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Modelling and optimization of the sound absorption of wood-wool cement boards

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ABSTRACT

The present article aims to characterize and improve the sound absorption of wood-wool cement boards (WWCB) with varying strand widths, densities, thicknesses and applied with varying air cavity thicknesses by using impedance models. Different rigid-frame impedance models were analysed to predict the acoustic impedance of this material, and their suitability for the WWCB was evaluated. The Johnson-Champoux-Allard (JCA) model with its parameters, porosity, flow resistivity, tortuosity and characteristic lengths, was found to be the most appropriate to model the normal incidence sound absorption. The relations between the bulk density of the board and the impedance model parameters are established for material characterisation and optimization. Optimum density values were found per strand in terms of the sound absorption in the frequency range 200–2500 Hz. Moreover, the use of a density variation in the boards leads to improvement of the sound absorption. Regarding the application of the board, the use of an air cavity with a thickness of 100 mm leads to an optimized sound absorption for every strand width.

1. Introduction

In order to avoid high noise levels or improve speech intelligibility, porous materials and green walls [1] are applied frequently in the built environment. A popular type of porous material is mineral wool [2], characterised by a high porosity in the range of 92–98% and by a flow resistivity of 5–30 kN s/m^4 [3]. In recent years, the interest in the use of sustainable natural resources in sound absorbing materials is growing, for instance by applying spruce wood-wool strands, hemp particles, straw, flax and coconut fibres and reeds [4–7]. This is attributed to their low density, high availability [8,9], possessing no adverse health effects [10] and low ecological footprint [11,7]. The use of natural strands, however, can be traced back to one century ago. Around 1920, after the invention of Portland cement, wood-wool cement boards (WWCB) were developed [12], possessing favourable mechanical, thermal and acoustical properties [11,13–15]. Moreover, due to the mineralisation of the wood-wool by cement, the boards possess excellent fire and biodegradation resistant properties [16], hence are more durable. Nowadays, this material is still widely applied, mostly as an acoustical ceiling e.g. in gyms, school buildings, parking garages but also utilized in sound barriers. Annually 16 million square meters of boards are produced [17]. To lower the environmental footprint of the boards, part of the cement can be further replaced by limestone powder or industrial by-products [18–20].

Generally WWCBs are characterised by a porosity in the range of 70–85% [14,21] and a flow resistivity of 1.7–8.5 kN s/m^4 [5], having sound absorbing properties which have not been reported yet. In contrast to mineral wool, the WWCB properties are inhomogeneous. This is due to the randomly distributed natural wood-wool strands with varied dimensions, which are covered by a thin layer of binder varying in thickness between 80–400 μm [22]. Although widely applied, no systematic study on the acoustical properties on WWCBs has not yet been reported. In the present study, a systematic investigation is carried out by making use of acoustic impedance models. The sound absorbing properties are studied for different design parameters of the WWCB as density and strand size. The suitability of an impedance model depends on the morphology of the used material and the number of input parameters consequently depends on complexity of the microstructure. Previous studies [13,23] reported good agreements between simulations and experiments of wood-based porous materials. Various models such as the Attenborough model [24] and a combination of the Johnson et al. model [25] and Zwikker and Kosten model [26], are used depending on the type of wood-based material [4,11,23]. Whereas the boards investigated in the

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mentioned studies consist of densely packed particle shaves, loosely packed long wood strands (± 25 mm) are used for producing WWCBs, making the WWCBs essentially different (density <550 kg/m^3) and more inhomogeneous compared to high density boards with natural fibres. Besides the WWCB material properties that influence the sound absorption, WWCBs are often mounted directly against the floor/ceiling construction, while implementation of a certain air cavity can lead to a significant improvement of the sound absorption and will provide valuable contribution on the speech intelligibility [27].

The aim of this paper is to characterize and optimize WWCBs primarily concerning their acoustic performance. A schematic overview of the study is presented in Fig. 1. First, WWCB samples are selected and the performed characterizations with respect to bulk density and wood to binder ratio and the used methodology and measurement techniques are explained in Section 2. Afterwards, the obtained bulk density and wood to binder ratio are reported and different impedance models are evaluated. Moreover, the open porosity and flow resistivity measurement results are discussed in Section 3. Next, relations between the impedance model input parameters and the bulk density are formulated for strands with different widths in Section 4. By making use of the developed relations and the chosen impedance model, the results are validated for different board thicknesses. Furthermore, the influence of the bulk properties, i.e. the strand size and density on the sound absorbing properties of the WWCB is analysed using the chosen impedance model in Section 5. Based on the analyses, optimization strategies of the sound absorbing properties of the WWCB are proposed.

2. Materials and experimental methodologies

2.1. Density and wood to binder characterisation of WWCB

Three commercial WWCBs (supplied by Knauf Insulation), having a thickness of 25 mm, with different strand widths (1.0, 1.5 and 2.0 mm), were investigated in this study. Attributed to the difference in strand width, the 1.0 mm strand width WWCB has a higher total strand surface area compared to the 1.5 and 2.0 mm, hence, more binder material (+18%) was needed to manufacture this type of board. The bulk density was determined by measuring the mass of the sample and dividing it by the bulk volume of the sample for a large number of samples (±25) per board.

The differences in board density are not only due to a fluctuating amount of material present in the samples, but is also related to the actual wood-to-binder ratio. Therefore, the wood and binder amount is determined applying the method as described in [28].

2.2. Acoustic impedance measurement

Surface impedance measurements were performed with the purpose to validate the used impedance models and predict the unknown input parameters. The surface impedance measurements were conducted by making use of a six-microphone impedance tube with an inner diameter of 40 mm. From on the obtained surface impedances, the normal incidence sound absorption of the samples was determined. With a cut-off frequency of 5022 Hz, it was found that until the 2800 Hz the impedance tube provide the absorption coefficient with a rather low deviation (<5%) when running an empty tube. The normal incidence sound absorption average (SAA-value) according to the ASTM C423 [29] calculation method is used in this study to describe and optimize the single value sound absorption. This value represents the average normal incidence sound absorption value over the 200–2500 Hz 1/3 octave bands.

2.3. Impedance models and their input parameters

Since the evaluated frequency range (177–2828 Hz) is much larger than the phase decoupling frequency (1–2 Hz) of the WWCB, the board is unable to support elastic wave propagation and can be considered as a rigid frame for this range [11]. Therefore, the following rigid-frame impedance models were considered in this study with the number of input parameters of these models in parenthesis: Attenborough model (4), Johnson-Champoux-Allard (JCA) model (5) and Johnson-Champoux-Allard-Lafarge (JCAL)

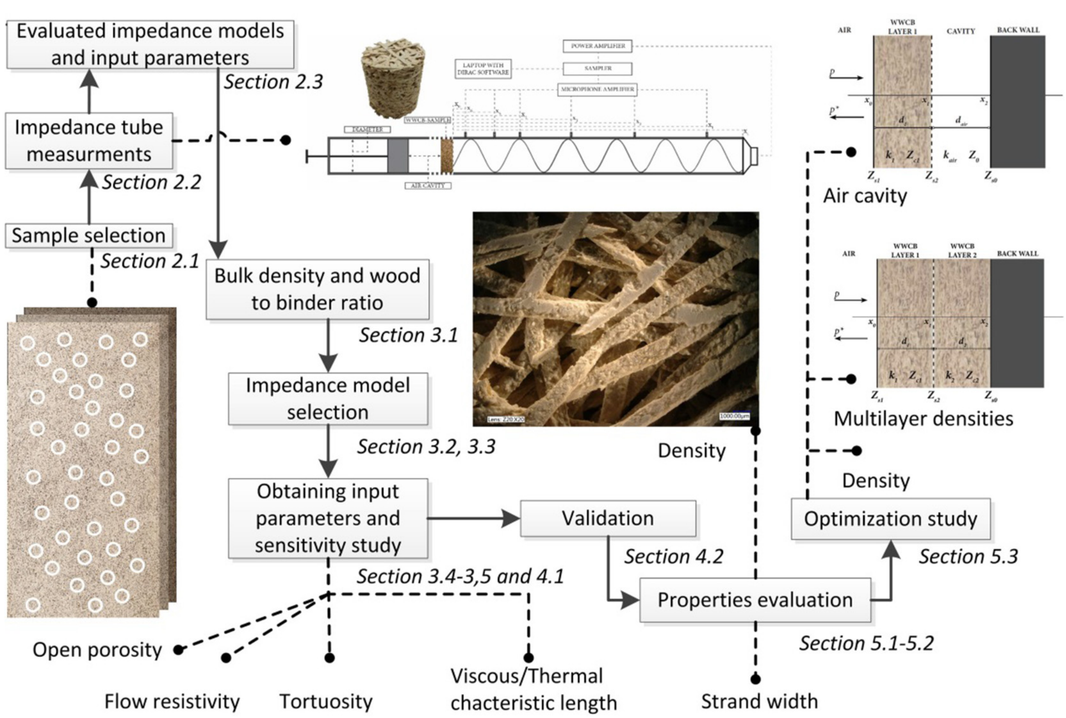

Fig. 1. Schematic overview of the current study, with the dashed lines indicating visualisations and sub sections.