Sound absorption prediction of innovative bituminous mixtures using image analysis

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ABSTRACT

Using porous surfaces shows the greatest sound absorption properties of pavements. The interconnected voids absorb tire-road interaction noise, engine and other environmental noises. The voids are produced by the particle size distribution of the aggregate. Such pavement types have an excellent advantage that it not only reduces traffic noise generation, but also eliminates the need for noise barriers, which are not effective in urban areas due to the noise diffraction phenomenon. So it is important to predict and optimize the sound absorption of those porous road materials.

For classical acoustical porous materials, many models have been developed. They are mainly based on viscous and thermal dissipation effects of the acoustical wave. The most used are semi-phenomenological models and are based on geometrical parameters which are generally directly measured. However, for this determination, samples must be done and cored. For road pavements, it can be difficult and it is sometimes expansive because the road may be closed for this coring. Because of the time to make the samples, the determination of parameters is not fast and it is difficult to follow the evolution of those parameters for safety reasons (for example to see if clogging appears). So we propose in the present paper a non-destructive method based on image analysis to predict the sound absorption coefficient of innovative bituminous mixtures.

A three-parameter semi-phenomenological model, well adapted to porous road materials, is used. The first geometrical parameter, porosity, is evaluated thanks to image analysis on high-quality digital photographs. A specific relation is assumed to obtain the second parameter which is the tortuosity. Then, by analyzing the obtained pore-size distribution (closed to a log-normal distribution), we show that it is possible to deduce flow resistivity which is the third parameter. The proposed methodology is tested on different innovative bituminous mixtures used for quiet roads.

Keywords: Sound absorption coefficient, porous road materials, pore-size distribution.

1. INTRODUCTION

Many studies deal with acoustical characterization on pavement [1-5]. For example, [6] has shown that it is possible to obtain an absorption peak using porous surfaces.

A tire that rolls along a surface produces noise caused by the compression and sudden expansion of air trapped in the tire cavities, which is accompanied by a “suction” or pumping effect. This phenomenon can be attenuated on a road pavement that has good porosity [7] allowing decrease of tire-road interaction noise. The interconnected voids are done by the particle size distribution of the aggregates. However, after a few year of uses, the absorption properties of porous road pavements are decreasing, especially in urban areas, because of the clogging phenomenon. Not only it is important to optimize sound absorption properties of such pavements but it is also crucial to predict properties of such pavements during their lifetime.

There are a lot of sound absorption models for porous materials [8] but less (for example [9]) for asphalt pavements. The classical models for asphalt pavements mainly deal with sound propagation above the porous road surface (for example [10]). All these models often require knowledge of many parameters not easily available, known and measurable in situ for porous road surfaces.

In order to predict sound absorption of ground surface, it is difficult and not reasonable to fit more than two model parameters as shown in [11]. For ground surfaces, one parameter semi-empirical model such as [12] or [13] are often used but they fail to give good fit for porous asphalt because they do not succeed to represent resonant phenomena and those models assume high porosity which is not the case for a granular skeleton such as road pavement.

Concerning acoustical properties of porous asphalt, some authors (like [1]) have developed phenomenological model (modified Zwikker and Kosten model [14]) which allows for frequency dependent thermal effects. Those two last models require three parameters: the porosity, the flow resistivity and a structure factor called tortuosity.

[15] has used a model allowing for arbitrary pore shapes and size and has developed an identical tortuous pore model. In [11], authors have shown that this last model is very appropriate for predicting the impedance (and so the sound absorption coefficient) of road asphalt and all those three-parameter phenomenological models (Hamet, Attenborough...) give similar results and well describe the viscous and thermal dissipation effects. In general, for porous materials the three parameters (flow resistivity, porosity and tortuosity) are directly measured. However, for this determination, samples must be done and cored. For road pavements, it can be difficult and it is sometimes expansive because the road may be closed for this coring. Because of the time to make the samples, the determination of parameters is not fast and it is difficult to follow the evolution of those parameters for safety reasons (for example to see if clogging appears): it is not a non-destructive method.

In the present paper, we propose to predict sound absorption with no curing, by developing a non-destructive method based on image analysis of the porous surface.

As shown by [11] it is possible to reduce the number of parameters to two in those previous mentioned models by using a specific and simple relationship between tortuosity and porosity. Those two geometrical parameters are the flow resistivity and the porosity. Those parameters are geometrical parameters so they can be determined by image analysis by analysing pictures of bituminous mixtures.

2. METHODOLOGY

We use a three-parameter semi-phenomenological model like [15] (with shape factor set by default at unity for regular pores as suggested by [16] and as performed in [11]) taking into account the viscous and thermal dissipation effects occurring into road asphalt. The three parameters are the whole connected porosity ϕ, the flow resistivity σ ($N.s.m^{-4}$) and the tortuosity α_∞. With this model, it is possible to predict the sound absorption coefficient α.

Then, as underlined in [11], it is possible to reduce the number of parameters to two by using a specific and simple relationship between tortuosity and porosity. [17] has suggested the following relation for granular media:

$$\alpha_\infty = \phi^{-n} \tag{1}$$

with n a constant depending on the grain shape factor .

In the present paper, we have chosen to take $n = 0.85$ as suggested in [18] and in [11] for porous asphalt. We have validated this value by performing several measurements on porosity and tortuosity of different samples.

2.1 Porosity evaluation

By using pictures (good-quality digital photographs) of the upper face of materials and by making a classical image analysis it is possible to determine the whole connected porosity ϕ. A matlab © code has been developed to obtain this parameter just by image processing (pixels area calculation) as shown in Figure 1 for a sample of bituminous mixture of diameter 40mm.

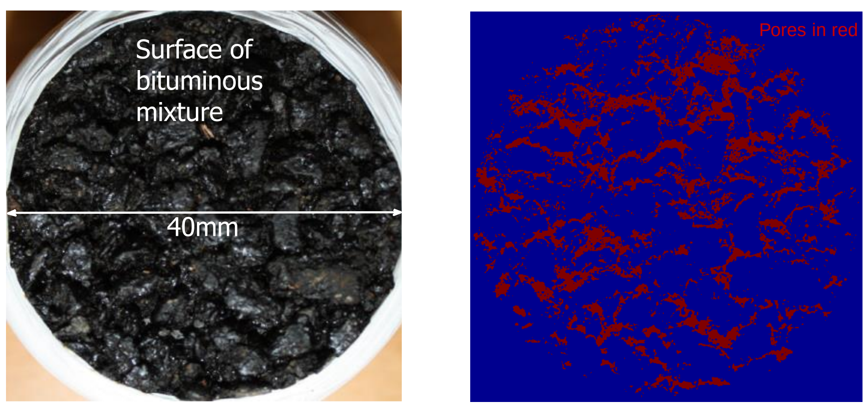

FIGURE 1 Evaluation of porosity thanks to image processing.

2.2 Resistivity evaluation

Even if the real geometry of pores is not exactly known, for practical applications it can be suggested (as done in lot of publications, for example in [19] and [20]) to assume circular pores. Even if the pores are not circular ones, an extent can be performed as exactly done in [20] by taking an equivalent radius of each connected region (pixels which are connected). Indeed, equivalent fluid models, assuming some hypothesis on the micro-structure, may be applied for complex pores network [8]. The pores are automatically countered and the equivalent radius R is automatically calculated as the radius of the circle with the same area. The probability density function can then be calculated for the radius R expressed in mm. An example of the obtained pore-size distribution is shown in Figure 2.

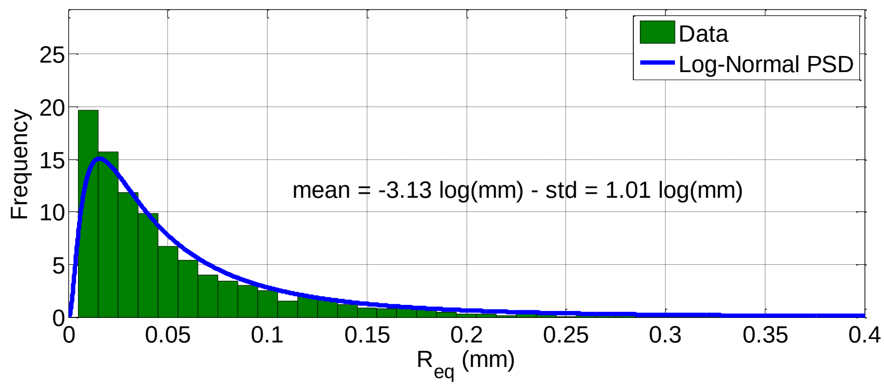

FIGURE 2 Pore-size distribution and associated log-normal distribution for a bituminous mixture sample.

For a lot of measurements, we obtain closely a log-normal distribution (as for granular materials). This hypothesis is thus taken into account in the present paper. The mean $\overline{R}$ and standard deviation σ_S are determined owing to the image processing. For circular pores it is easy to show [21] that resistivity σ can be related to the equivalent median pore size R_{eff} as :

$$\sigma = \frac{8\alpha_\infty \mu}{\phi \, R_{eff}^2} \tag{2}$$

where μ is the dynamic viscosity of air and:

$$R_{eff}^2 = \int_0^{+\infty} R^2 e(R) dR \tag{3}$$

Where $e(R) = E'(R)$ with $E(R)$ the cumulative pore size distribution.

Moreover, for a log-normal distribution, because of the given density probability function we obtain:

$$R_{eff}^2 = \overline{R}^2 e^{2(\sigma_S \ln 2)^2} \tag{4}$$

Thus, owing to $\overline{R}$ and σ_S previously determined and with porosity ϕ and tortuosity α_∞ previously evaluated, it is possible to evaluate resistivity σ with Eq.(2).

3. EXPERIMENTAL VERIFICATION

The proposed methodology is tested on different innovative bituminous mixtures used for quiet roads. Those bituminous mixtures have been developed and patented by the company Eiffage Infrastructures and are characterized by a high void content. Those three materials are a classical Microphone® mixture (MI), a classical Nanophone® mixture (NA) and a modified mixture (MNA). Those mixtures are shown in Figure 3 where good-quality digital photographs have been taken (more than 35 pixels/mm).

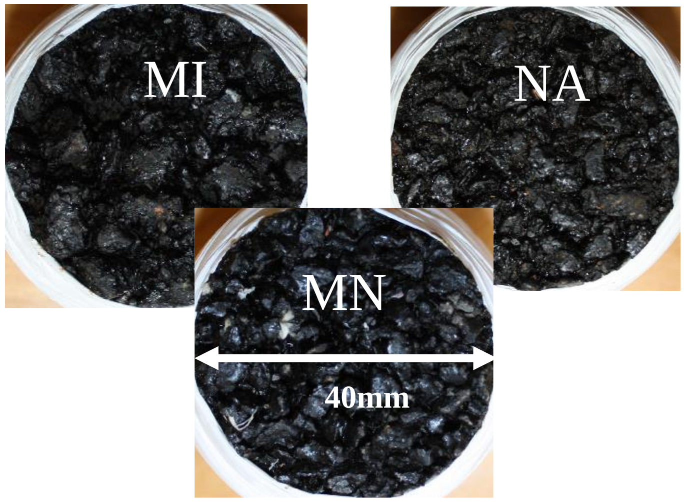

FIGURE 3 Photographs of bituminous mixtures for image processing

Sound absorption measurements have been performed using the impedance method. They have been performed using a home-made tube (46mm diameter) to measure the sound absorption in a frequency interval [50-4300Hz]. The noise absorption coefficient is measured using the transfer function method. This method is defined in standard EN ISO 10534-2, 2003 [22]. Measuring the transfer function between two microphones gives the noise absorption coefficient in normal incidence α .

Figure 4 shows the measured and predicted sound absorption coefficients for the three bituminous mixtures.

The agreement is quite good. The locations of the absorption peaks are well predicted. The overall shape of the curves is respected both qualitatively and quantitatively. It should be noticed that the model slightly under-predict the amplitude of the absorption peaks.

It is logical that predictions are not excellent for higher absorption since we are using a three-parameter model. Indeed, the model can be enhanced by incorporating more parameters such as thermal and viscous characteristic lengths but in the present paper the aim is to use few parameters directly accessible by image analysis to obtain a quite good prediction.

To verify the proposed methodology and model, we have also measured directly porosity, resistivity and tortuosity. We have found that values of parameters obtained by the present methodology are coherent (by taking into account uncertainties and repeatability errors of measurements, predicted range is in range of direct measured values). The prediction is less good for MNA. This material is more porous and the surface image of the material sample seems to be less representative with respect to its internal structure but the approximation remains acceptable.

Mean relative errors between the measurements and the mean of the prediction range for all frequencies of interest for applications are less than 10%. This result illustrates the fact that the predictions are good but not excellent at certain frequencies. Even if the prediction can be enhanced, the agreement between experimental measurements and predictions seems sufficient to give good indicators for road materials engineers.

3. CONCLUSIONS

Geometrical parameters used in acoustical models adapted for bituminous mixtures have been determined thanks to image analysis. Sound absorption coefficients have been predicted owing to image processing of digital-photographs of bituminous mixtures surface. The proposed methodology is mainly based on pore-size distribution. This pore-size distribution is very close to log-normal. Three geometrical parameters have been determined and used in an acoustical model: porosity, resistivity and tortuosity. A specific relation between tortuosity and porosity is assumed. Porosity is directly measured by image analysis and the resistivity is deduced by mixing image processing data and the previous parameters values.

The proposed methodology has been tested on three real bituminous mixtures (of various porosities ranging from 14 to 29%) with success. For small porosities (under and about 0.2), we have shown that the prediction remains quite good but uncertainties appear for higher porosities.

It remains to apply the proposed methodology in-situ in roads which are designed to absorb noises. The model can also be used to obtain a desired sound absorption coefficient. With inverse methods, it will be possible to obtain the ideal pore-size distribution to obtain a given sound absorption coefficient.

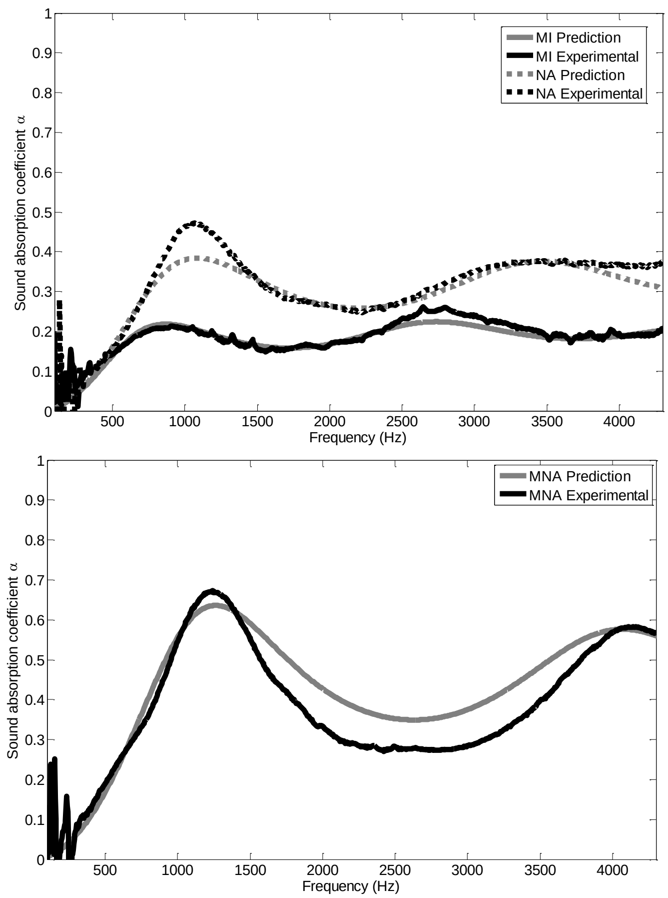

FIGURE 4 Measured and predicted sound absorption coefficients

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