Characterizing and modelling the sound absorption of wood wool cement boards (WWCB)

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The present article aims to characterize and, by using impedance models, predict the sound absorption of wood wool cement boards (WWCB). The main challenge lies in the inhomogeneity of the WWCB; the samples taken from different commercial boards do not only greatly differ in density, but also in wood-to-binder ratio. Different models, able to predict the acoustic impedance of rigid-frame porous materials, have been analysed and their suitability for the WWCB has been evaluated. It is concluded that the Johnson-Champoux-Allard (JCA) model was found to be most appropriate to fit the normal incidence sound absorption values as measured in the impedance tube. From the five input parameters for this impedance model, the flow resistivity has been measured. The open porosity, tortuosity and viscous and thermal characteristic lengths, have been determined by making use of an inverse calculation method, a curve fitting approach, based on the measured acoustic absorption coefficients in the impedance tube. The tested WWCBs are made of three different strand widths (1.0, 1.5 and 2.0 mm) and of different thicknesses, densities and wood cement ratios. By making use of the found relations between the bulk density and the input parameters, it is concluded that it is possible to predict the normal incidence sound absorption of the WWCB by only making use of the bulk density and thickness as input parameters.

1. Introduction

A wood wool cement board (WWCB) is a building material produced since 1920, consisting of wood wool mineralized by Portland Cement (PC) [1]. The boards are mainly applied in parking lots and underneath balconies as in- and outdoor ceiling material and used as sound barriers. The boards possess a high fire resistance, are having a high durability and low maintenance, hence are still popular nowadays [2]. Due to the high open porosity (± 80%) and the internal pore structure, the boards can acoustically be considered as porous absorbers. Its sound absorption coefficient values have previously been measured [2]. However, no systematic study exists explaining the sound absorption behaviour of the WWCB, which would enable to increase and finally optimize its acoustical properties.

Furthermore, during this study, a wide range of densities was measured within the WWCBs, which makes them more difficult to characterize in comparison to homogeneous porous materials. To study the parameters influencing the acoustic impedance of the WWCB, impedance models are evaluated to predict its sound absorbing properties. Various studies have shown that impedance models are able to predict the acoustic impedance of rigid-frame porous materials by one to eight input parameters, depending on the internal pore structure. From Cox & Antonio [3] it is known the key parameters are the open porosity and the flow resistivity. Moreover, it is expected that for this material, having a complex internal pore structure, an impedance model taking into account this internal pore structure (i.e. by the pore shape factor or the viscous and thermal characteristic lengths), is required. Previous studies on other types of porous wood-based materials, found good agreements between theory and measurements by making use of the Attenborough model [4] or Johnson-Champoux-Allard model...
[5-6] depending on the type of wood-based material [8-10]. In this study, WWCBs with three different strand widths (1.0, 1.5 and 2.0 mm) and different board thicknesses (15, 25 and 35 mm) are tested. Measurements of the density, wood-to-binder ratio, porosity, flow resistivity and surface impedance are performed. Due to the difficulty to measure them in practice, using the selected impedance model the remaining parameters are fitted to the normal incidence sound absorption values defined from measured impedance values in the impedance tube.

2. Material properties and modelling

2.1 Characterization of density, porosity, flow resistivity and surface impedance.

2.1.1 WWCB bulk properties

The bulk properties of the tested WWCB-samples, taken from a large number of samples per board, are presented in Table 1. The range in density per strand width and the difference in wood-to-binder ratio, which is a result of the production process and the used recipes, is showing the board’s inhomogeneity.

Table 1: Properties of the tested WWCB.

<table>
<thead>
<tr>
<th>Strand width (mm)</th>
<th>Density range (kg/m$^3$)</th>
<th>Thickness (mm)</th>
<th>Wood-to-binder ratio* (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>365-544</td>
<td>15,25</td>
<td>0.43-0.50</td>
</tr>
<tr>
<td>1.5</td>
<td>300-400</td>
<td>15,25</td>
<td>0.53-0.55</td>
</tr>
<tr>
<td>2.0</td>
<td>310-486</td>
<td>25,35</td>
<td>0.54-0.57</td>
</tr>
</tbody>
</table>

*Indicative values defined by measuring the loss on ignition up to 750 °C.

2.1.2 Flow resistivity and open porosity

From a number of samples taken from different WWCBs, the flow resistivity (sample diameter 100 mm) was measured according to ISO 9053 with a flow resistivity meter and the open porosity (sample diameter 40 mm) with a helium pycnometer (Micromeritics AccuPyc II 1340). The results of the measurements including the regression lines and the belonging Root Mean Square Errors (RMSE), are shown in Figure 1a. The relations belonging to these regression lines will later on be used to create an impedance model for the WWCB, where for its practical use only the density and the thickness are input parameters.

![Flow resistivity vs Density](image1)

Figure 1: (a) Relations between the density and the porosity (linear) and flow resistivity (exponential) and (b) a picture of a WWCB-sample.

From Figure 1a, it can be concluded that the porosity values for boards having different strand widths are in the same order of magnitude. The observed difference in porosity-values, between the strand widths and for the same density, is attributed to the different wood-to-binder ratios but is not significant due to the small amount of solid volume present. The influence of the strand width and binder amount is greater for the flow resistivity values.
Regarding the binder amount, at the same porosity level, the flow resistivity is lower when having a higher binder amount. This indicates that the volume of wood fibres is a more influential with respect to the flow resistivity compared to the binder amount. In Table 1 it can be seen that the boards having a 1.0 mm strand width having a higher binder amount, which is a result of a different recipe. As a result, the flow resistivity is lower compared to the other strand widths having the same density. Comparing the same density for a 1.5 and 2.0 mm WWCB, meaning the same volume of wood fibres, the number of wood fibres inside the 1.5 mm board is higher due to the smaller strand width. This results in a board with smaller openings and a higher flow resistivity.

In Figure 3b, the wood-to-binder ratio for a `standard’ WWCB is compared to boards produced with other recipes, one with a low and one with a high binder amount having the same density. From this figure it can be seen that a lower wood-to-binder ratio, resulting in a lower porosity and a higher flow resistivity and the sound absorption will increase.

Based on a study by Wasselief [8] and after investigating the influence of the porosity on the sound absorption, it was concluded that not all the pores, measured by the helium pycnometer, take part in the acoustical process (some pores are too small). In Figure 3a this is confirmed by increasing the moisture content of different samples, which leads to a decrease of the micro-porosity (in the saturated variant it is assumed all the cell walls of the wood wool strands are filled with water). This figure indicates that closing the micro pores by moisture does not influence the sound absorption significantly. Hence, not all the micro pores take part in the acoustical process. Therefore, to compute the surface impedance from a prediction method, the open porosity measured with the helium pycnometer is not used but is instead determined by an inverse calculation method, see Section 3.1.

### 2.1.3 Impedance tube measurements

Surface impedance measurements were performed by making use of a six-microphone impedance tube. Out of the measured surface impedance, the normal incidence sound absorption of samples (diameter of 40 mm) are determined. Due to the reliability of the tube, the evaluated range in this study is from 200 to 2800 Hz. In Figure 2 the measured values are given for the three different strand widths.

![Figure 2: Typical measured normal incidence sound absorption curves for the three strand width samples.](image)

![Figure 3: Normal incidence sound absorption of WWCB samples for variation in (a) moisture content and (b) binder amount (d=25 mm).](image)
2.2 Impedance models

Since the evaluated frequency range (200-2800 Hz) is much larger than the phase decoupling frequency (1-2 Hz) of the WWCB, the board is unable to support wave propagation and can be considered as a rigid frame for this range [11]. Therefore, to model the impedance and sound absorption of WWCB, different rigid-frame impedance models were evaluated. As the WWCB does not meet the requirements for the Miki [12] model, this model is considered being unable to predict the sound absorption. The Attenborough [4], Johnson-Champoux-Allard (JCA) [5-6] and Johnson-Champoux-Allard-Lafarge (JCAL) [5&7] models, ordered in the number of input parameters, have been implemented to fit the measured impedances and are all showing values close to the measured ones.

Due to the high number of fitting parameters for the JCAL model, no unique values for the input parameters were found making use of the inverse calculation method. For this reason only the Attenborough and JCA model are shown in this paper. Besides the open porosity, flow resistivity and tortuosity, the Attenborough model takes into account a pore shape factor and the JCA-model a viscous and thermal characteristic length. The calculated relative deviation (Eq. 1) from the measured normal incidence sound absorption per 1/3 octave band in the range from 200 to 2500 Hz for the best fit of the two models (for 30 samples in total) is presented in Figure 4.

\[
\epsilon_{\text{1/3 octave band}} = \frac{\alpha_{\text{model,1/3 octave band}} - \alpha_{\text{measured,1/3 octave band}}}{\alpha_{\text{measured,1/3 octave band}}}.
\]  

![Figure 4: Relative deviation from the measured impedance tube values of the WWCB](image)

From Figure 4 it can be seen that the absolute value of \( \epsilon \) for both models is around the 0% above 1000 Hz, but increases below 500 Hz.

It can be concluded that the obtained deviation for the normal incidence sound absorption for the JCA model is lower, especially in the lower frequencies, in comparison to the Attenborough model and therefore better able to predict the sound absorption of the WWCB. Therefore, the JCA model will be used hereafter.
2.2.1 Johnson-Champoux-Allard (JCA) model

The JCA-model involves five physical parameters: the open porosity, flow resistivity, tortuosity and the viscous and thermal characteristic lengths. Based on these input parameters the effective density (Eq. 2), describing the viscous effects, and the effective bulk modulus (Eq. 3), describing the thermal effects, can be calculated.

\[
\rho_\varepsilon(\omega) = \frac{\alpha_\infty \rho_0}{\phi} \left(1 + \frac{\sigma\phi}{i\omega\rho_0\alpha_\infty} \sqrt{1 + \frac{4i\alpha_\infty^2 \eta \rho_0 \omega}{\sigma^2 \Lambda^2 \phi^2}}\right),
\]

(2)

\[
K_\varepsilon(\omega) = \frac{\gamma \rho_0}{\phi} \left(\gamma - (\gamma - 1) \left(1 + \frac{8\eta}{i\Lambda^2 N_{pr} \omega \rho_0} \sqrt{1 + \frac{i\rho_0 \omega N_{pr} \Lambda^2}{16\eta}}\right)\right)^{-1},
\]

(3)

with \(\alpha_\infty\) is the tortuosity [-], \(\rho_0\) the density of air [kg/m³], \(\phi\) the porosity [-], \(\sigma\) the flow resistivity [Ns/m⁴], \(i\) the imaginary number [-], \(\omega\) the angular frequency [1/s], \(\eta\) the viscosity of air (≈ 1.84 \times 10^{-5}) [-], \(\Lambda\) the viscous characteristic length [μm], \(\gamma\) ratio of the specific heat capacity (≈ 1.4), \(P_0\) the atmospheric pressure (≈101,320) [-], \(\Lambda'\) the thermal characteristic length [μm] and \(N_{pr}\) the Prandtl number (≈1.4) [-].

Based on these equations, the characteristic impedance \(Z_c\) \((Z_c = \sqrt{K_c(\omega) \rho_\varepsilon(\omega)})\) and the wavenumber \(k = \omega\sqrt{\rho_\varepsilon/K_c}\) can be determined. Out of these parameters the surface impedance \(Z_s\) \((Z_s = -jZ_c \cot(kd))\) can be defined with \(d\) the board thickness and finally the normal incidence sound absorption can be calculated \((\alpha = 1 - \left|\left(Z_s - \rho_\varepsilon c\right)/(Z_s + \rho_\varepsilon c)\right|^2)\) with \(\rho_\varepsilon c\) representing the impedance of air (Pa•s/m).

3. Results and characterization of the WWCB

3.1 Determining the input parameters

By making use of the measured normal incidence sound absorption in the impedance tube, an inverse calculation method was used to determine the tortuosity, open porosity and the viscous and thermal characteristic length. In Figure 5 an overview is given of the inverse calculation study for the JCA-model, where the open porosity, tortuosity and the characteristic lengths are fitted on the measured sound absorption curve. The values obtained from this fitting are visible in the legends of Figure 5 and this is done for thirty samples. The found values including the belonging regression lines are presented in Figure 6 and 7, where the grey areas correspond to the root mean square error ranges to the plotted regression lines. For the model’s practical use, the input parameters for the impedance models are related to the WWCBs bulk density based on the equations belonging to these regression lines. This is done because the bulk density is easy to measure, where the input parameters are not.
Increasing the bulk density leads to an increase of the acoustically effective open ‘acoustical’ porosity and the tortuosity and a decrease of the viscous and thermal characteristic length. The relations for the tortuosity, viscous and thermal characteristic lengths are in line with the expectations. While the measured porosity decreases when the density increases, the opposite appears when determining the ‘acoustical’ porosity. Besides the micro-porosity, the big pores in the lower densities are not efficiently taking part in the acoustical process. This can be explained by the same principle as perforated panel absorbers having bigger openings, where the wall friction is less efficient to damp the vibrations [13]. This finally results in an unexpected increased open porosity with increase of the density.
Table 2: WWCB parameters.

<table>
<thead>
<tr>
<th>Strand width (mm)</th>
<th>Measured density range (kg/m³)</th>
<th>Open porosity (%)</th>
<th>Flow resistivity (Ns/m⁴)</th>
<th>Tortuosity (-)</th>
<th>Viscous characteristic length (µm)</th>
<th>Thermal characteristic length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>400</td>
<td>58</td>
<td>2795</td>
<td>1.99</td>
<td>191</td>
<td>204</td>
</tr>
<tr>
<td>1.5</td>
<td>400</td>
<td>65</td>
<td>4436</td>
<td>3.78</td>
<td>204</td>
<td>242</td>
</tr>
<tr>
<td>2.0</td>
<td>400</td>
<td>65</td>
<td>3400</td>
<td>3.38</td>
<td>216</td>
<td>242</td>
</tr>
</tbody>
</table>

Now the impedance model is validated, the WWCB can be characterized. In Table 2 an overview is given of the WWCB input parameters for the model for the three strand widths with a density of 400 kg/m³.

### 3.2 Demonstration of the model

To show the applicability of the model for other board thicknesses as well as boards on an air-cavity, the normal incidence sound absorption values for these WWCBs are predicted making use of the equations belonging to the regression lines from Figure 1, 6 and 7, and compared to the measured values. The results, presented in Figure 8 and 9, show that the created model is able to predict the measured sound absorption with a root mean square error of 0.02 for 1/3 octave bands in the range of 200 to 2500 Hz.

![Figure 8](a) d=15 mm (1.5 mm strand width) (b) d=35 mm (2.0 mm strand width)

Figure 8: Demonstration of the created JCA-model for WWCBs with different thicknesses.

![Figure 9](a) 25 mm air-cavity (1.0 mm strand width) (b) 50 mm air-cavity (1.0 mm strand width)

Figure 9: Demonstration of the created JCA-model for WWCBs (d=25 mm.) on an air-cavity.

### 4. Conclusion

In this article, the sound absorption behaviour of WWCBs is studied. By making use of the Johnson-Champoux-Allard (JCA) model the sound absorption is characterized and predicted, allowing to evaluate properties like board thickness, density and strand width. The sound absorption was studied by using measured and predicted input parameters for the JCA-model. Moreover, the influence of the moisture content and wood-to-binder ratio was considered. Based on the obtained results the following conclusions can be drawn:
The studied WWCB samples differ greatly in density and in wood-to-binder ratio.
- The five parameter JCA-model is able to predict the sound absorption of the inhomogeneous WWCB with a root mean square error between 0.01 and 0.03 for the 1/3 octave bands in the 200-2500 Hz frequency range in all the evaluated WWCBs.
- Not all the pores, measured by the helium pycnometer, take part in the acoustical process.
- For the evaluated WWCBs, the wood-to-binder ratio per strand width does not need to be treated separately; it is incorporated in the input parameters.
- In case the recipe is changed in comparison with the studied WWCBs by significantly in- or decreasing the wood-to-binder ratio, new relations between the bulk density and the input parameters need to be determined to be able to predict its sound absorption.

By making use of the model and the created relations, it is possible to increase and optimize the sound absorption, which is part of the future work of this study.

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REFERENCES