Porous top layer optimization of cement concrete slabs for tyre/road noise reduction

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ABSTRACT

The I-STREET CUD-SF project aims at developing an urban pavement made of cement concrete slabs that can be easily removed and replaced for maintenance purposes. These slabs are made of a dense cement concrete body and a functionalized porous top layer ensuring water drainage and sound absorption. In order to optimize the porous layer for the reduction of tyre/road noise, several mix recipes with different porosities and maximum aggregate sizes were considered. The recipes with the most interesting absorption properties were preliminary selected based on absorption coefficient measurements performed on cylindrical test specimens with an impedance tube. A second phase was dedicated to the evaluation of texture induced coast-by rolling noise levels with the tyre/road noise prediction model HyRoNE from 3D texture scans performed on rectangular laboratory samples. Finally, based on a porous medium model and a propagation model considering the tyre/road noise

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source as an omnidirectional point source over an impedance plane surface, the porous layer thickness of the selected mix was adjusted to minimize the predicted noise at roadside for different reference rolling speeds. This paper gives an overview of the results obtained at the different stages of the optimization process, prior in situ assessment of the industrial solution in a near future.

1. INTRODUCTION

The I-STREET project is a research operation funded by PIA3 French national program and operated by which brings together several projects concerning innovative road pavements. Among these, the I-STREET CUD-SF project aims to design a road surface adapted to the urban environment which is made up of cement concrete slabs that can be easily removed and replaced for maintenance or access to the under-pavement network (the French acronym CUD-SF stands for “Removable Urban Pavement with Functionalized Surface”). The slabs consist of a dense concrete body and a porous surface layer to drain water and absorb noise. The purpose of this article is to present the approach to optimize the acoustic performance of the slab surface with respect to rolling noise before in situ implementation of the industrial solution. This optimization was carried out in several stages addressed in four parts.

In Part 2, the principle of the pavement as well as the different mix recipes of porous cement concrete developed for the surface layer are presented. These recipes have been preliminary tested for sound absorption properties with an impedance tube for selecting the most interesting with respect to rolling noise reduction. This is described in Part 3.

To complete the acoustic characterization, three-dimensional texture measurements were carried out on plates manufactured for each selected mix recipe. The readings were used to predict surface roughness-induced rolling noise levels using the HyRoNE [1] model for three reference rolling speeds. The results and ranking obtained are presented in Part 4.

Finally, the combination of roughness induced rolling noise levels predicted with the HyRoNE model and the attenuation due to sound absorption was used to adjust the porous layer thickness of the slabs to minimize the noise levels received at roadside, for each of the considered reference speeds. The results are presented in Part 5, before conclusion in Part 6.

2. CEMENT CONCRETE SLABS AND POROUS TOP LAYER

The general concept of removable urban pavement (RUP) is shown in Figure 1 and described in [2]. The cement concrete slabs are different from traditional paving stones. They are hexagonal in shape and quite large in size with an edge length of 46 cm and an inscribed circle diameter of 80 cm. The slabs are positioned so that their edges are not perpendicular to the rolling direction in order to limit impact noise that might be caused by gaps or steps between slabs.

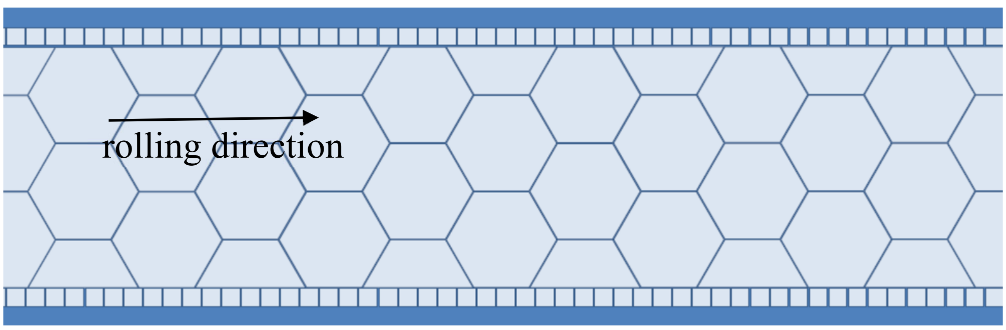

Figure 1: Sketch of hexagonal cement concrete slab assembly.

2.1. Precast slabs

The slabs are precast using a formwork. The porous layer is laid and compacted first in the formwork so as to ensure a flat slab surface through conformation of the surface aggregates against its bottom. The dense concrete of the slab body is then poured, with controlled percolation into the porous concrete for bonding both layers. The slab structure and mechanical strength allow the adjustment of the porous top layer thickness to a certain extent. An example of a precast slab is shown in Figure 2. Lateral shoulders can be noticed that are intended to reduce gaps and rocking between slabs and to inter-connect the slabs to bear the traffic.

Figure 2: Precast slab with porous top layer.

2.2. Porous top layer

Due to the relative complexity of production, the study phase on the acoustic properties of the slabs was carried out on laboratory samples of the porous layer only. Several Porous Cement Concrete (PCC) mix recipes were considered with different aggregate sizes and target porosities. Three maximum aggregate sizes were tested: 4 mm, 6 mm and 10 mm. For PCC 0/4 and 0/10, three target porosities were tested: 15%, 20% and 25%. For PCC 0/6, only the 25% porosity was tested.

3. SOUND ABSORPTION PROPERTIES

Measurements of sound absorption coefficient were carried out with an impedance tube using the transfer function method [3] on the different PCC mix recipes. For each, 3 or 4 cylindrical samples of 100 mm diameter were measured for absorption characterization up to 1600 Hz. The nominal sample thickness was 30 mm for PCC 0/4 and 0/10, and 40 mm for PCC 0/6. Examples of cylindrical samples are shown in Figure 3.

Figure 3: 25% porosity 100 mm diameter samples of PCC 0/4 (left), 0/6 (middle) and 0/10 (right).

The average absorption coefficients and associated standard deviations are plotted in Figure 4. The influence of porosity is noticeable. As expected, the strongest absorption coefficients are obtained for the target porosity of 25% with peak values above 0.8. For PCC 0/4, the porosities of 15% and 20% give lower values but still present peaks around 0.5. On the other hand, for PCC 0/10, the absorption peaks obtained for these porosities are quite low. The three aggregate sizes give similar results for the highest porosity but shifted towards low frequencies for PCC 0/6 due to its larger thickness. Following this stage, the 25% porosity mix recipes were selected for further characterization.

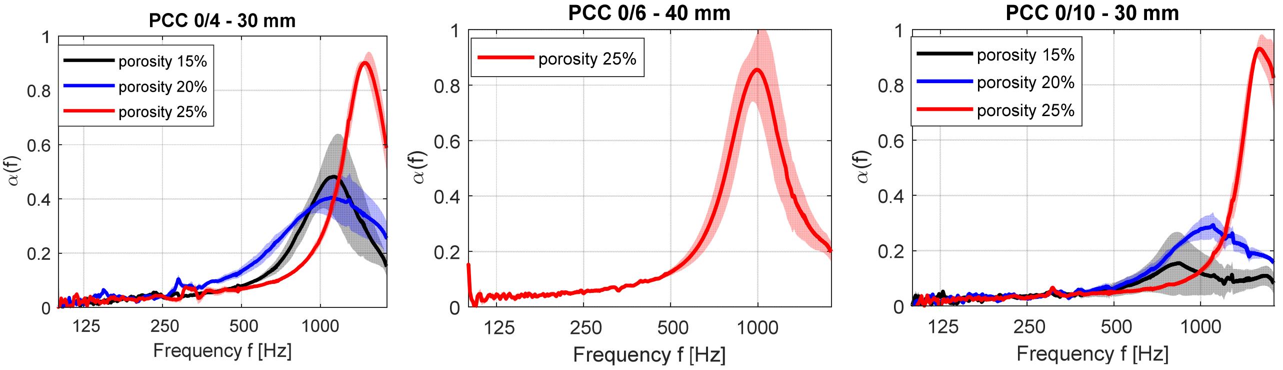

Figure 4: Absorption coefficients measured on 100 mm diameter PCC samples (with the variation range).

4. PREDICTION OF ROUGHNESS INDUCED NOISE LEVELS

One-third octave roughness-induced rolling noise levels were evaluated for the three PCC formulations with the target porosities of 25%. These evaluations were carried out using the HyRoNE model from texture scans performed on laboratory-manufactured samples.

4.1. 3D texture measurements

Three slabs of width 40 cm by length 60 cm were produced in the laboratory for each mix recipe tested using rectangular moulds in accordance with the slab manufacture and compaction method. The slab surface obtained at the bottom of the mould was measured. These measurements were carried out with a three-dimensional texture measurement system [4] that includes a 2D laser profile sensor and allows the reconstruction of 35 cm wide surfaces. The measurement system and extracted parts of the scans are shown in Figure 5.

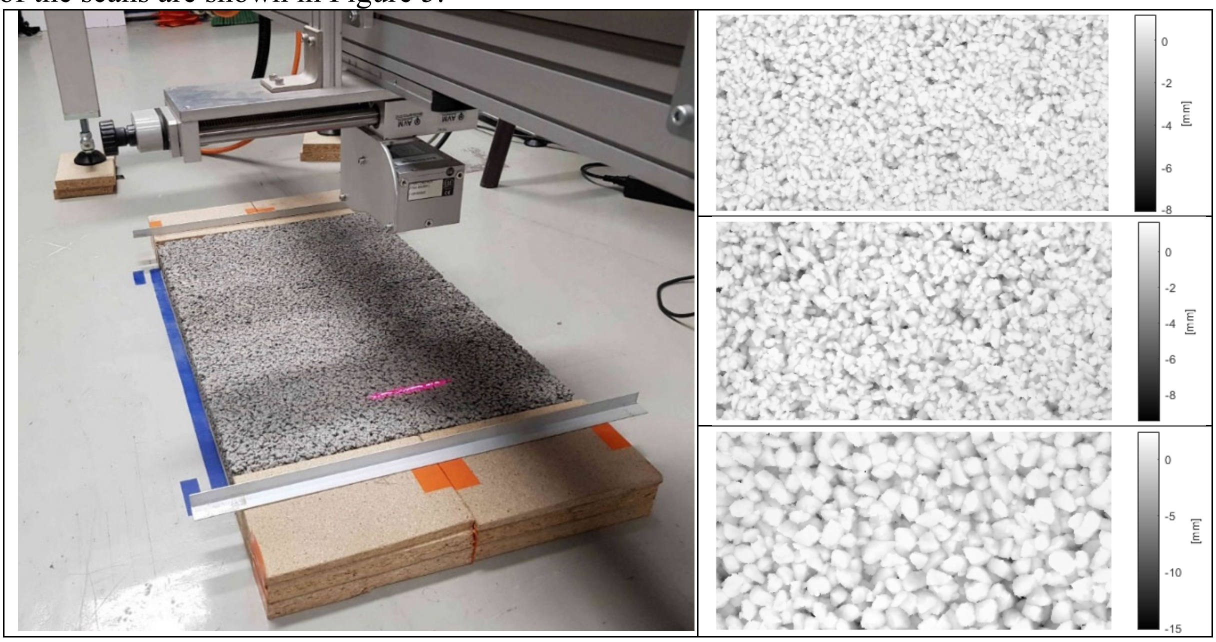

Figure 5: Scanning of a 40 cm by 60 cm PCC slab (left) – Extracts of 10 cm by 20 cm from scans of PCC 0/4, 0/6 and 0/10 (from top to bottom).

4.2. Predicted roughness induced noise levels

The HyRoNE model used to predict noise levels is described in [1]. It predicts Coast-by (CB) noise levels produced by a Renault Scenic fitted with Michelin Energy E3A 195/60 R 15 tyres. One-third octave band noise levels are predicted from roughness levels. In the low and medium frequency domain, the roughness used is a combination of the road surface texture and the tyre tread pattern obtained after an envelopment procedure to account for partial contact [5]. In the high frequency domain, raw texture levels at small wavelengths are used.

The prediction relationships are build using an experimental database that includes texture and CB noise measurements for a wide range of dense road surfaces. The model is built for the prediction of CB noise levels at three reference rolling speeds 50 km/h, 70 km/h and 90 km/h. These noise levels are obtained by logarithmic regression on speeds between 30 km/h and 65 km/h, 50 km/h and 90 km/h, 70 km/h and 110 km/h respectively.

The predicted combined tyre/road roughness induced noise spectra of PCC 0/4, 0/6 and 0/10 are drawn in Figure 6 (left) for the reference speed of 50 km/h. The spectra obtained for a Dense Asphalt Concrete (DAC) 0/10 and a Very Thin Asphalt Concrete (VTAC) 0/4 are added for comparison. As can be observed the spectra obtained for the PCC 0/4 and PCC 0/6 are close to each other, and up to 5 dB lower than that of the PCC 0/10 in the low and medium frequency range. The latter is similar to the one obtained for the DAC 0/10, while the spectrum obtained for the PCC 0/4 is very close to that of the VTAC 0/4.

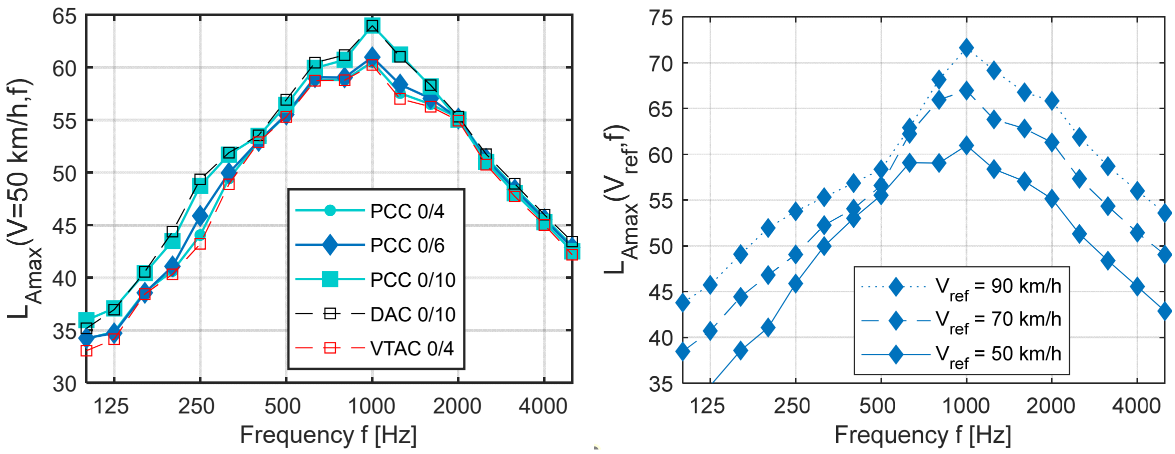

Figure 6: Predicted roughness induced noise spectra at 50 km/h for all PCC recipes (left) and for PCC 0/6 at 50, 70 and 90 km/h (right).

The predicted noise spectra for the PCC 0/6 are drawn in Figure 6 (right) for the three reference speeds considered. As expected a pronounced peak at 1 kHz is observed for 90 km/h. On the other hand the peak obtained for 50 km/h is spread out between 630 Hz and 1 kHz. For 70 km/h an intermediate spectrum shape between those observed for 50 and 90 km/h is obtained.

5. OPTIMISATION OF POROUS TOP LAYER THICKNESS

Based on the sound absorption and roughness-induced noise results of the different PCC mix recipes and other non-acoustic considerations, the PCC 0/6 with 25% porosity was selected for the top layer of the slabs. To account for sound absorption, the attenuation with respect to a perfectly reflective road surface was assessed at roadside and applied to the noise spectrum induced by the tyre/road roughness evaluated in Part 4. The thickness of the porous layer was then adjusted to minimize the overall pass-by noise level for the three reference speeds considered.

5.1. Noise level attenuation due to absorption

The attenuation due to the absorption effect between the vehicle tyres and the roadside is attributed here to the effect of the absorbing ground for an omnidirectional source. The horn effect is not taken into account.

The attenuation is estimated in two steps. First, the parameters of the porous medium are evaluated to express the impedance and the wave number of the medium. The phenomenological model of Hamet-Bérengier [6] is used. Its three parameters (porosity φ, airflow resistivity σ and shape factor q^2) are identified by best fit between measured and predicted absorption coefficients. The model/measurement correspondence for the four tested PCC 0/6 samples is given in Figure 7 (left). The corresponding identified parameters are given in Table 2 together with the thickness of each sample.

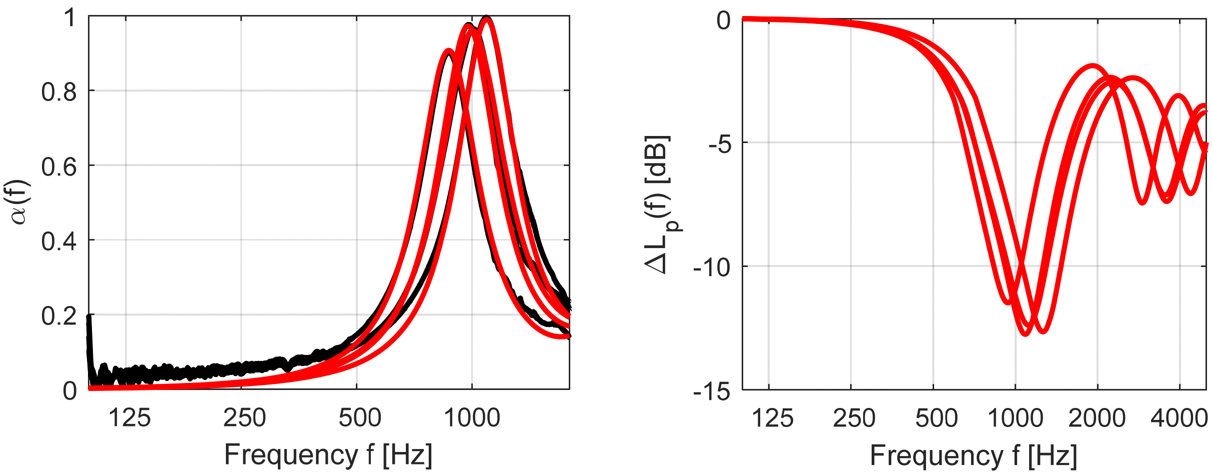

Figure 7: Measured (black curves) and predicted (red curves) absorption coefficient of PCC 0/6 samples (left) – Corresponding attenuation at roadside (right).

Table 2: Hamet-Bérengier porous medium model identified parameter values for PCC 0/6 samples.

Sample	φ	σ [Nsm^{-4}]	q^2	e [mm]
1	0.21	32.2	4	42
2	0.21	12.1	2.7	41
3	0.22	20	3.2	42
4	0.23	24	3.1	41

Secondly, the noise attenuation ΔL_p due to the absorption of the porous top layer with respect to a perfectly reflecting ground is evaluated for the standard pass-by configuration (receiver at 7.5 m from the road center and 1.2 m above the ground) with the tyre/road noise source considered on the ground using the Weyl-Van der Pol formula with a spherical wave reflection coefficient. The attenuation evaluated for each sample of Table 2 is drawn in Figure 7 (right). This attenuation averaged over all samples and for each one-third octave band is then added to the roughness induced noise levels before recomposition of overall CB noise levels.

5.2. Optimal thickness

The optimum porous layer thickness of the slabs was estimated for each reference speed by minimizing the overall noise level recomposed from the predicted one-third octave band noise levels induced by the tyre/road roughness after mitigation for the absorption effect averaged over the parameter values in Table 2. The overall noise levels are plotted as a function of thickness *e* ranging between 30 mm and 70 mm in Figure 8 (left). Due to the differences in shape of the roughness-induced noise spectra (see Figure 6 (right)), the thickness that minimizes the overall noise level depends on the reference speed considered. It was found to be 42 mm for 90 km/h (equal to that of test samples), 48 mm for 70 km/h and 54 mm for 50 km/h. The corresponding attenuations are plotted in Figure 8 (right). The corresponding maximum attenuations occur at the frequencies of 1100 Hz, 950 Hz and 840 Hz respectively.

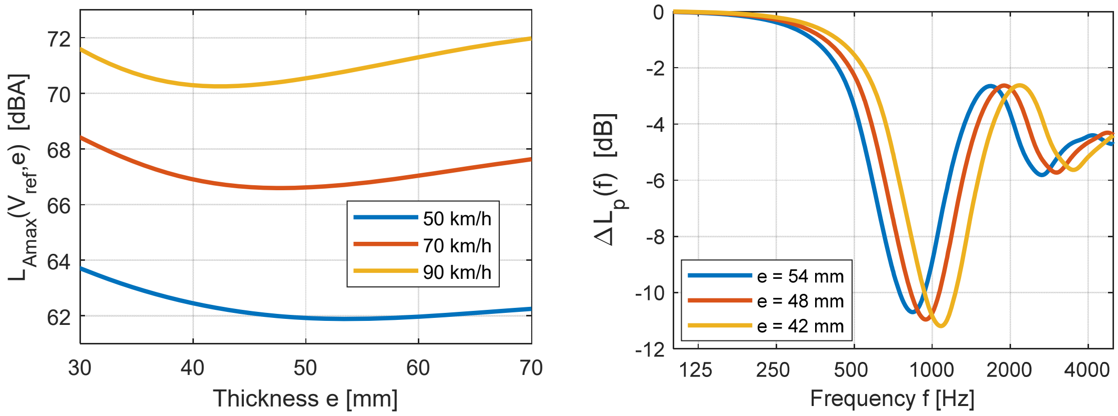

Figure 8: Predicted CB overall dBA noise levels versus porous layer thickness (left) - Attenuation due to absorption for optimal thicknesses (right).

The spectra obtained for the optimal thicknesses are plotted (blue continuous lines) in Figure 9. Also included are the roughness-induced noise spectra (dotted black lines) and the attenuated spectra for the average test samples thickness of 42 mm (blue dashed lines). For the 50 km/h speed, the predicted broadened peak without absorption between 630 Hz and 1 kHz is separated into two maxima at 500 and 1600 Hz. For speeds of 70 and 90 km/h, the spectra obtained show a relatively flattened shape between the frequencies of 630 Hz and 2 kHz.

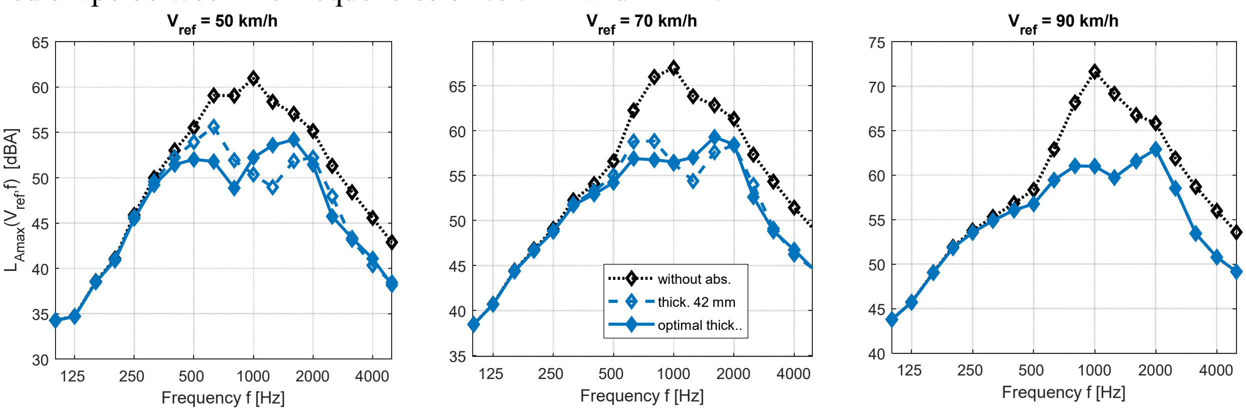

Figure 9: Predicted CB noise spectra for optimal thicknesses, for average PCC 0/6 samples thickness (42 mm) and without correction for absorption effect, for the three reference speeds considered.

6. CONCLUSION

In this study, the porous surface layer of cement concrete slabs intended for the construction of an urban road pavement was optimized with respect to the rolling noise emitted by a light vehicle. The optimization was based on the experimental characterization of sound absorption and texture of laboratory-made samples, and on the use of rolling noise prediction models from road surface characteristics.

The various stages of the study led to the selection of a porous concrete mix with a 0/6mm aggregate size whose thickness was optimized for the minimization of CB rolling noise at different reference speeds of 50, 70 and 90 km/h. Due to the evolution with rolling speed of the shape of the noise spectra induced by the combined tyre tread and road roughness, different optimal thicknesses were identified, ranging from 43 mm for 90 km/h to 54 mm for 50 km/h.

The solution identified for the 50 km/h speed will be implemented within the framework of an experimental demonstrator in an urban environment. One of the challenges for the success of this implementation is also the control of joints between slabs to avoid potential impact noise that could be generated.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. Klein, P & Cesbron, J. Prediction of Coast-by tyre/road noise levels at peri-urban and urban speeds. *Proceedings of FORUM ACUSTICUM 2020,* Lyon, France, December 2020.
2. de Larrard F., Sedran T. and Balay J.-M. , Removable urban pavements: an innovative, sustainable technology, *International Journal of Pavement Engineering*, vol 14 issue 1, pp1-11 (DOI:10.1080/10298436.2011.634912), January 2013.
3. ISO 10534-2:1998, Acoustics – Determination of sound absorption coefficient and impedance in impedance tubes – Part 2: Transfer-function method.
4. Cesbron, J., Gary, V., Klein, P & Clairet, J.-M. On site characterization of optimized very thin asphalt concrete. *Proceedings of Euronoise 2015*, Maastricht, The Netherlands, May-June 2015.
5. Klein, P & Cesbron, J. A 3D envelopment procedure for tyre belt radiated noise level prediction. *Proceedings of INTER-NOISE 2016*, Hamburg, Germany, 2016.
6. Hamet, J.F. & Bérengier, M. Acoustic characteristics of porous pavements: a new phenomenological model. *Proceedings of INTER-NOISE 93*, vol. 2, pp. 641-646. Leuven, Belgium, 1993.