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ESTIMATION OF THE POROSITY OF ASPHALTS BY SURFACE IMPEDANCE MEASUREMENT

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Road surfaces made of porous asphalt have several advantages: e.g. the high amount of air void reduces noise and drains water. These effects depend strongly on the porosity that is achieved in the laying process.

By now the usual way to determine the porosity is to measure it on cores taken from the road surface. But this method is destructive and the cores can be taken from few positions only, which is not sufficient for statistics. Furthermore, the porosity can be determined only after the construction work is finished. So it is not possible to influence the air void inbuilt during the laying process.

In the paper a new method for the determination of the porosity without these disadvantages is presented. The approach bases on acoustical properties that can be measured at the road surface without damaging it. In connection with the Phenomenological Model the material properties can be calculated. So it is possible to compute the porosity immediately during the laying process.

1. Introduction

Open graded porous asphalt reduces the traffic noise of cars at medium speed significantly. It acts as acoustic absorber but also reduces the generation of noise by suppressing the air pumping of the tyre-road system. When driving on porous asphalt the pumped air is pressed into the open channels and not set into vibrations by being compressed and expanded between road and tyre surface. The sound absorption as well as the ability to drain water from the surface depends strongly on the porosity that is achieved in the laying process. In order to obtain the best effect it must have values between 10 % and 30 %, depending on the type of asphalt. The porosity is influenced by the rolling process. The difficulty consists in finding the best time to stop the rolling, i.e. to detect if the porosity has achieved the desired value. By now the usual way to determine the porosity is to measure it on cores taken from the road surface. This method is destructive and the porosity can only be determined after the construction work is finished. So it is not possible to influence the porosity created during the asphalt construction.

This work suggests a non-destructive method that can be applied during the road construction process.

2. Theory

The sound field above a porous media can be calculated by the surface impedance $\underline{Z}_S$. In this case the surface has to be even and large compared to the wavelength. If there is a layered porous media with the thickness of i-th layer d_i the following recursive equation (the surface impedance of the upper layer is calculated by that impedance of the neighboring bottom layer) is applied:

$$\underline{Z}_{s_i} = \underline{Z}_i \frac{\underline{Z}_{s_{i+1}} + i\dfrac{\underline{Z}_{Ai}}{\cos\vartheta_i}\tan\vartheta_i}{\dfrac{\underline{Z}_{Ai}}{\cos\vartheta_i} + i\underline{Z}_{s_{i+1}}\tan\vartheta_i}, \quad \vartheta_i = k_{Ai} d_i \cos(\underline{\vartheta}_i)\cdot \tag{1}$$

In this work the open porous asphalt is considered as a porous media. Thus the formula above allows beneath others the calculation of double layered asphalts. For the prediction of the surface impedance of a "one layer" of asphalt the surface impedance of the bottom layer can be assumed as infinite. So the equation (1) simplifies to

$$\underline{Z}_s(\omega) = -i\underline{Z}_A \cot(\underline{k}_A d).$$

In Equation (1) the characteristic impedance $\underline{Z}_{Ai}$ and the characteristic wave number $\underline{k}_{Ai}$ have to be predicted by an absorber model. There exist a number of models which connect these characteristic values of a porous media with the parameters of the material. The base of the method presented here is the so-called Phenomenological Model [Hamet93]. It describes the porous asphalt as a homogeneous medium which dissipates sound into thermal energy and can be characterized by the values of the characteristic impedance and the wave number. This characterization by averaged parameters is justified because of the relevant frequency range from about 200 Hz to 3000 Hz. Here the interesting wavelength in asphalt is much larger than the typical grit size (<1 cm).

The advantage of the phenomenological model is that it requires only three input parameters which can be measured directly: the porosity σ , the tortuosity τ and the flow resistance Ξ . The porosity is the relation between the volume of the accessible cavities and the total volume. It is the most important control parameter for the effectiveness of noise reduction of the asphalt. With help of a PU-probe [Bree96] the surface impedance

$$\underline{Z}_S(\omega) = -i\underline{Z}_A(\sigma,\tau,\Xi,\omega)\cdot\cot\left(\underline{k}_A(\sigma,\tau,\Xi,\omega)\cdot d\right) \tag{2}$$

is measured. The characteristic impedance $\underline{Z}_A$ and the wave number $\underline{k}_A$ depend on the material parameters. To determine the porosity σ from the measured surface impedance $\underline{Z}_S$, equations (1) and (2) have to be inverted in some way. The complicated dependencies indicate that it is not possible to give a simple analytical solution for this problem. Furthermore, the system of equations is over-determined because equations (1) and (2) are valid for each frequency ω . That implies statistical methods to be suitable to estimate the parameters from the impedance. The principal idea is to fit the parameters by minimizing the difference between the measured values and the model.

The material parameters are not independent. Hence it, there exist statistical relations between them [Saaradj06]. They allow the tortuosity and the flow resistance to be expressed in terms of the porosity. So equation (2) changes to

$$\underline{Z}_S(\omega) = -i\underline{Z}_A\big(\sigma,\tau(\sigma),\Xi(\sigma),\omega\big)\cdot\cot\big(\underline{k}_A(\sigma,\tau(\sigma),\Xi(\sigma),\omega)\cdot d\big). \tag{3}$$

Thus there are only two parameters that have to be estimated: the porosity σ and the thickness *d*.

Estimation procedures, e.g. Newton approximation, are usually iterative methods. After starting with initial values the procedure tries to converge to a local minimum of an objective function (4) which quantifies the deviation of the fitted values $f(\underline{Z}_S^{theory}(\omega))$ from the measured data $f\big(\underline{Z}_S^{data}(\omega)\big)$:

$$F(\sigma,d) := \frac{1}{Z_0}\sqrt{\sum_{i=1}^{n}\left|\underline{Z}_s^{data}(\omega_i) - \underline{Z}_s^{theory}(\omega_i)\right|^2} \longrightarrow \min . \tag{4}$$

The well known crucial point is the choice of the starting values. The PU-probe measures the complex surface impedance $\underline{Z}_s^{data}$, so the function *F* can depends on $\underline{Z}_s^{theory}$ only.

In a first step an estimation procedure for the starting values was developed by use of the Euclid's algorithm [Ditrichlet78]. However the test of the accuracy of this algorithm shows no satisfying results. But the simplification in (3) leads to a short computing time. So there is the possibility to start with pool of starting values. The value of the grid is given by the wavelength of the oscillations of the function *F* shown in Figure 1. Moreover the range of the values is given by technical restrictions: At the starting of the rolling process of the asphalt the porosity is approximately 40 %. If the rolling process is finished the porosity should have values above 20 %. In many cases the thickness of one layer has to be in the range of 40 mm. The thickness at the starting of the rolling process is approximately 50 mm. So the starting values of the iterations process have to lie in the range of [20 %, 40 %] und [30 mm, 50 mm].

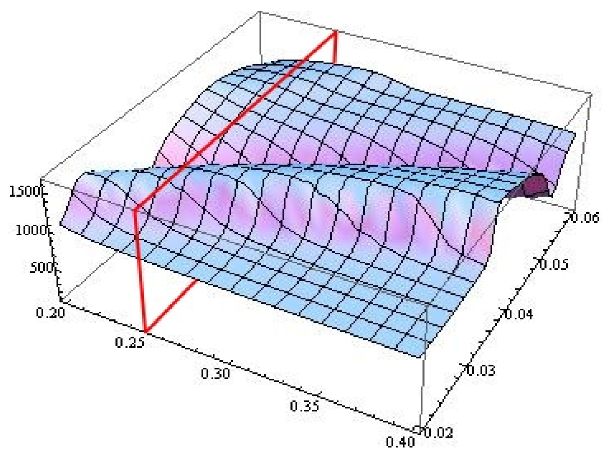

Figure 1. *Function F* in equation (4) in dependency of porosity and thickness of the layer.

3. Laboratory tests

To proof the algorithm the surface impedance was computed by equations (1) and (2) and by given values of the parameter of porous asphalts: the porosity σ, the tortuosity τ and the flow resistance Ξ and the thickness *d*. The data computed were used as input values $\underline{Z}_s^{data}$ in equation (4).

By that the porosity σ and thickness d have been estimated. The comparison of the estimated and the given values shows a 100 % agreement of the values.

In a second step the validation was carried out by applying the equation (4) on the data of a pool of 200 Marshall Specimen. The surface impedance of the specimen was measured in Kundts Tube. The porosity σ and thickness d are estimated by equation (4). Following the estimated and the directly measured data (porosity, thickness) have been compared. In Figure 2 the result of that comparison is shown as a relative frequency of occurrence of the deviations of the data.

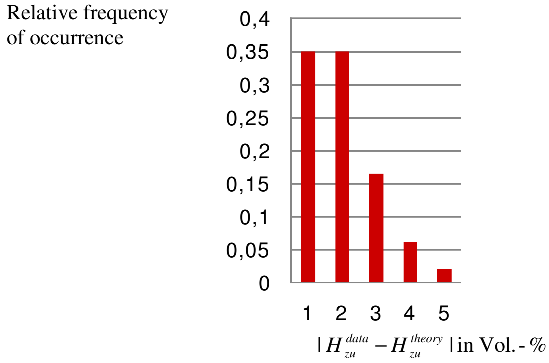

Figure 2. *Relative frequency of occurrence of the deviation of data of the porosity estimated by equation (4) and the results of directly measured values (pool of 200 Marshall Specimen).*

The calculation of the 95% quantile gave a deviation limit of 3,4 Vol. %. From a practical point view this deviation has to be classified as to high for the monitoring of the road construction process.

Parameter studies to the accuracy of the approach were carried out. It pointed out, that the Phenomenological Model is one of the important reasons which explain the insufficient accuracy. For certain amount of Marshall Specimen the prediction of the acoustical behavior fails by use of the model. As an example Figure 3 shows a strong deviation between the results of measurement by Kundts–Tube and the prediction by Phenomenological Model.

By neglecting those specimens which are not correct described by the absorber model the accuracy of the estimation approach (Eq. 4) is strongly increased. The practical relevance of this limitation has to be clarified. Moreover the derivation of a simple empirical model in the given range of parameter seems to be sense full.

4. Summary

In the present work an approach to a non-destructive and instant determination of the porosity of open graded porous asphalt was presented. It bases on the measuring of the surface impedance with the help of a PU probe and on the calculation scheme that uses the phenomenological model for porous absorbers. The calculation of the 95% quantile of the deviations gave a limit of 3.4 Vol. %. From the practical point view this deviation has to be classified as to high for the monitoring of the road construction process.

The Phenomenological Model has to be mentioned as one of the reasons of the insufficient accuracy of the predictions. By neglecting those specimens which are not correct described by the absorber model the accuracy of the estimation approach is strongly increased.

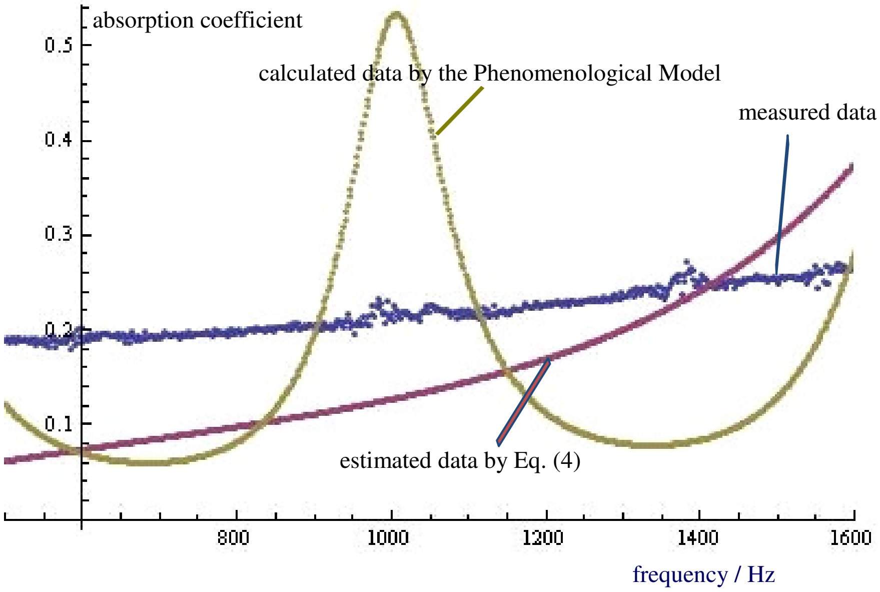

Figure 3. *Deviation of the results of measurement carried out by Kundts–Tube and the prediction by Phenomenological Model.*

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