ABSTRACT

During the European PERSUADE project, a full scale test section with a poroelastic road surface (PERS) has been built on a road with regular traffic in Herzele in Belgium. The acoustical performance of the PERS test section has been monitored during ten months. SPB, CPB and CPX measurements were performed and showed no significant deterioration of the acoustical properties over time. The noise reduction was remarkable. Noise reductions up to 9 dBA were measured in comparison with an old asphalt concrete at the reference speed of 50 km/h. Several road properties influencing tyre/road noise have also been measured in situ. Mean Profil Depth (MPD) and road texture spectra were assessed from texture measurements with a dynamic laser profilometer. Sound absorption was measured following ISO13472-1 and appeared to be relatively low for a porous road surface. Mechanical impedance of the road surface was also measured using a specific impact method. Thus, the dynamic Young modulus of the road surface was estimated using a single degree of freedom approach. The stiffness was relatively high for a PERS but much less than a traditional asphalt concrete, having a good potential for reduction of tyre/road interaction via the elasticity of the road surface.

Keywords: Tyre/road noise, Low-noise road surfaces   I-INCE Classification of Subjects Number(s): 52.3

1. INTRODUCTION

Poroelastic Road Surfaces (PERS) have been developed since the 70's and, despite their fast degradation, first trials have proved their exceptional acoustical properties with respect to conventional road surfaces (1). The EU financed PERSUADE project (2) aimed at developing PERS with high noise reducing properties together with increased lifetime under road traffic (3). Therefore a comprehensive research program has been carried out and led to the construction (4) and performance monitoring (5) of several full-scale PERS test sections within partner countries (6).

This paper focuses on the acoustical performance and road surface properties of one of the full-scale test sections which was built on a road with regular traffic in Herzele in Belgium. The PERS test section will be further described in the next section.

Section 3 deals with different noise measurements performed on the full-scale test section. First Controlled Pass-By (CPB) noise measurements are reported for comparison with the acoustical properties of a pilot small-scale PERS test section, which was built in an area without traffic and which was based on the same PERS mix. Then several Statistical Pass-By (SPB) measurements have been performed during the first six months of the full-scale PERS test section to monitor the acoustical performance of the PERS under actual traffic conditions. Close-ProXimity (CPX) tests have also been performed to characterize tyre/road noise levels and spectra of the PERS.

Section 4 concerns in situ characterization of road surface properties that are known to influence tyre/road noise emission the most, i.e. texture, sound absorption and mechanical impedance. These properties are discussed in relation with noise results before drawing conclusions in section 5.

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2. DESCRIPTION OF THE TEST SECTION

2.1 Location

The poroelastic test section was located on the N464 (“Schipstraat”) in Herzele in Belgium, approximately at 40 km west from Brussels. The construction of the test section was managed by BRRC and took place during two days on the 2nd and 3rd of September 2014 (4). The test section was built on a not too busy country road where on average 2000 vehicles pass per day of which about 5% are heavy vehicles. The speed limitation of the test site was 50 km/h. The poroelastic road surface was laid on a single lane of the road (Figure 1). The dimensions of the test section were 40 m long by 3 m wide. Figure 1 (left) gives a picture of the test section just after construction in September 2015. The white aspect is due to sand which was used to enhance the initial skid resistance. Figure 1 (right) shows a picture of the test section in the beginning of June 2015, i.e. 9 months after construction. Despite the traffic mentioned before, the test track showed a remarkable good raveling resistance during its existence. No glimpse of local or global raveling was observed as texture or color change of the pavement. Neither was loose aggregate ever found in the gutter. In the 8th month of its lifetime some loosening was observed at the edge and in the 9th month also some in the first 10 m, apparently caused by setlings in the under layer which did not resist to the direct exposure of the forces exerted by heavy vehicles. Unfortunately, the situation deteriorated quickly and the experiment had to be aborted in the 10th month after the construction, i.e. by the end of June 2015.

Figure 1 – Poroelastic full-scale test section located in Herzele (Belgium) just after construction in September 2014 (left picture) and in the beginning of June 2015 (right picture)

2.2 Poro-Elastic Road Surface (PERS)

The PERS presented in this section was one of the nine full-scale test tracks built during the PERSUADE project (4). Two batches were mixed in a mobile cement concrete plant in Zaventem (Belgium) and then transported to the test site with a truck. The wet PERS mix was on the site loaded in a classical asphalt finisher and spread. Then it was compacted several times. The PERS layer was 45 mm thick with a density of 65 kg/m². The mix was composed (% of weight) of rubber aggregates 2/4 (about 20%), stone aggregates 2/5 (about 68%), polyurethane binder (about 10 %) and small fractions of cellulose fibers and polyols. Figure 2 gives a close-up photo of the PERS just after completion. The final result looked quite nice both in terms of texture and evenness.
2.3 Measurement Campaigns

The performance of the PERS test section was monitored during its lifetime as a part of an extensive measurement program developed during the PERSUADE project (5). Many properties have been measured among which surface texture, surface unevenness, pavement deflection, rut resistance, thin and plane sections analysis, air voids content, drainability, acoustical absorption, mechanical impedance, acoustical quality and skid resistance. The results of all measurements performed on the test section can be found in (7). This paper focuses on the acoustical performance of the PERS test section and on road surface properties that are the most likely to influence tyre/road noise emission, i.e. surface texture, sound absorption and mechanical impedance. Although they also have been assessed in laboratory (8), the paper deals here with in situ characterization of these road properties.

3. NOISE MEASUREMENTS

3.1 Controlled Pass-By (CPB) Noise Measurements

Before the full-scale construction, a so called small-scale test section was experienced on the grounds of BRRC in Sterrebeek near Brussels. This pilot test section had only a limited length of 15 m long and very little traffic. Therefore only Controlled Pass-By (CPB) measurements were performed on this small-scale test section. The results are reported in (9). To be able to compare with this first try-out test section, a similar CPB measurement was performed on the full-scale PERS test section presented in section 2. All CPB measurements were performed with the help of students of the University of Antwerp in the frame of their master thesis (10, 11).

The measurement configuration and principle are described in the ISO standard ISO 11819-1 about Statistical Pass-By (SPB) measurements. Instead of a wide range of vehicles only one specific car was used to perform the pass-by at different vehicle speeds between 30 km/h and 60 km/h. The microphone was set up at 7.5 m from the axis of the test vehicle and at a height of 1.2 m above the level of the pavement to be tested.

The same measurements were also performed on a reference location, namely the Fokkersdreef in Sterrebeek (Figure 3, left). On this location the pavement is a dense asphalt concrete with maximum aggregate size of 16 mm (DAC 0/16). A small Citroën C1 car was used (Figure 3, right) for the tests.
The relation between pass-by maximum noise level and the logarithm of vehicle speed was analyzed by means of a classical regression analysis. Figure 4 gives the CPB regression results for the reference DAC 0/16, the small-scale PERS test section and the full-scale PERS test section. The acoustical performance of the full-scale test section is comparable to the small-scale test section based on the same PERS mix.

![Figure 3 – Reference DAC 0/16 test section (left) and CPB measurements with Citroën C1 (right)](image)

Table 1 gives the CPB noise levels at the reference speed of 50 km/h in the case of the Citroën C1 test vehicle. The 95% confidence interval of the regression is also given for each maximum noise level. All results have been corrected to a reference temperature of 20°C with a correction of -0.07 dBA per °C as agreed by the consortium based on specific research regarding temperature correction in the project (5). The slope of the regression analysis is also given in dBA per decade of speed. Table 1 illustrates the noise reduction for the CPB measurements that was found on the PERS test sections with respect to the reference DAC 0/16. A noise reduction of 7.6 dBA was measured for the small-scale test section while 7.9 dBA was obtained for the full-scale test section two months after its construction. Moreover, the slope values indicate that at higher speeds higher noise reduction can be obtained with respect to the old DAC 0/16.

![Figure 4 – CPB measurement results in Sterrebeek (small-scale test section) and in Herzele (full-scale test section) with Citroën car](image)
Table 1 – CPB noise results at 50 km/h (Citroën C1, temperature corrected at 20 °C)

<table>
<thead>
<tr>
<th>Road surface</th>
<th>Date</th>
<th>Tair (°C)</th>
<th>L_{Amax}(50) [dBA]</th>
<th>Slope [dBA/dec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAC 0/16</td>
<td>18/02/2014</td>
<td>7.2</td>
<td>69.4 ± 0.2</td>
<td>33.6</td>
</tr>
<tr>
<td>PERS (small-scale)</td>
<td>18/02/2014</td>
<td>8.2</td>
<td>61.8 ± 0.2</td>
<td>26.8</td>
</tr>
<tr>
<td>PERS (full-scale)</td>
<td>28/10/2014</td>
<td>10.9</td>
<td>61.5 ± 0.5</td>
<td>30.6</td>
</tr>
</tbody>
</table>

3.2 Statistical Pass-By (SPB) Monitoring

Over a period of 10 months several SPB measurements were performed by BRRC on the full-scale PERS test section. The SPB test set up is shown in Figure 5. The microphone has been placed at the opposite side of the road to comply with the standard regarding ground absorption. The measurement Reference Point (RP) was located at 20 m after the beginning of the test section, corresponding to the middle of the test section.

Figure 5 – SPB test set up at the Herzele test site

An overview of the measurements is given in Table 2. Results are given for a reference speed of 50 km/h. The 95% confidence interval of the regression is also given for each maximum noise level. A temperature correction of -0.07 dBA/°C has been applied. As not enough heavy vehicles were passing the test location, only the results for light vehicles are given. It can be stated that the acoustical quality of the PERS remains stable over time. The regression slope is slightly increasing with the age of the road surface and ranges between 23.0 dBA/dec and 28.0 dBA/dec.

Table 2 – SPB results at 50 km/h on the full-scale PERS test section (temperature corrected at 20 °C)

<table>
<thead>
<tr>
<th>Date</th>
<th>Age</th>
<th>Tair [°C]</th>
<th>Troad [°C]</th>
<th>L_{Amax}(50) [dBA]</th>
<th>Slope [dBA/dec]</th>
<th>Number of vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>09/09/2014</td>
<td>6 days</td>
<td>21.1</td>
<td>37.0</td>
<td>63.8 ± 0.6</td>
<td>23.0</td>
<td>118</td>
</tr>
<tr>
<td>16/09/2014</td>
<td>13 days</td>
<td>23.3</td>
<td>39.0</td>
<td>63.5 ± 0.7</td>
<td>26.6</td>
<td>122</td>
</tr>
<tr>
<td>28/10/2014</td>
<td>1.5 months</td>
<td>10.0</td>
<td>15.0</td>
<td>65.2 ± 0.8</td>
<td>24.9</td>
<td>100</td>
</tr>
<tr>
<td>13/03/2015</td>
<td>6.5 months</td>
<td>12.0</td>
<td>27.0</td>
<td>63.8 ± 0.4</td>
<td>28.0</td>
<td>105</td>
</tr>
</tbody>
</table>

3.3 Close-ProXimity (CPX) Noise Measurements

CPX noise measurements were performed at 50 km/h by BRRC by means of a CPX trailer according to ISO 11819-2 (Figure 6). The trailer was equipped with the P1 tyre (SRTT reference tyre as specified in ISO/TS 11819-3, Figure 6 right). The measurements have been done on May 2015, 8 months after the construction of the PERS test section.
Table 3 gives the $L_{CPX,P,50}$ noise levels measured for the left and right wheel tracks. All values are temperature corrected at 20°C with a correction factor of -0.07 dBA/°C. No significant difference is noted between the wheel tracks. Noise levels seem to remain stable over time, although surface degradation of the PERS had begun (see section 2.1).

Table 3 – CPX results at 50 km/h on the full-scale PERS test section (P1 tyre, temperature corrected at 20 °C)

<table>
<thead>
<tr>
<th>Date</th>
<th>$T_{\text{air}}$ [°C]</th>
<th>$L_{CPX,P,50}$ [dBA]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left track</td>
</tr>
<tr>
<td>11/05/2015</td>
<td>23.4</td>
<td>82.7</td>
</tr>
<tr>
<td>28/05/2015</td>
<td>15.5</td>
<td>83.0</td>
</tr>
</tbody>
</table>

In comparison, the $L_{CPX,P,50}$ noise level of a new stone mastic asphalt (SMA) with a maximum aggregate size of 10 mm tested with the same CPX trailer is about 90.0 dBA (12), leading to a noise reduction between 6.7 and 7.1 dBA with the PERS. This is quite remarkable since this new SMA was not the noisiest recorded. In fact, typical values are usually 1 to 2 dBA higher for SMA 0/10 (13), increasing the potential CPX noise reduction of PERS to 8 to 9 dBA. This is well illustrated in Figure 7, were a noise reduction between 5 dBA and 10 dBA is observed with PERS in the frequency range between 630 Hz and 5000 Hz, in comparison with the new SMA.
4. ROAD SURFACE PROPERTIES

4.1 Surface Texture

Surface texture of the PERS was measured in situ with the dynamic laser profilometer of BRRC (Figure 8) in the right, the middle and the left wheel tracks. The laser has a high sample frequency (78 kHz) and a small diameter laser beam (0.2 mm). The laser profilometer has a vertical measuring range of 64 mm and is a 16-bit system. The vertical resolution is thereby 1 μm. It has a horizontal resolution of 0.2 mm.

A first texture measurement was performed on 10 September 2014 (one week after construction) and a second texture measurement took place on 13 March 2015 (6 months after construction). Only small differences were found for the texture spectra between the left, the middle and the right wheel tracks. Therefore, Figure 9 gives the average texture spectrum and the standard deviation in the three wheel tracks. A change can be seen over a period of 6 months. After 6 months, texture levels become about 1 to 2 dB lower in the wavelength range between 0.0032 m and 0.3175 m.

In comparison with SMA 0/10, the PERS test section has low megatexture levels (favorable to tyre vibrations reduction) probably explaining a part of noise abatement in the CPX spectra (Figure 7).

MPD values were also calculated from texture profiles at each 5 m of the PERS test section. An increase in MPD can be seen over a period of 6 months (Table 4). The highest MPD values are found for the middle of the test section, probably due to some after-compaction in the other wheel tracks more exposed to traffic.
Table 4 – Average MPD values with standard deviations for left, middle and right wheel tracks

<table>
<thead>
<tr>
<th>Date</th>
<th>Left track</th>
<th>Middle track</th>
<th>Right track</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/09/2014</td>
<td>0.79±0.04</td>
<td>0.92±0.05</td>
<td>0.85±0.03</td>
</tr>
<tr>
<td>15/03/2015</td>
<td>0.95±0.04</td>
<td>1.01±0.06</td>
<td>0.93±0.04</td>
</tr>
</tbody>
</table>

### 4.2 Acoustical Absorption

Sound absorption of the PERS was measured in situ by IFSTTAR at the beginning of June 2015. The average temperature of the air was 16°C and the speed of the wind was less than 5 m/s. The equipment was a stationary system following the recommendations of ISO 13472-1. It is composed of a sound source and a microphone respectively positioned at a distance $d_s=1.25$ m and $d_m=0.25$ m above the road surface (Figure 10). During the measurement, the source and the receiver were first positioned vertically with the microphone at the bottom. A white noise signal was driven through the loudspeaker and the signal/noise ratio was improved by repeating the acquisition and averaging the microphone response. Then the system was reversed vertically (microphone upward) to get the free field response which was subtracted from the downward time response in order to isolate the reflected contribution.

![Figure 10 – Sound absorption measurement system of IFSTTAR complying with ISO 13472-1](image_url)

Sound absorption was measured in the middle of the tested lane at three different Reference Points (RP) respectively located at 10 m, 20 m and 34 m from the beginning of the PERS test section. Note that RP at 20 m corresponds to the location of the SPB noise measurements. Then sound absorption was measured at five spots around each RP. The spacing between two consecutive spots was 2 m wide. For each spot, a free field measurement was also performed.

The measurement method is based on the determination of the incident and the reflected frequency transfer functions between the source and the receiver, which can be evaluated from the separation of the impulse responses of the direct and the reflected paths in the time domain. The narrow bandwidth sound absorption coefficient $\alpha$ can then be calculated. It is given in Figure 11 for RP 20 m. The sound absorption curve is given for the five spots as well as the average absorption coefficient over the five spots. It is observed that the absorption is quite inhomogeneous from one spot to another. In the best case, a peak of about 0.4 is observed around 500-600 Hz and around 1000-1250 Hz, but in some cases the absorption is very low with a magnitude around 0.2 between 500 Hz and 2500 Hz. Similar results were observed at RP 10 m and 34 m.
Despite some dispersion between the spots in Figure 11, the average absorption curves have quite similar shapes at the three RP. Thus the 15 spots have been averaged in order to obtain the 1/3 octave band sound absorption coefficient over the PERS test section in Herzele. Figure 12 shows a first absorption peak of magnitude 0.3 at 500Hz followed by a second peak of magnitude 0.25 at 1250 Hz. The results are quite different from the absorption coefficient obtained in laboratory with the impedance tube method on PERS samples from Herzele (8), for which a higher absorption of about 0.65 at 800 Hz and 1000 Hz was obtained. The differences may be due to the different measurement methods but also to a different compaction rate between the test section and test slabs. The PERS test section may also have been clogged during time leading to less absorption in comparison with test slabs built at the initial state. Clogging and wear due to traffic may have led to changes in the intrinsic properties of the poroelastic road surface influencing absorption, such as tortuosity or specific flow resistance. Nevertheless, the absorption coefficient measured in situ (Figure 12) may explain a part of noise reduction of the PERS observed in Figure 7 in comparison with a new SMA within the frequency range between 500 Hz and 2500 Hz.

4.3 Mechanical Impedance

The mechanical impedance of the PERS test section was measured in situ by IFSTTAR (Figure 13, left). The experimental method had already been used in laboratory (8) and in situ on the first poroelastic full-scale test section built in Denmark (14). The measurement principle and experimental setup are based on the frequency response function between an impact hammer and an impedance head.
measuring the direct force and acceleration at the impact spot (Figure 13, right). In this study, 15 different spots were tested along the 40 meters long test section. The spots are the same as for absorption measurements described in section 4.2, i.e. five spots around three reference points respectively located at 10 m, 20 m and 34 m from the beginning of the test section.

The tests were performed at the beginning of June 2015, between 10:00 and 15:00. During that period, traffic was closed on the PERS test section, but still open on the other lane of the road. Thus the mechanical impedance was not measured when vehicles were passing on the other lane in order to avoid any bias of the vibration signals. The temperature of the air varied between 18°C and 22°C during the tests. The temperature of the road surface was measured with a sensor embedded in the PERS by BRRC (1 cm deep). The temperature of the surface of the PERS increased during the day and varied between 23°C in the morning and 45°C in the afternoon.

Figure 14 gives the magnitude and the phase of the direct mechanical impedance measured at each spot around RP 20 m. All curves have a similar shape which, in first approximation, is similar to a Single Degree Of Freedom (SDOF) system consisting in a mass over a parallel spring/dashpot combination. At low frequency, there is a linear decrease of the magnitude which is typical of an ideal spring. At high frequencies, there is a linear increase of the magnitude which is typical of an ideal mass. At medium frequencies, there is a minimum value of the magnitude at a frequency corresponding to the resonance of the mass spring system. The minimum value corresponds to the damping of the system. At the resonance frequency a typical phase shift is also observed.

Figure 14 – Example of direct mechanical impedance measured around RP 20 m
The parameters of the SDOF system can be estimated from experimental data and allow, knowing the thickness of the PERS layer, the estimation of the dynamic Young’s modulus E of the PERS (15). Thus E was estimated for the 15 spots and the results are given in Table 5. The average value of the dynamic Young’s modulus E is 167 ± 25 MPa at RP 10 m for a temperature of the road surface during the tests around 41°C, 235 ± 33 MPa at RP 20 m for a temperature of the road surface during the tests around 31°C and 197 ± 17 MPa at RP 34 m for a temperature of the road surface during the tests around 44°C. It seems that the increase of temperature of the PERS has a softening effect on the material as observed between RP 20 m and RP 10 m. The average value of the dynamic Young’s modulus over the 15 spots is 199 ± 35 MPa for an average temperature of the road surface of 39 ± 5°C during the tests. Thus, the full-scale PERS test section is much less stiff than a traditional asphalt concrete and has a good potential for reduction of tyre/road interaction via the elasticity of the road surface. This probably explains a large part of noise reduction observed in Figure 7.

Table 5 – Estimated dynamic Young modulus of the full-scale PERS test section

<table>
<thead>
<tr>
<th>RP</th>
<th>T_{surf} (°C)</th>
<th>E [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m</td>
<td>41±1</td>
<td>167 ± 25</td>
</tr>
<tr>
<td>20 m</td>
<td>31±5</td>
<td>235 ± 33</td>
</tr>
<tr>
<td>34 m</td>
<td>44±1</td>
<td>197 ± 17</td>
</tr>
<tr>
<td>Average</td>
<td>39 ± 5</td>
<td>199 ± 35</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

In this study, the acoustical performance of a full-scale PERS test section built within the framework of the PERSUADE project has been presented. The test section was built in Herzele in Belgium and was exposed to traffic of about 2000 vehicles per day with 5 % of heavy vehicles. The speed limitation of the test site was 50 km/h.

The noise reduction at 50 km/h (corrected to 20°C) is remarkable and varies between 6 dBA and up to 8 dBA for pass-by noise measurements (CPB and SPB) in comparison with an old DAC 0/16. The CPB results with a passenger car (Citroën C1) on the full-scale test section showed a similar noise reduction as a small-scale pilot test section based on the same PERS mix. SPB measurements showed no significant deterioration of the acoustical properties of the PERS during the first six months of the test track.

The CPX noise reduction at 50 km/h (P1 tyre, corrected to 20 °C) of the PERS in comparison with a new SMA 0/10 is about 7 dBA and could reach 8 to 9 dBA in comparison with the typical average value of SMA 0/10 category. Regarding the CPX spectra, the noise reduction may be due to a high macrotexture combined with a low megatexture, moderate sound absorption within the frequency range between 500 Hz and 2500 Hz and a relatively low dynamic Young’s modulus in comparison with conventional road surfaces. The combination of these three properties leads to favorable reduction of vibrational and aerodynamic mechanisms that are active in tyre/road noise emission.

ACKNOWLEDGEMENTS

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REFERENCES

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