Monitoring of Artificial Defects within a Pavement Structure with Ultrasonic Pulse Echo

Jean-Michel SIMONIN¹, Géraldine VILLAIN¹, Pierre HORNYCH¹
¹ LUNAM Université, IFSTTAR, Route de Bouaye, CS4, F-44344 Bouguenais Cedex France
Phone: +33 2 40 84 58 29, Fax: +332 40 84 59 94
jean-michel.simonin@ifsttar.fr, geraldine.villain@ifsttar.fr, pierre.hornych@ifsttar.fr

Abstract
This paper presents the monitoring of a pavement structure with Ultrasonic Pulse Echo (UPE) on site. The pavement structure, which contains artificial defects, has been built on the full scale accelerated pavement testing facility of IFSTTAR in Nantes. The 25 meter long test section is made of two bituminous layers over a granular subbase. Three types of defects have been included at the interface between the two bituminous layers: sand, textile, absence of tack coat. Then, the experiment consisted in applying loads with dual wheel axles, loaded at 65 kN, to the pavement. The objectives of the experiment are to study the effect of such sliding interfaces on the mechanical behaviour of the pavement, to survey their evolution with traffic, and to test different NDT methods to detect and locate defects. The paper presents the monitoring of the test section with an UPE device at different stages of the experiment.

Keywords: Pavement monitoring, Ultrasonic Pulse Echo (UPE), Non Destructive Technique (NDT), bituminous material

1. Introduction

French roads consist mainly of old bituminous pavements often more than 30 years old. Usually, they have been maintained several times with thin overlays (less than 8 cm thick). In recent years, potholes and alligator cracking has been frequently observed, in particular after periods of heavy rain or freeze/thaw. Frequently, this type of damage is associated with moisture effects linked to interface debonding between the overlays and the old pavement. Such debonding mechanisms reduce the residual life of the pavement, and thus their early detection is a very important issue for pavement maintenance [1]. To detect such interface damage, non-destructive techniques (NDT), such as seismic wave propagation methods, appear as promising approaches.

This paper presented tests performed on a pavement structure with Ultrasonic Pulse Echo (UPE). Shear waves have been used to detect and locate debonding during an experiment carried out on the large pavement fatigue carrousel of IFSTTAR in Nantes. Additional tests, based on propagation of compression waves, have been performed to characterize the mechanical behavior of the wearing course.

2. Description of the full scale experiment
2.1 Description of the test site

The test site is located on the pavement fatigue carrousel of IFSTTAR (Figure 1). A full scale experiment investigating low traffic pavements started on the test track in March 2011. A first
part concerned mainly the testing of pavements with geogrid reinforcement and consisted in loading the outer radius (19 m) during 1.2 million load cycles [2]. The second part started in the spring of 2012, and consisted in loading the inner radius (16 m), where the section with defects is located. This test section is 25 m long and consists of two bituminous layers (8 cm thick base layer, and 6 cm thick wearing course), over a granular subbase (30 cm thick). Several types of defects were intentionally incorporated at the interface between the two bituminous layers.

Figure 1. The pavement fatigue carrousel of IFSTTAR

2.2 Material characteristics and pavement construction

The pavement structures were built on the existing subgrade of the test track, which is a sand with about 10% fines, sensitive to water. The modulus of this subgrade is approximately 70 MPa. The structure built on this subgrade includes the following layers:

- A granular subbase consisting of 30 cm of 0/31.5 mm unbound granular material (UGM). After construction, this subbase was covered with a spray seal;
- A bituminous base layer, consisting of 8 cm of Road Base Asphalt material (RBA) (0/14 mm grading);
- A bituminous wearing course, consisting of 6 cm of bituminous concrete (BC) (0/10 mm grading).

Complex modulus tests on trapezoidal specimens were performed on the two bituminous mixes. The standard elastic moduli obtained for the 2 materials at 15°C and 10 Hz were respectively 11 320 MPa (RBA) and 10 700 MPa (BC). Using the Huet-Sayegh visco-elastic model [3], infinite moduli (at very high frequency) can be extrapolated and have been estimated to 23 GPa (RBA) and 29 GPa (BC).

The construction of the pavements was carried out by a road construction company, using standard equipment. Rectangular debonded areas were incorporated at the interface between the two bituminous layers. Table 1 presents their dimensions and the technique used: sand, textile, or absence of tack coat. Figure 2 presents a photograph of the debonded areas before
the wearing course construction (2a) and a map of the experimental section, with the location of the different defects (2b).

These defects were centered on the radius \( R = 16 \text{ m} \), which corresponds to the center of the wheel-path. The total width of the wheel-path (with lateral wandering) was approximately 1.0 m (between 15.5 m and 16.5 m). The debonded areas I1, I2, I3, I10, I11 I12 and I13 are centered on the radius of 16 m. I4 to I9 are small defects, 0.5 x 0.5 m, with a textile interface, located in and outside the wheel path.

Table 1. Characteristics of the different defects introduced in the pavement

<table>
<thead>
<tr>
<th>Defects zone</th>
<th>Type</th>
<th>Dimension (m) length x width</th>
<th>Position (m) at radius R=16m</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>Sand</td>
<td>0.5 x 2</td>
<td>[2.5 - 3]</td>
</tr>
<tr>
<td>I2</td>
<td>Textile</td>
<td>0.5 x 2</td>
<td>[3.5 - 4]</td>
</tr>
<tr>
<td>I3</td>
<td>Tack coat free</td>
<td>0.5 x 2</td>
<td>[4.5 - 5]</td>
</tr>
<tr>
<td>I4 to I9</td>
<td>Textile</td>
<td>0.5 x 0.5</td>
<td>[6.5 - 9]</td>
</tr>
<tr>
<td>I10</td>
<td>Textile</td>
<td>3 x 1</td>
<td>[9.5 - 11.5]</td>
</tr>
<tr>
<td>I11</td>
<td>Sand</td>
<td>1.5 x 2</td>
<td>[13.5 - 15]</td>
</tr>
<tr>
<td>I12</td>
<td>Textile</td>
<td>1.5 x 2</td>
<td>[17 - 18.5]</td>
</tr>
<tr>
<td>I13</td>
<td>Tack coat free</td>
<td>1.5 x 2</td>
<td>[20.5 - 22]</td>
</tr>
</tbody>
</table>

2.3 Pavement loading and monitoring

The main objective of the experiment was to compare different NDT techniques based on mechanical (deflection measurement, modal testing, US wave propagation) or electromagnetic (Radar) phenomena for detecting different geometrical characteristics of artificial defects. Other objectives were to follow the evolution of the defects during loading and to evaluate their effect on pavement performance. This will be helpful in optimizing pavement monitoring with the different NDT methods. Investigations have been done at different stages of the experiment:

- At the beginning of the experiment to characterize the initial state of the pavement;
- After 10 000 loads when the structure is consolidated;
- After 50 000, 100 000, 200 000, and 300 000 loads to survey the structure.
The experiment started in the spring of 2012, with 100,000 loads applied in April and May. Then wheels have been moved to the 19 m radius to test another pavement. Different NDT methods have been performed when the fatigue machine was stopped for maintenance. At the beginning of July, 100,000 loads have been applied again on the debonded sector. Different NDT methods have been performed. First results didn’t show any evolution of the debonded zones. So, it has been decided to apply 100,000 additional loads before the end of July. Thus 300,000 loads have been applied to the road. After this experiment, the fatigue machine has been transferred to another test site. However, the test site with the debonded area has been left in place and is still available to test NDT methods.

The structure has been investigated using the following NDT methods:

- Deflection measurements using Falling Weight Deflectometer or inclinometer [4];
- Mechanical response of the pavement to an impact loading to estimate the Frequency Response Function (FRF) using the COLIBRI prototype [5];
- Radar devices: two classical Ground Penetrating Radars with a coupled 2.6 GHz antenna and a step frequency radar which uses a network analyzer [4];
- Ultrasonic Pulse Echo (UPE) system based on the propagation of ultrasonic waves (either compression or shear waves) at a frequency of 55 kHz.

This paper presents only the results obtained with the UPE system. Some results obtained with the other NDT methods have been published in other papers [4, 5].

2.4 Ultrasonic Pulse Echo measurement device

Ultrasonic Pulse Echo (UPE) tests have been performed using an antenna array (ACSYS system) which includes 24 piezoelectric transducers. Half of them emit waves, with a central frequency equal to 55 kHz, into the structure while the others record the reflected waves. At each measurement point the antenna is applied and maintained on the road surface during a few seconds. Compared with the practice on hydraulic concrete [6], the data analysis is more difficult due to wave attenuation phenomena in the bituminous material, which increase at high temperature.

Two antenna arrays are available and can be used one after the other, either equipped with shear S-wave transducers or compression P-wave transducers.

Concerning the structural survey to monitor the evolution of the debonding, the UPE S-wave device was used at different test times corresponding to 10,000 (April 2012), 50,000 (May 2012), 100,000 (May 2012), and 300,000 cycles, the last both in September 2012 and later in July 2015.

Regarding the mechanical characterization and the evaluation of the dynamic modulus, tests were carried out with both S-wave and P-wave devices, only after 300,000 cycles in July 2015.
3. **Survey with shear wave system**

3.1 **Description of the tests**

The UPE S-wave device was used to investigate a longitudinal profile at the 16 m radius above the large debonded areas (I1, I2, I3, I11, I12 & I13). These profiles began 0.20 to 0.5 m before the defect and ended 0.2 to 0.5 m after. Measurements were made at points spaced at a distance of 0.05 m far from the theoretical limits of the defect and 0.02 m close to the limits. Moreover, three 1.5 m long transverse profiles have also been performed with a measurement spacing of 0.02 m to survey the lateral extension of the I10 textile debonded zone. Two profiles were recorded above the I10 zone and one reference profile was recorded between I10 and I11.

3.2 **Analysis of the time signals**

Figure 3 compares 15 signals without gain recorded in different conditions after 50 000 loads:
- Red signals were recorded in zone including sand (I11);
- Green signals were recorded in zone including textile (I12);
- Blue signals were recorded in zone without tack coat (I13);
- Cyan signals were recorded in zone with well bonded interface (the first five measurements of each profile).

All signals show a high amplitude wave with a saturation of the signal before 50 µs. This wave corresponds to the direct wave at the road surface. Then the signal is highly attenuated, and echoes are difficult to detect. However, the differences are significant between the signals corresponding to different defects. The gain, that can be imposed or not, enables to improve the visualization of the differences.

![Figure 3. Comparison of UPE signals (S-Wave) above 3 different types of defects and above well bonded interface after 50 000 loads (May 2012)](image-url)
3.3 Detection and location of debonded zones

To detect and locate debonded zones, measurements along each profile are used to present a B-Scan where:

- The X-coordinate is the abscissa along the road section;
- The Y-coordinate is time (UPE);
- Colors (or levels of gray) represent the signal amplitude.

Figure 4 compares B-scans obtained with the measurements recorded on the zones I11 to I13. The colors represent the amplitude level from amplitude -100 (blue) to 100 (red). So, the surface echo is presented with a saturated color. Above the debonded zone, an interface echo (yellow line) can be detected at around 60 µs. This echo is easier to detect for the debonded interfaces with sand (from abscissa 0.8 m to 2.3 m) and textile (from abscissa 0.85 m to 2.35 m) than for the interface without tack coat (from abscissa 0.5 m to 2.1 m). The length of the debonded zone is consistent with the design and with measurements done with other NDT methods such as GPR and FWD[4, 5]. The limits of defects I11 and I12 have an offset which is due to positioning of the system at the beginning of the measurement sequence. UPE mappings are able to detect and locate the debonded areas and to evaluate the severity of the defect.

![B-scans comparison](image)

Figure 4. B-scans of UPE (S-wave) measurements above the I11 (upper), I12 (middle) and I13 (lower) defects after 50 000 loads (May 2012)

Tests performed with the UPE S-wave device during the loading phase of 2012 allowed detecting the different defects. B-scans were used to estimate the size of each defect. A small increase of the defect size (≈ 3 to 5 cm) can be noticed between 10 000 load cycles and 300 000 load cycles, but it is not very significant compared with the spacing between consecutive measurement points (2 or 5 cm). The site has been preserved and it is planned to apply additional loading (at least 500 000 loads) in conjunction with other accelerated pavement testing as soon as possible.
4. Mechanical characterization with shear and compression wave system

4.1 Description of the tests

Both the S-wave and the P-wave UPE devices were used to investigate a longitudinal profile at the 16 m radius above the large, most visible, debonded areas (I1, I11 and I12). After a quick GPR scan to detect the visible defaults, it was decided to begin the measurements 0.20 m before the defect and to end 0.2 m after. In reality, there was an error of about 0.10 m on the expected position of the defects, and so the measurements started 0.10 m before the defect and ended 0.3 m after. The measurement spacing was equal to 0.05 m. Acquisition parameters were identical in the 2 cases. The surface temperature was 28°C.

4.2 Analysis of the signals

Figure 5 compares signals recorded with the S-wave antenna (upper graph) and the P-wave antenna (lower graph). Both graphs show signals without gain recorded in different conditions:

- Red signals were recorded in zone I1 (above sand);
- Green signals were recorded in zone I11 (above sand);
- Blue signals were recorded in zone I12 (above textile);
- Cyan signals were recorded in zone with well bonded interface (2 signals of each longitudinal profile).

![Figure 5. Comparison of S-wave (upper) and P-wave (lower) signals obtained in different conditions after 300 000 loads in july 2015](image_url)

S-wave signals show a high amplitude wave with a saturation of the signal before 50 µs. This wave corresponds to the direct wave at the road surface. Then the signal is highly attenuated, but the differences are significant between the signals corresponding to different defects. The first reflected wave can be picked at around:
• 85 µs (100 µs) for the maximum (minimum) value for I1 and I11;
• 90 µs (105 µs) for the maximum (minimum) value for I12;
• 80 µs (95 µs) for the maximum (minimum) value on the well bonded interface.

The second reflected wave is more difficult to pick. The amplitude of the P-wave is lower than the amplitude of the S-wave. The direct wave is not saturated. This is probably due to a lower energy emitted with the P-wave antenna. The P-wave velocity is higher than the S-wave. The reflected waves have to be picked sooner at around 50 µs for the positive pick and 55 µs for the negative one.

4.3 Detection and location of debonded zones

To detect and locate the defects, a B-scan has been constructed for each profile. B-scans obtained with the S-wave test and with the P-wave test on the same profile are clearly different. However B-scans obtained with the same antenna on the different profiles are similar. Figure 6 compares B-scans obtained with the measurements recorded on the zone I12 (textile) with the S-wave antenna (upper) and the P-wave antenna (lower). The presence of textile is easy to detect and locate on the S-wave B-scan between the abscissa 0.1 m to 1.7 m. On this B-scan, the negative pick (blue) is easier to read at the time 105 µs. The presence of textile is difficult to detect on the P-wave B-scan. Other tests will need to be done to choose the best parameters with the P-wave antenna to make the detection easier.

Figure 6. B-scans obtained with S-wave (upper) and P-wave (lower) signals above the textile defect I12 after 300 000 loads in July 2015

4.4 Evaluation of mechanical properties of pavement material

Once the position and extension of the defaults are know, it is possible to calculate the mechanical characteristics of the bituminous concrete with or without defect. The density, roughly equal to 2440 kg/m³, was controlled after construction. The thickness of the bituminous wearing course was measured on a core taken outside the debonded sector and outside the wheel-path; and was about 0.07 m. It was assumed that the layer thickness was the
same where the UPE measurements were performed before and above the studied defects. Consequently, knowing the thickness, the P-wave and S-wave velocities can be estimated from travel time picking. Then, using the density, the dynamic Young’s modulus ($E_{dy}$) and Poisson’s ratio ($\nu$) of the pavement material can be evaluated at 55 kHz and in the testing conditions, at a temperature of 28°C. These mechanical parameters have been evaluated for each signal.

The results are summarized in Table 2. Without defect, the elastic modulus is about $25.4 \pm 1.3$ GPa and the Poisson’s ratio about $0.30 \pm 0.03$. These values are quite close to the “infinite” modulus (corresponding to an infinite frequency), calculated with the Huet-Sayegh model, which was around 28.9 GPa, and to the “infinite” Poisson’s ratio, which was around 0.35 [7]. The differences could be explained by the 55 kHz frequency of the test which is not infinite and the high temperature during testing in July 2015, which effect is equivalent to reducing the frequency on the master curve [3].

Besides, above defaults, the Poisson’s ratio is not different from the one of the well bonded zone, whereas the elastic modulus is slightly lower. This could be due to an error in the estimation of the thickness, or to the fact that the reflection occurs under the textile or sand layer, and that the wave velocity is modified by this thin soft layer, thus leading to underestimating the properties of the bituminous concrete layer.

Future experiments will improve the interpretation of data using the mastercurve of the bituminous material, to take into account the temperature and frequency effects [7].

### Table 2. Dynamic Young’s modulus and Poisson’s ratio at 55 kHz and $T = 28 °C$

<table>
<thead>
<tr>
<th>Defect</th>
<th>Edyn (GPa)</th>
<th>$\nu$ (-)</th>
<th>Edyn (GPa)</th>
<th>$\nu$ (-)</th>
<th>Edyn (GPa)</th>
<th>$\nu$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without default</td>
<td>24.6 ± 0.9</td>
<td>0.30 ± 0.03</td>
<td>26.4 ± 1.3</td>
<td>0.30 ± 0.02</td>
<td>25.1 ± 0.8</td>
<td>0.29 ± 0.04</td>
</tr>
<tr>
<td>Above default</td>
<td>24.1 ± 1.2</td>
<td>0.31 ± 0.02</td>
<td>23.7 ± 1.02</td>
<td>0.30 ± 0.03</td>
<td>21.2 ± 1.4</td>
<td>0.31 ± 0.02</td>
</tr>
</tbody>
</table>

### 5. Conclusions and outlooks

This paper presents an experiment performed on the IFSTTAR Accelerated Pavement Testing facility to evaluate the UPE method for the detection and location of different debonded interfaces, their evolution under traffic and to estimate the material properties of the wearing course. A pavement section with different artificial defects has been built and tests performed using first only the shear wave system before and during loading of the pavement. Complementary tests have been recently performed including the compression waves system. First results show some potential and limitations of the method. Practice of UPE on site is easy and fast. However, signals are highly attenuated by bituminous concrete. Acquisition conditions need to be optimizing taking into account the temperature and the energy emitted to obtain large amplitude signals. Yet results show very good sensitivity to debonded areas. The method could provide to the road engineer a picture of the internal damage of the road.
base and wearing course. Signals analysis can deliver other information such as depth of defect or mechanical properties (E, v) of the wearing course.

After 300 000 loads, only a small evolution of the interfaces has been observed with the UPE method whereas visual surveys do not detect any damage. This test section will receive additional loading, in conjunction with other test programs on the carousel, to perform at least 500 000 loads. NDT tests will be continued on the pavement at regular intervals.

The experiment also points out some research needs. Sensitivity of the test to measuring conditions, particularly to temperature, has to be studied in detail to optimize the acquisition conditions and to facilitate the interpretation of data. The interpretation of results could be improved by using the master curve of the bituminous material, taking into account temperature and frequency effects. A monitoring of the dynamic modulus, which can be easily determined, could be used as a damage indicator of the material. Numerical and experimental studies are planned to investigate these different issues.

References