Influence of Pore Structure on Sound Absorption in Porous Road Surfaces

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Introduction

Porous asphalt surfaces are commonly applied on Dutch roads, due to their water drainage capacity and their ability to reduce traffic noise by sound absorption. For highways, double layer porous asphalt is a common noise abatement measure for populated areas with high traffic loads. Double layer porous asphalt has a fine surface texture, which reduces mechanical excitation of the tyres, combined with a high degree of sound absorption.

The sound absorption characteristics of porous materials strongly depend on the microstructure of the air voids. For porous asphalt surfaces, the pore structure is a result from the structural design and normally not from any acoustical design objective. The structure depends on mixture design as well as compaction methods and circumstances, and is subject to changes over time due to traffic loads and pollution.

For a better control of the sound absorption, there is a need for better understanding of the influence of stone mixture, bitumen content, layer thickness, compaction and other choices during the design and application of porous road surfaces. Extending the knowledge in this area will lead to practical guidelines for road constructors with regards to design, production and application.

Influence of sound absorption on traffic noise

A sound absorbing road surface effectively reduces the noise emitted by the road vehicles. The most important noise reduction mechanism is the reduction of the so-called ‘horn-effect’.

Rolling noise from the vibrating tyre surface is mainly radiated efficiently from the region around the tyre/road contact patch. There, the noise is amplified by the horn-shaped geometry formed by the curved tyre and the road surface, similar to the horn of a trumpet or a vintage gramophone.

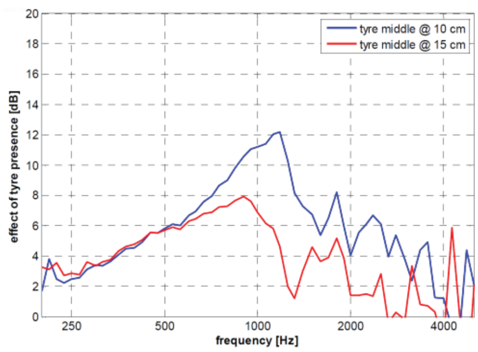

Figure 1: The horn-effect leads to amplification of tyre/road noise for a passenger car tyre up to 12 dB around 1 kHz

This horn effect leads to a noise amplification of up to 12 dB around 1000 Hz for a regular passenger car tyre, as was found from in-situ measurements [1] and from lab measurements by others, e.g. [2], see Figure 1. The amplification is considerably lower at low frequencies (< 500 Hz) and at higher frequencies (> 2 kHz).

The amplification of tyre/road noise by the horn effect can be quite effectively reduced by applying a sound absorbing road surface. The radiation efficiency of the horn is drastically reduced, since the reflections on one side of the horn are partially eliminated [1].

Porous asphalt surfaces consist of stones of different sizes, filler (usually sand) and bitumen (asphalt). The specific structure of these porous surfaces leads to sound absorption at distinct frequency ranges: at certain frequencies, the absorption coefficient may reach 0.9 or more, while at neighboring frequencies the sound absorption is close to zero (see Figure 2, top graph). To effectively reduce the tyre/road noise, sound absorption should ideally occur at the frequencies for which the horn amplification is high. Figure 2 shows that the same amount of sound absorption (around 90%) has a lower effect around 650 Hz than it has around 900 Hz, as was measured with a passenger car tyre. It is important to tune the sound absorption frequencies to the noise spectrum emitted by the road vehicles. For passenger cars, sound absorption should occur around 800 – 1000 Hz; for trucks, around 600 – 800 Hz.

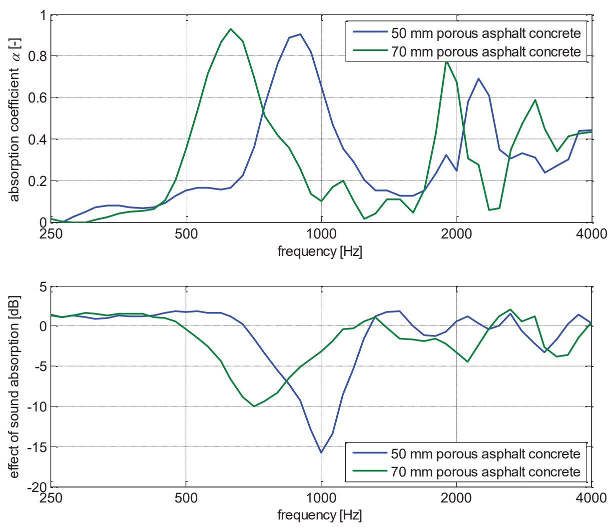

Figure 2 top: sound absorption spectrum measured in-situ on porous asphalt concrete (50 mm single layer, 70 mm double layer); bottom: reduction of the horn amplification measured on these surfaces

Relations between pore structure and sound absorption

The sound absorption characteristics of porous asphalt surfaces depend mainly on the structure of the air voids (pores) between the stones, filler and bitumen. The relations between sound absorption and pore structure have been studied and described in models by e.g. Hamet [3] and Attenborough [4]. Both derive from earlier work by Zwikker and Kosten [5]. These models describe the relation between the pore structure and absorption using four parameters:

- porosity: the fraction of air voids in the volume;
- flow resistivity: the specific airflow resistance per unit length (thickness), in N·s/m^4;
- layer thickness;
- shape factor: the definition of shape factor varies between models; it includes the tortuosity, as an effective length factor, and may also include variations in channel width, leading to modification of the sound wave speed.

Other models that describe sound propagation in relation with pore structure exist. The descriptions by Johnson [6] and Allard [7], for instance, introduce thermal and viscous characteristic lengths, which describe the pore shapes in more detail than the general shape factor described above.

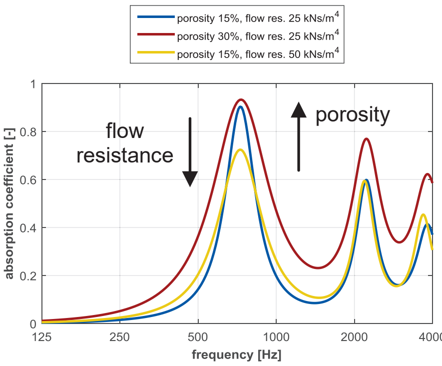

Figure 3: For a single porous layer, flow resistance and porosity mainly affect the amount of sound absorption; arrows indicate the effect of increasing parameter values

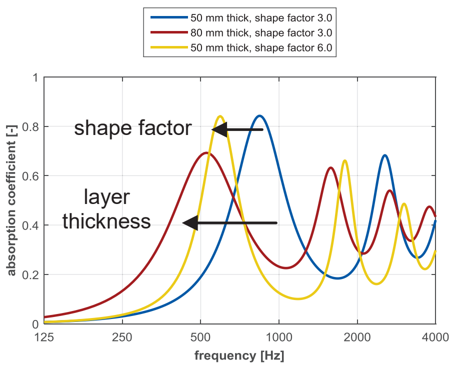

Figure 4: For a single porous layer, the layer thickness and shape factor affect the frequency at which absorption occurs; arrows indicate increasing parameter values

The influence of parameter variations on the sound absorption characteristics of a porous road surface is illustrated in Figures 4 and 5. Changes to the porosity and/or flow resistance affect the height and width of the peaks, but not the frequencies of the absorption maxima (Figure 3). The layer thickness and shape factor influence the effective length of the pores, thus the resonant frequencies in the porous layer and hence the frequencies at which the absorption maxima occur (Figure 4).

Investigating pore structure in porous asphalt

To investigate the pore structure of porous asphalt, we have taken a series of bore cores, drilled four different highway test sections of double layer porous asphalt concrete. The sound absorption for these bore cores was measured in a 100 mm impedance tube according to ISO 10534-2 [8].

The pore structure of the asphalt mixture of the bore cores was investigated by using computed tomography (CT-scans) made at the TU Delft. The scans were made on the 100 mm bore cores, up to 80 mm in height, with a horizontal voxel resolution of 0.21 mm and a vertical resolution of 0.6 mm.

To extract the air void geometrical structure, we have developed a processing method based on image analysis. The grayscale images of the slices and a grayscale threshold value were used to extract only the air voids (see Figure 5). A connected-component labeling technique was then applied to separate the different voids for each slice in 2D. Then, the different pores have been reconstructed by a tree network search algorithm (i.e. starting from each void in the top slice and finding which voids in the slice below are connected, stepping downward slice by slice to find the entire channel, see Figure 6).

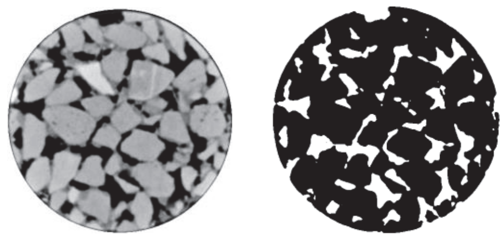

Figure 5: One horizontal slice from a CT-scan of a porous asphalt concrete bore cores (PAC 11/16); left: grayscale image (black = air, dark/light gray = bitumen/stone stone); right: binary image of the same slice, with white indicating the air voids

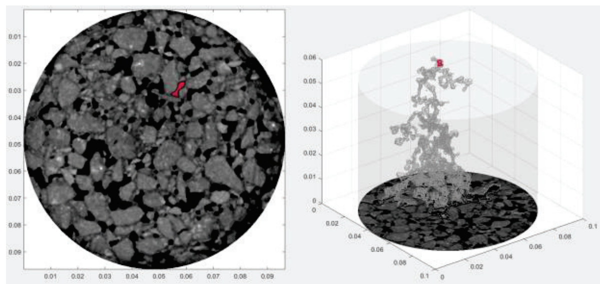

Figure 6 left: CT-scan for the top slice of the bore core, with one pore entrance indicated in red; right: the entire 3D air channel connected to this entrance, 60 mm in height

Porosity in double layer porous asphalt

Using the CT scans and analysis technique described above, the shape of the different pores inside the porous material can be investigated. This analysis also provides information about the distribution, as a function of depth, of the air voids in the material. Common techniques to measure the void content in porous asphalt rely on the difference in volume between the original and the crushed material, or measure the volume change by submerging the sample in a fluid. The second technique is somewhat less accurate, because the fluid may not fill the entire pores. The first technique has the disadvantage that is measures the total void content of the material, including inaccessible (closed) voids that do not contribute to the sound absorption. The difference between the total void content and the accessible void content has shown to be quite large especially for asphalt surfaces with lower porosity values.

Figure 7: Double layer porous asphalt has a top layer, 15 – 30 mm thick, with small stones (≤ 8 mm), and a bottom layer, 30 – 60 mm thick, with larger stones (≤ 16 mm)

A double layer porous asphalt surface typically consists of a fine-graded top layer and a coarse-graded bottom layer (see Figure 7). To model the sound absorption, it is important that we know the porosity of the top and bottom layer separately. Also, at the interface between the top and bottom layer, the porosity may locally be lower, because the smaller stones of the top layer are pressed into the voids between the bottom layer stones during compaction of the asphalt. This may lead to a lower sound absorption and hence a lower noise reduction than expected.

Figure 8 shows the porosity as a function of the height in the two double layer porous asphalt bore core samples, coded P2-3R and P1-2R. The graph is obtained by calculating, for each CT slice, the percentage of the surface area occupied by accessible voids. The accessible porosity is then plotted on the horizontal axis, versus the vertical position in the sample on the vertical axis. The dashed horizontal grey line indicates the interface between the top and bottom layer. The average values for porosity of the top and bottom layer are also shown. From these two samples, and also from the other samples we have measured, we conclude that the expected local decrease in porosity at the interface is not very prominent for the current test sections.

The sound absorption measurement results for these two bore cores are shown in Figure 9. The maximum absorption coefficient for P2-3R is lower than for P1-2R, which corresponds to the lower porosity of the top layer. The analysis also showed that the average cross-sectional area of the pores in the top layer is approximately 30% lower for the P2-3R than for the P1-2R, which is likely to result in a higher flow resistance, although the flow resistance was not measured. Higher flow resistance leads to a lower and wider absorption peak (see Figure 3).

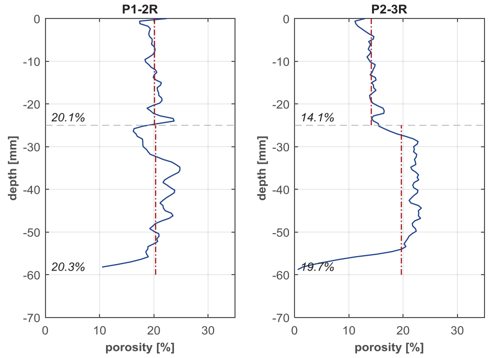

Figure 8: Accessible porosity as a function of height for two bore cores: P2-3R has a considerably lower average void content in the top layer than P1-2R

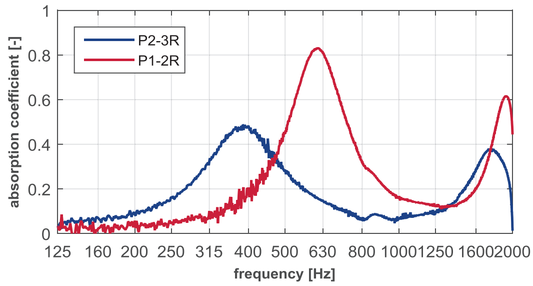

Figure 9: Sound absorption measurement results for bore cores P1-2R and P2-3R

The frequency for the first absorption maximum is around 600 Hz for P1-2R, and around 380 Hz for P2-3R. For a single layer porous asphalt, we concluded that porosity does not influence this resonance frequency (see Figure 3). For a double layer porous asphalt surface, the frequency of the first absorption peak depends on the ratio of the porosities of the top and bottom layer. This was known from model calculations for two-layer porous materials (see Figure 10), but now it is confirmed from measurements on actual double layer porous asphalt surfaces. Part of the frequency shift could also be explained by a difference in shape factor, but we've not yet been able to confirm or disprove this.

The effect can be understood from Helmholtz' theory of graduated resonators. In fact, it can be derived this theory that the ratio of frequencies of the first absorption peak (f_1) and the second absorption peak (f_2) has a linear relation with the square root of the ratio of top and bottom layer porosities [9]. Figure 11 shows that this relationship also applies for the experimental data found from eight bore cores examined.

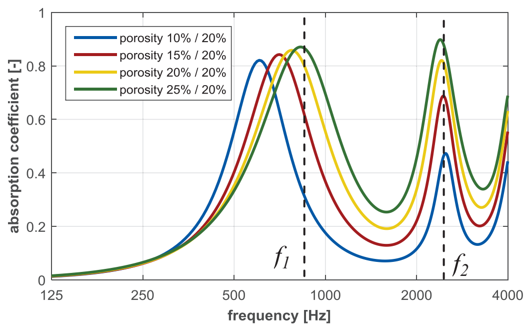

Figure 10: Calculations using the Hamet model show that the ratio of top and bottom layer porosities affect the frequency of the first absorption peak (f_1)

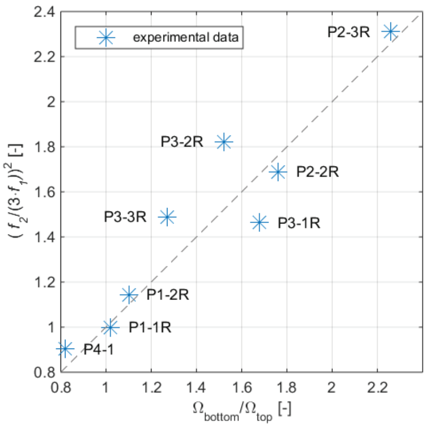

Figure 11: The squared ratio $f_2/3 \cdot f_1$ for the first two resonance frequencies versus the ratio of porosities of bottom / top layer, for eight different double layer porous asphalt bore cores

Investigating the shape factor

Although the shape factor used in the various absorption models has different definitions, it does in general relate to the tortuosity. To investigate this, we have approximated the tortuosity from the CT-scans and compared it with estimated shape factors from the absorption models. To approximate the tortuosity from the CT-scans, we developed an algorithm that works as follows:

- for one 3D air channel (see Figure 6), find every unique path running from the top of the channel in a downward direction; every bifurcation means a new unique path;
- for each unique path, calculate the total 3D path length l_e
- for each unique path, approximate the tortuosity by dividing the path length by the layer thickness: $\tau = l_e / l$

Using this algorithm we were able to determine the average tortuosity values for the top and bottom layers. These were compared with the estimated shape factor values, found from a numeric fit of the absorption model parameters to the measured sound absorption spectra. This showed to be not a good approximation of the shape factor: the values found for tortuosity from the CT-scan analysis were generally higher than the values found for the shape factor. We expected to find that the approximated tortuosity was lower than the shape factor because our approximation does not include variations of channel cross-section. Variations in cross-sections lead to dispersion of the microscopic velocity and a further increase of the apparent air density, hence an increase of the shape factor, as suggested by Carman [10] and others (see [7]).

We conclude that our results for the tortuosity, which merely expresses the physical increase of the path length, are, in any case, an overestimation. In our search for a better relation between the 3D pore structure and the absorption, we will also consider more detailed descriptions based on thermal and viscous length factors [6][7].

Conclusions

The analysis of the pore structure of porous asphalt in 3D, using CT-scans, has proven to be a valuable tool for investigation of the relations between pore structure and sound absorption. It showed that the porosity varies as a function of depth position in the layer and this variation leads to a shift of the frequencies of the absorption maxima in comparison with a layer with homogeneous porosity. The case of double layer porous asphalt is an extreme example of this, but variations of porosity also occur in road surfaces that are considered homogeneous on a macro level. Modelling these layers with a single porosity value may lead to deviations from the measured absorption.

We developed an approximation of the tortuosity by averaging the path length of individual 3D pores and dividing this with the overall layer thickness. This approximation leads to an overestimation of the tortuosity.

Our future research will aim a finding a better relation between the 3D pore structure and the shape factor used in the absorption models. The relation between the pore width and the flow resistance will be included. These new insights will help us in optimizing the asphalt design and production process for road constructors.

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