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Evaluation of interface bonding condition on mechanical responses of full-scale asphalt pavements with and without grid reinforcement

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ABSTRACT: The construction and maintenance of road infrastructure with a view to sustainable development must nowadays integrate the problems of a future scarcity of raw materials such as petroleum products. Glass fiber grids are an efficient and economical solution for reinforcing asphalt pavements in order to increase their service life and reduce crack propagation. In this context, the French National Research Agency-funded SolDuGri project aims to develop more rational and more mechanical approaches for the evaluation of grids, and for the design of reinforced pavements. An accelerated full-scale test (APT) of experimental pavement structures without and with reinforcement using glass fiber grids was carried out on the fatigue carousel at Nantes Campus of Gustave Eiffel University. During the test, the mechanical behavior of the pavements was monitored using sensors installed in the pavement layers and surface measurements. This paper focuses on analyzing the influence of interface bonding condition between the asphalt layers on the pavements behavior in non-damaged condition. Horizontal strains measured at the bottom of the asphalt layers and surface deflections showed clearly that the reinforced pavement has lower interface bond level than the reference section. Moreover, inverse analysis using FWD measurements and a horizontal shear stiffness parameter allows quantifying field conditions of the asphalt layer interface bonding in both unreinforced and reinforced structures. Associated laboratory interface bonding tests made on specimens extracted from the full-scale pavements and fabricated in laboratory attest the aforementioned impact of the presence of glass fiber grids.

Keywords: Asphalt pavement, glass fiber grid, interface bond, structural behavior, APT

1 INTRODUCTION

Road networks play a crucial role in guaranteeing the mobility of goods and people. As a result, evaluating the structural condition of these networks is essential for optimizing their design life. In many countries, generally more than 90 % of the network consists of asphalt pavements, which are multi-layer structures. When there is more than one asphalt layer, one of the key elements for ensuring a good performance of the pavement is the bond between the asphalt layers. Evaluating and improving the bond between pavement layers is among the principal objectives in many national and international studies (Raab et al. 2009, Canestrari et al. 2013, Zofka et al. 2015, Petit et al. 2018, DVDC, RILEM TC272-PIM, among others). However, these studies are mainly focused on laboratory evaluations. Until now, few studies have investigated this issue at structural level on real-scale pavement (Chun et al. 2015, Nguyen et al. 2016, Grellet 2018). One of the difficulties, at structural level, is the variability of different parameters, such as material properties, loading conditions, environmental factors. In that case, appropriate monitoring methods need to be employed.

Furthermore, for pavements reinforced with glass fiber grid to increase their service life and reduce crack propagation, the presence of such interlayer system will have a significant effect on the pavement behavior. This is due not only to the reinforcing characteristics of the grid (high Young's modulus and high tensile strength), but also to the bonding condition at the pavement layers interface where it is placed, generally between the asphalt layers. While the first aspect is measurable directly from the grid, the second one still needs further investigations, for a better understanding of its impacts. For the last one, several recent studies have been conducted by testing on reinforced material specimens in laboratory (Gharbi et al. 2017, Freire et al. 2018, Canestrari et al. 2018) and on actual full-scale pavement structures as well (Nguyen et al. 2013, Graziani et al. 2014). However, the aforementioned difficulties of the above studies at structural level were effectively revealed.

The objective of the present study is to evaluate the influence of the interface bonding condition between the asphalt layers on the mechanical responses of full-scale pavements with and without glass fiber grid reinforcement (Figure 1). It is based on the analysis of strain measurements in the asphalt layers with well-characterized material properties under well-controlled load characteristics (level, position and speed) and of falling weight deflectometer (FWD) deflection measurements on the pavement surface, in non-damaged condition of the evaluated pavements. It is noteworthy that the fatigue behavior and design of glass grid reinforced pavements are discussed in another recent work (Nguyen et al. 2021).



Figure 1. Full-scale pavement sections with and without glass fiber grid reinforcement before application of the overlay during the construction.

The paper first presents the tested pavement structures and materials tested in the APT experiment as well as test methods. A synthetic theoretical background of a mechanical indicator for consideration of the layers interface bonding condition and its implementation in the multi-layer elastic pavement design program Alizé are then introduced. Main results of horizontal strains and FWD deflections measured in the asphalt layers and on the pavements surface respectively and their numerical simulations using Alizé with the special implementation option for interface bond condition are presented and discussed. An associated laboratory test campaign of interface bond strength measurements on specimens extracted from the full-scale pavements and fabricated in laboratory provides additional results in accordance with the observed structural responses.

2 GENERAL CHARACTERISTICS OF PAVEMENT STRUCTURES AND TEST METHODS

2.1 Presentation of pavement structures, asphalt material and experimental program

The two experimental pavement sections (Figure 1 and Figure 2) were constructed from 25th to 29th September 2017 on the carrousel test track in Nantes Campus, Gustave Eiffel University (UGE). Those sections, noted S1 and S2, were placed at the radius of 19 m, corresponding to a track of 120 m length and 3 m width, and were instrumented with strain gauges and temperature probes. Section S1 was considered as the reference section with conventional pavement structure, which was designed by the French pavement design method (NF P98-086 standard), including two asphalt (AC) layers of targeted thickness of 6 cm and 5 cm for surface and base layers respectively, over an unbound granular (UGM) subbase of 30 cm and a 260 cm-thick sandy subgrade. The asphalt material was a hot mix asphalt (HMA) with the formulation of a standard semi-coarse asphalt concrete (SCAC-10 Class-3 based on EN 13108-1 standard). Its complex modulus was determined according to EN 12697-26 standard. Section S2 had the same structure and materials as section S1 but was reinforced with a glass fiber grid (associated with a thin non-woven polyester layer of no more than 20 g/m²) of 100 kN/m in tensile strength at the interface between the two asphalt layers (see Figure 2). A tack coat layer of classical cationic rapid setting bitumen emulsion (according to EN 13808-2013 standard) with rates of application of 350 g/m² and 700 g/m² respectively (in residual bitumen) was used for reference and reinforced sections. These applications rates have been chosen because they led to the best performance according to the results from an associated laboratory study where tests at different application rates have been performed (Nguyen et al. 2021).

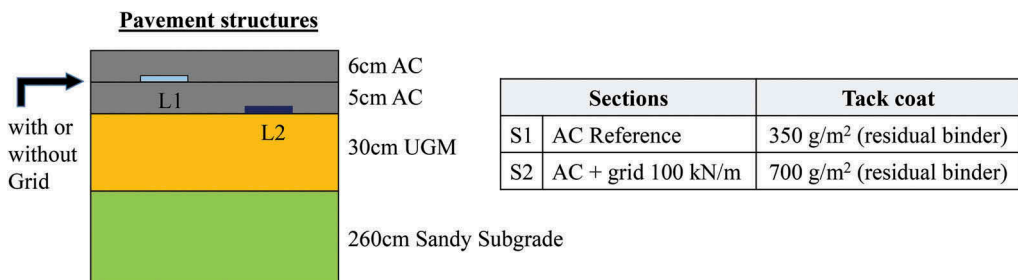


Figure 2. Design of the evaluated pavement structures.

The full-scale experiment, presented in this study, was carried out on the carrousel test track from 28th May 2018 to 8th February 2019. A traffic simulator with four loading arms was operated to produce real traffic with dual-wheel configurations. The test program was as follows: the

first 2 000 cycles was performed with 45 kN loads, the 3 000 following cycles were performed at 55 kN load level, and then loads of 65 kN were applied. At the end of the experiment, a total of 1 850 000 cycles were applied. In this paper, the study only focuses on data obtained during the first 10 000 cycles where it is assumed that no damage happened to the pavement structure.

2.2 Monitoring methods

Pavement instrumentation

To follow pavement responses during the full-scale experiment, each section was instrumented with asphalt strain gauges (L1, L2), model TML-100HAS, placed at the bottom of the asphalt layers and a temperature probe (TP) placed at a depth of 6 cm in the asphalt layers (see Figure 2). Temperature data was recorded every 10 minutes.

FWD measurements

The FWD measurements were performed on 5th April 2018, before the start of loading, with a spacing of 2 m between the measurement points on the test track. The equipment used is a Super Heavy Weight trailer mounted Deflectometer (SHWD) inducing a load of 65 kN on a circular load plate (30 cm in diameter). A series of geophones located at positions of 0; 0.3; 0.4; 0.6; 0.9; 1.2; 1.5; 1.8; 2.1m from the center of the plate, recorded deflection responses to the load. The average temperature during the tests was 15°C at a depth of 6 cm in the asphalt layers.

3 THEORETICAL BACKGROUND AND IMPLEMENTATION IN NUMERICAL SIMULATIONS

In order to evaluate the bonding level of the interface between layers, Goodman (Goodman 1986) has introduced a parameter K_s (equation (1)), which is the shear or bonding stiffness of the interface, to describe the interfacial response to pavement loading.

$$K_s = \frac{\tau}{\Delta u} \quad (1)$$

where, τ is the shear stress and Δu is the relative horizontal displacement at the interface between layers induced by the pavement loading.

This formula has been implemented in the Alizé pavement design software (based on the multi-layer linear elastic model of Burmister (1943)), in considering the above linear relationship between the relative horizontal displacement of the two asphalt layers on either side of the interface and the shear stress, to simulate the bonding conditions. For these numerical simulations, the value of the elastic modulus of the asphalt layer was determined from results of laboratory complex modulus tests on asphalt material extracted from the pavement. The asphalt temperature was the one recorded in the pavement and the loading frequency was determined from the loading time of the measured strain signal according to (Barksdale 1971).

4 EVALUATION OF INTERFACE BONDING CONDITIONS IN THE FULL-SCALE PAVEMENTS

4.1 Evidence from strain measurements

In this section, the longitudinal strain responses measured from the full-scale test and modelled with two interfacial bonding conditions (bonded and debonded) in the multi-layer linear elastic model (Alizé) are compared to evaluate in-place bonding level between asphalt layers.

Figure 3 and Figure 4 present the measured and modelled strain signals at the respective bottom of the surface and base asphalt layers, for the two pavement sections. The experimental signals were collected at around 5 600 cycles under the 65 kN load, a traffic speed of

57 km/h and asphalt temperature of 20°C. These loading conditions were also used for the simulations. The figures show a strong influence of the level of bonding on the strain signals at the bottom of the surface and base asphalt layers. On section S1 (without grid), the strain signals calculated with a bonded condition are in good agreement with the experimental measurements. On section S2 (with grid), however, high tensile strains are measured at the bottom of the surface layer, and the values are close to the predictions obtained with the model with debonded interface. This indicates a poor interlayer bond on section S2, leading to tension at the bottom of the surface asphalt layer, and potentially to fatigue of the surface layer.

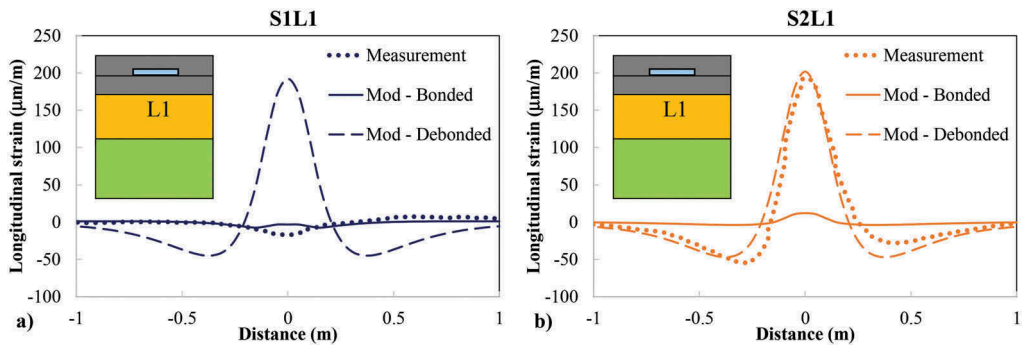


Figure 3. Comparison of measured longitudinal strain signals at the bottom of the surface asphalt layer with Alizé simulations (with bonded and debonded interfaces) in a) Section S1 and b) Section S2, after 5 600 cycles (Load level of 65 kN, traffic speed of 57 km/h, asphalt temperature of 20°C).

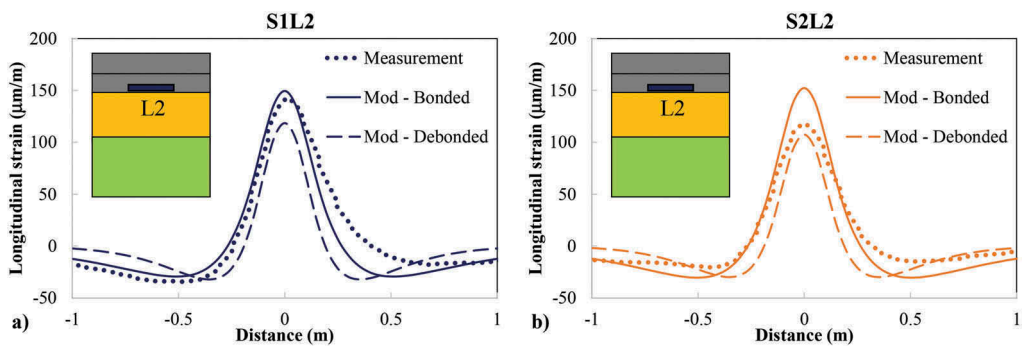


Figure 4. Comparison of measured longitudinal strain signals at the bottom of the base asphalt layer with Alizé simulations (with bonded and debonded interfaces) in a) Section S1 and b) Section S2, after 5 600 cycles (Load level of 65 kN, traffic speed of 57 km/h, asphalt temperature of 20°C).

To observe the evolution of the bonding condition with temperature, the maximum longitudinal strains obtained during the first 10 000 load applications were compared with the simulations with two interface bonding conditions (bonded and debonded) with average measured thicknesses of the two asphalt layers of the two sections (6.4 cm and 4.8 cm respectively for the surface and base layers), for a range of asphalt temperatures, for a 65 kN dual-wheel load. As mentioned in section 2.1, the load level was increased at the beginning of the full-scale experiment: the first 2 000 cycles were performed at 45 kN, the following 3 000 cycles at 55 kN load level, and then the remaining cycles at 65 kN. For that reason, the strain values were

normalized with respect to the load level, according to equation (2), assuming a linear elastic response of the pavement.

$$\varepsilon_t^{normalized} = \varepsilon_t \frac{F_{ref}}{F_{exp}} \quad (2)$$

where, $\varepsilon_t^{normalized}$ can be obtained from the experimental strains ε_t , the reference load ($F_{ref} = 65$ kN), and the applied load ($F_{exp} = 45, 55, \text{ or } 65$ kN).

The normalized strain data was then plotted in Figure 5. As can be seen from that figure, for section S1, the measured strains correspond well with the modelling results with a bonded interface condition, both for the surface layer and for the base layer, up to a temperature of about 25°C. For temperatures higher than 25°C, the strains in the base layer decrease and get closer to the curve corresponding to the debonded condition, indicating a change of bonding level. This evolution is probably due to the sensitivity of the interlayer (bitumen) to temperature. For section S2, the measured strains are close to the curve corresponding to a debonded interface, for both layers and for all temperature levels, confirming a poor bonding of the interface with grid.

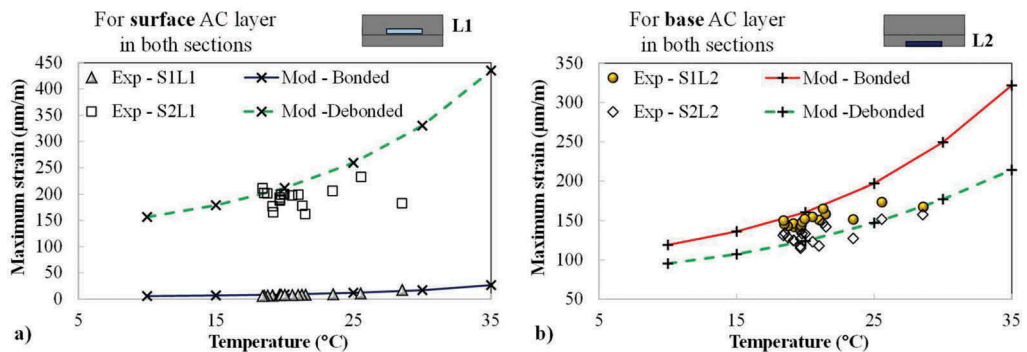


Figure 5. Comparison of measured and calculated maximum longitudinal strains at the bottom of the a) surface and b) base asphalt layers with bonded and debonded interfaces, for different temperatures.

4.2 Quantitative evaluation based on the analysis of FWD measurements

In this section, both back-calculation and forward-calculation procedures were employed to verify the bonding condition of the asphalt layer interface, using the multi-layer linear elastic model of the Alizé software. In the back-calculation procedure, the two asphalt layers, in both reinforced and unreinforced sections, were assumed as a single and homogenous layer characterized by an equivalent modulus.

As mentioned in section 2.2, the FWD measurements were carried out every 2 meters along the test track. Figure 6a shows all the deflection basins measured in each section and their corresponding characteristic basins (defined as the real basin which are closest to the average basin of the section). The actual layer thicknesses (obtained during the construction by leveling measurements) were taken into account in the backcalculation process, to improve the accuracy of the calculations. The average values of backcalculated layer moduli, and corresponding asphalt layer thicknesses are presented in Table 1. It can clearly be seen that, with the same pavement structure and materials, the “equivalent” modulus of the two asphalt layers is about 38% lower on the reinforced section (S2), mostly due to the asphalt interlayer system. In other words, the lower bonding level on section S2 leads to a decrease of the “equivalent” asphalt layer modulus.

Table 1. Average backcalculated layer moduli and average layer thickness.

Section		1	2
Asphalt layer	Modulus (MPa)	11 784	7 299
	Thickness (cm)	11.3	11.1
UGM layer	Modulus (MPa)	176.8	176.3
	Thickness (cm)	30	30
Soil layer	Modulus (MPa)	169.5	170.3
	Thickness (cm)	260	260

To precise the bonding level of the asphalt layer interface, forward-calculations were performed using the Alizé software. The calculations were performed with average actual thicknesses of the two asphalt layers (6.4 cm and 4.8 cm respectively for the surface and base layers) in both sections. The asphalt layer moduli were determined from laboratory test results, while the moduli of the granular layer and of the subgrade were respectively 177 MPa and 170 MPa (corresponding to average backcalculated values). In Figure 6b, the deflection basins modelled for two bonding conditions (bonded and debonded) are compared with the experimental characteristic basins. These figures indicate that deflection basins in section S1 correspond to a well bonded interface, whereas those in section S2 correspond to a poor bonding condition. These findings confirm the observations made in section 4.1.

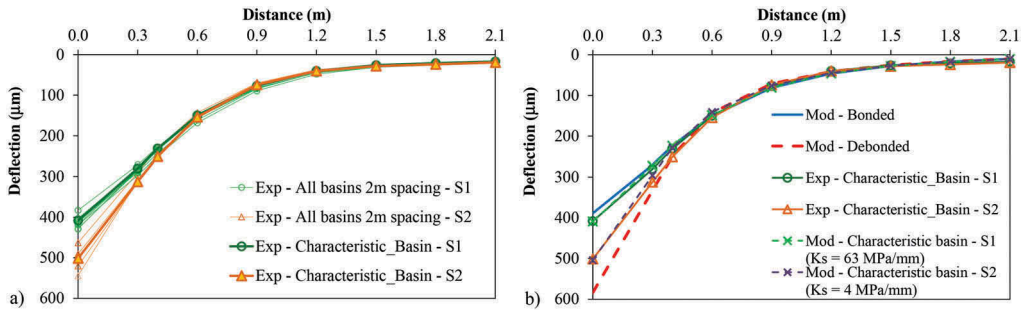


Figure 6. FWD deflections at the asphalt temperature of 15°C: a) All measurements in sections S1 and S2 and their corresponding characteristic basins; b) Characteristic basins measured in S1 and S2 and their modellings (with experimentally fitted K_s values) and fully bonded and debonded conditions.

To quantify the asphalt interfacial bonding level, the bonding stiffness K_s , as mentioned in section 3, was introduced in the calculations with Alizé. The calculations were performed with average measured thicknesses of the two asphalt layers (6.4 cm and 4.8 cm respectively for the surface and base layers). The asphalt layer moduli were determined from laboratory test results, while the moduli of the granular layer and of the subgrade were respectively 177 MPa and 170 MPa (corresponding to average backcalculated values). A trial-and-error procedure was then applied to match the modelled basins to the experimental characteristic basins in sections S1 and S2 as displayed in Figure 6b. In this figure, bonding stiffness values K_s of 63 MPa/mm and 4 MPa/mm were obtained for section S1 and section S2, respectively. These values also indicate a much better interlayer bonding condition on section S1. The K_s value on section S2 is less than 10 MPa/mm, indicating poor bonding according to the criterion proposed in several previous studies (Bachar et al. 1999, Tu et al. 2020, Roussel et al. 2020).

With the same values of K_s , good predictions were also obtained for the longitudinal strain signals in the two experimental sections. Due to the limited length of the paper, the details of these result are not presented.

5 ASSOCIATED LABORATORY TEST OF INTERFACE BOND STRENGTH

Additional results of laboratory tests, performed to evaluate the interface bond strength on double-layered specimens, are presented in this section. For this study, the direct tension bonding (DTB) test (Figure 7) developed at the research center of Colas was used. The initial double-layered specimen (rectangular or cylindrical) had sufficient dimensions to drill a 100mm diameter core. A core drill was used to make a circular groove, going 5 mm deeper than the layer interface. A fixing cap was glued to the top of the created cylindrical specimen. A monotonic tensile loading, at a rate of 200 N/s, was then applied to the cylindrical specimen, at a constant temperature (20°C in this study), until the specimen failed.

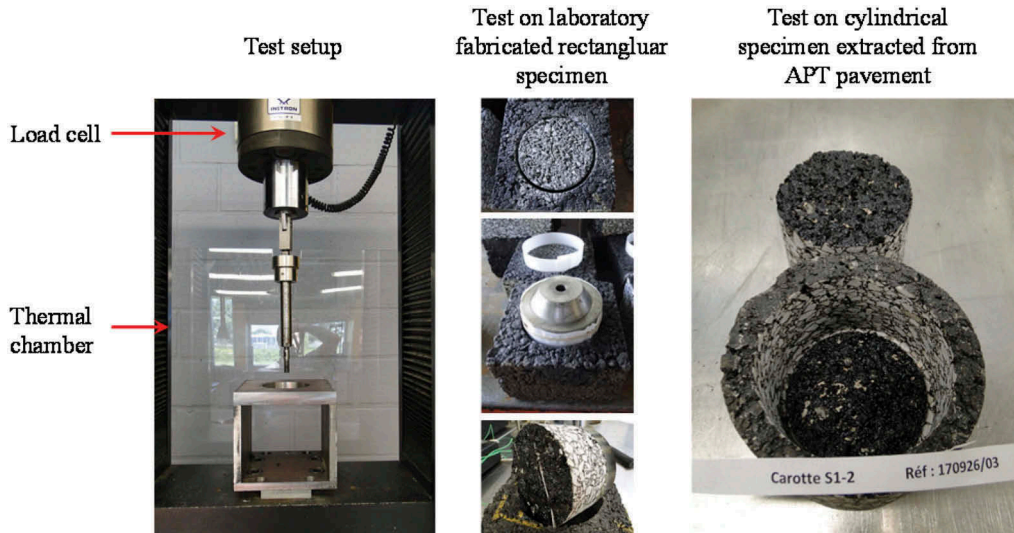


Figure 7. Direct tension bonding (DTB) test setup and tested specimens.

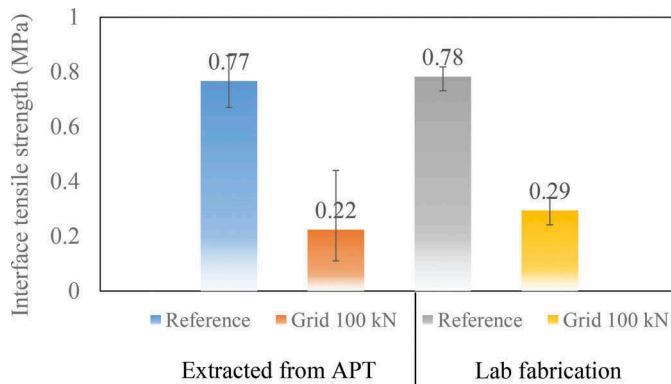


Figure 8. Laboratory test results of the interface tensile strength at 20°C.

Tests were conducted on double-layered cylindrical specimen extracted from the two full-scale pavement sections and on specimens fabricated in the laboratory. The results of the tests are presented in Figure 8. For both types of specimens, extracted from the APT pavement sections and fabricated in the laboratory, the average tensile strengths of the specimens with a grid at the interface (0.22 and 0.29 MPa respectively) are about three times lower than those

of the specimens without grid (0.77 and 0.78 MPa respectively). This result confirms again that the presence of a glass fiber grid at the interface between the asphalt layers reduces the interface bond strength.

6 CONCLUSIONS AND PERSPECTIVES

The results of the present study lead to the following conclusions and perspectives:

- The distribution of horizontal strains is modified when the bonding condition at the asphalt layers interface changes due to the presence of the glass fiber grid. Measured and simulated horizontal strains at the bottom of each asphalt layer on both sides of the interface showed a less bonding condition in case of pavement with a grid than without a grid. This phenomenon is similar to the effect of a stress absorbing membrane interlayer (SAMI) which could contribute to a delay of the offset of reflective cracking.
- Similar observations were obtained for deflection basins measured under FWD tests, on sections with and without grid at the interface.
- Using the notion of a pseudo dynamic interface stiffness modulus implemented in the multilayer pavement design software Alizé, it is possible to determine by inverse analysis a corresponding value of interface stiffness that fits the experimental measurements in terms of strain signals and of FWD deflection, for each interface bonding condition.
- Associated laboratory studies, using a direct tension bonding test, on material specimens extracted from the APT pavements and fabricated in the laboratory confirmed the influence of the interface conditions with and without grid on the measured bond strength.
- More complete experimental results, with different testing conditions, will be analyzed in the next steps of the work.
- A first numerical parametric analysis of the structural behavior shows that the reduced bond strength, associated with the high horizontal tensile strength of glass fiber grids, can lead in some cases to a reduction of the maximum tensile stresses in the asphalt layers (due to strain redistribution), leading to a better performance of the reinforced pavement. This study is not presented in this paper, due to its limited length, and will be developed in the next steps of the work.
- Additional numerical parametric analyses of structural behavior will be carried out, to evaluate the influence of the interface bonding condition, of the grid tensile strength, and of the grid position, on pavement performance.

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