evolution of pavement damage with traffic, during an APT experiment. The combination of these three indicators leads to a better understanding of the damage mechanisms of the pavement.

Keywords: Accelerated Pavement Test, Asphalt Pavement, Damage Analysis, Falling Weight Deflectometer, Strain, Temperature Correction.

1 Introduction

The evaluation of pavement damage has been a major topic of in-service pavement assessment. Thanks to APT, the full-scale performance and deterioration of pavements can be monitored by carrying out different measurements with the repeated application of heavy traffic loads [1–4]. The Nantes Campus of Gustave Eiffel University (UGE) has been operating since 1982 a heavy traffic simulator, namely the fatigue carousel, designed to test full-scale pavement structures up to failure under controlled loading conditions. This facility can apply up to 500 000 heavy vehicle loads per month [5, 6]. In this study, a full-scale experiment on a low traffic pavement is used to analyze and compare different methods, of evaluation of pavement damage under traffic: deflection measurements, asphalt strain measurements and evolution of surface cracking.

2 Presentation of the full scale test

The full-scale test presented in this paper was carried out from 28th of May 2018 to 8th of February 2019 on six different pavement sections to evaluate the in situ performance

of the reinforcement on their lifetime. However due to limited space, only results obtained on one section are presented in this paper. The 22m-long pavement structure consisted of two asphalt layers, with a total thickness of 11cm, an unbound granular subbase (30cm thick) and a sandy subgrade, with a total thickness of 260cm. A total of 2.2 million load cycles were applied, with the 65kN French standard dual-wheel load. The temperature in the asphalt layers (at 6cm-depth) was recorded continuously, every ten minutes, by a temperature probe. To monitor pavement performance, three types of tests were performed during the APT: (1) FWD tests, carried out on the pavement surface before the start of loading, and after 0.5, 0.75, 1 and 2.2 million load cycles; (2) Longitudinal strain measurements, at the bottom of the asphalt layers. These measurements were made using TML strain gauges (model KM-100A). Two longitudinal strain gauges, L1 and L3, were placed at the bottom of the asphalt layers at two different longitudinal positions; (3) Distress survey of surface cracks.

3 Pavement damage evaluation from FWD tests

3.1 Backcalculation of asphalt layer moduli

The FWD measurements made at different stages of the experiment were used to back-calculate pavement layer moduli, using the Alizé-LCPC pavement design software, based on a multi-layer linear elastic model. The actual thicknesses of asphalt layers, obtained by levelling measurements during pavement construction, were used in these calculations. Due to space limitations, only results from FWD tests made at one position on the pavement surface, above strain gauge L1, are taken into account.

3.2 Evaluation of pavement damage from asphalt layer moduli

Following the back-calculations, the variation of asphalt layer moduli with the number of load cycles was used to evaluate pavement damage [11]. For that purpose, a damage parameter noted D_E^T (Eq. (1)), was introduced, to take into account the decrease of asphalt layer moduli with loading, at a fixed temperature.

$$D_E^T = \frac{E_{N_0}^T - E_{N_i}^T}{E_{N_0}^T} \quad (1)$$

Where: D_E^T is the damage ratio of the asphalt layer at temperature T; $E_{N_0}^T$ and $E_{N_i}^T$ are respectively asphalt layer moduli at load cycle zero (N0) and load cycle N_i , and at temperature T.

Due to low and intermediate temperature conditions during the experiment (from 12°C to 19°C), it was assumed that the damage ratio D_E^T is the same for different tested temperatures [7]. The calculation of this damage ratio for a given temperature T requires determining the initial layer modulus $E_{N_0}^T$ at the same temperature. As the initial FWD tests were performed at 15°C, only a modulus at 15°C ($E_{N_0}^{15^\circ}$) could be determined exper-

imentally. Therefore, to calculate the initial moduli for other test temperatures, a correction was applied, based on laboratory complex modulus tests. The results of these tests were fitted using the Huet-Sayegh viscoelastic model [8, 9], and the model was used to calculate moduli at different temperatures.

The calculated initial moduli, at different temperatures, and the corresponding damage ratios D_E^T at different numbers of load cycles are presented in Table 1. The calculated damage attains 73% at the end of the experiment.

Table 1. Asphalt layer moduli and damage ratios at different numbers of load cycles.

Loading cycles	Asphalt layer modulus at temperature T (Mpa)				Damage ratio D_E^T
	12°C	14°C	15°C	19°C	
0	13609	12537	11711	9482	0%
500 000	-	-	-	9103	4.0%
750 000	-	8324	-	-	33.6%
1 000 000	7113	-	-	-	47.7%
2 200 000	-	3389	-	-	73.0%

4 Pavement damage evaluation from strain data analysis

4.1 Comparison of measured and calculated strains in the asphalt layer

As mentioned above, strain levels at the bottom of the asphalt layers were measured using two longitudinal strain gages, L1 and L3. The strains measured during the first part of the experiment, where the asphalt layers presented no damage (up to 600 000 cycles), are plotted in Fig. 1, in function of the measured temperature.

Calculations were made with the Alizé-LCPC software, to compare the measured strains with theoretical values. For these calculations, it was necessary to take into account the actual depth of the gauges in the asphalt layer, which can vary slightly, due to the installation process. For that purpose, strains were calculated using Alizé-LCPC, for four different depth levels (0, 0.5, 1.0, and 1.5 cm above the asphalt layer interface), and compared with the experimental values.

Table 2. Comparison of measured and calculated strains, to determine the actual depth of the gauges in the asphalt layer.

Asphalt layer thickness (cm)	Strain gauge	ϵ	ϵ	ϵ	ϵ	ϵ
		measured at 20°C ($\mu\text{m/m}$)	calculated for h = 0cm ($\mu\text{m/m}$)	calculated for h = 0.5cm ($\mu\text{m/m}$)	calculated for h = 1.0cm ($\mu\text{m/m}$)	calculated for h = 1.5cm ($\mu\text{m/m}$)
11.5	L1	138.26	187.5	169.0	151.3	134.5
11.2	L3	171.28	192.7	173.2	154.6	136.6

Table 2 compares the measured and calculated strains, for a temperature of 20°C. The results show that for gauge L1, the best match is obtained for a level of the gauge $h = 1.5\text{cm}$ above the layer interface. For gauge L3, the best match is obtained for a level $h = 0.5\text{cm}$.

After defining the most probable positions of the gauges, calculations were carried out with Alizé-LCPC, considering four different conditions of the asphalt layers interface: bonded, semi-bonded, fully de-bonded and partially bonded. In this last case, the interface was modelled as a thin layer (2mm thick) of bitumen [10], with a complex modulus representative of a 30/50 grade pure bitumen. The strains calculated with these four interface conditions are present in Fig. 1. The results show that at low and intermediate temperatures (less than 26°C for strain gauge L1 (Fig. 1a) and less than 22°C for strain gauge L3 (Fig. 1b)), the measured strains are close to those corresponding to the fully bonded condition. However, at higher temperatures (30°C at position L1 and 25-30°C at position L3), the measured strains are lower than those predicted with a fully bonded interface, and are closer to those obtained with partially bonded conditions. This means that at high temperature, some sliding occurs at the interface, leading to a redistribution of strains in the two asphalt layers. This interesting result is in accordance with other research on the influence of layer interface conditions on pavement behavior, in particular work of the RILEM TC 272-PIM.

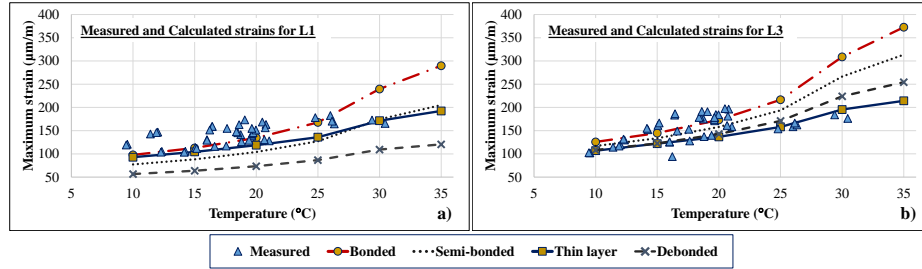


Fig. 1. Calculated and measured longitudinal strain values at the bottom of the asphalt layers, as a function of temperature: a) gauge L1, b) gauge L3.

4.2 Evaluation of pavement damage from strain evolution

In order to evaluate asphalt layer damage from strain data, a damage parameter D_{ε}^T was introduced, to describe the increase of strains with traffic (Eq. (2)).

$$D_{\varepsilon}^T = \frac{\varepsilon_{Ni}^T - \varepsilon_{N0}^T}{\varepsilon_{Ni}^T} \quad (2)$$

Where: D_{ε}^T is a damage ratio considering strain at the bottom of the asphalt layer at temperature T; ε_{N0}^T and ε_{Ni}^T are respectively strains measured at the start of the APT (at cycle N0) and at load cycle N_i , at temperature T.

Calculated strains were also determined using Alizé-LCPC, based on the backcalculated moduli of asphalt layers obtained from FWD tests. To illustrate this approach, only measurements of strain gauge L1 are considered.

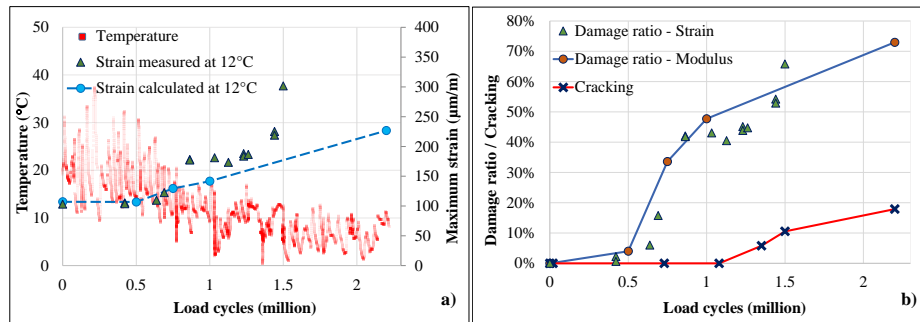


Fig. 2. Evolutions of temperature, strains (a) damage ratio and surface cracking (b) versus number of load cycles.

Fig. 2a presents the evolutions of asphalt layer temperatures, and experimental and calculated strains with the number of loading cycles. As the strains were all measured at a temperature close to 12°C, the calculations were done for this temperature. Fig. 2a shows that the calculated strains are very similar to the experimental values up to nearly 0.75 million cycles. After 0.75 million cycles, and up to 1.5 million cycles, the measured strains increase much more than the calculated values. This can be explained by the fact that the experimental values represent local measurements, at the position of the strain gauge, where cracks probably appeared [7], whereas the calculated strains, determined from back-calculated moduli of different layers, represent global values.

The damage ratio D_{ε}^T is plotted in Fig. 2b and compared with D_E^T (see Eq. (1)). The values of D_{ε}^T follow very well the evolution of D_E^T , up to 1 million load cycles. After 1.1 million cycles, D_{ε}^T starts to increase more rapidly. As already mentioned, this can be explained by the development of local cracks at the strain gauge position. Fig. 2b also presents the evolution of surface cracking of the pavement with the level of traffic. The percentage of cracking on Fig. 2b corresponds to the percentage of the length of the test section affected by cracks.

By comparing the three damage indicators presented on Fig. 2, it can be concluded that:

- Up to 0.6 million cycles, the structure presents practically no damage: there is no significant evolution of strains or modulus, and no surface cracking.
- Between 0.6 million and 1.1 million load cycles, the two damage indicators, based on strain and modulus give similar results, and indicate a significant increase of damage, but no surface cracking is observed. This second phase probably corresponds to a phase of damage initiation, where micro-cracks started to develop at the bottom of the asphalt layer but did not propagate to the pavement surface [5]. After 1.1 million cycles, the level of damage is close to 50%.

- In the last part of the experiment, after 1.1 million cycles, cracks start to propagate to the pavement surface, and this is also associated with a rapid increase of the strain-based damage ratio. The increase of the modulus-based parameter D_E^T is more gradual. It can be noted that the onset of surface cracks corresponds to a damage level of about 50%. The same observation is made by Mateos [11].

5 Conclusions

Different methods of evaluation of pavement damage, in a full-scale flexible pavement, based on the evolution of asphalt layer modulus, asphalt layer strains and surface cracking were analyzed and compared. By combining these indicators, it is possible to better understand the damage mechanisms. In a first phase, up to about 1.1 million load cycles, no cracks were observed on the pavement surface; during this phase, damage ratios based on measured strains, and on measured asphalt layer moduli gave very similar results. After 1.1 million load cycles, corresponding to a threshold level of damage of about 50%, cracks started to propagate to the pavement surface, and this was also detected by an increase of the strain-based damage indicator.

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