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Waste Durian Husk Fibers as Natural Sound Absorber: Performance and Acoustic Characterization

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Abstract: The paper presents the sound absorption coefficient of acoustic absorbers fabricated from natural durian husk fibers, which are currently still considered as agricultural wastes, especially in Malaysia. Samples were fabricated with different fiber densities and thicknesses and the sound absorption performance was measured using the impedance tube method. The results reveal that the durian husk fibers can have absorption coefficient of more than 0.5 above 1 kHz for a minimum thick sample of 20 mm and with minimum density of 160 kg/m^3. The optimised macroscopic parameters for various densities were calculated using the inverse method employing the well-known Johnson-Champoux-Allard (JCA) model for porous material.

Keywords: durian fiber; sound absorber; acoustics; acoustic material; absorption coefficient

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1. Introduction

Studies on finding alternative materials for sound absorbers, which are more environmentally friendly are still progressing. The candidates are natural materials, which have been demonstrated not only to have good acoustic properties, but also good thermal conductivity and durability [1]. Or et al. [2] studied the fibers from the fruit bunch of oil palm which demonstrated good absorption coefficient of 0.85 in average above 500 Hz for 50 mm thick sample. Kenaf fibers, which possess softer and lighter fibers showed almost the same performance of sound absorption with fibers from the oil palm fruit bunch above 500 Hz, but with only one-third of density [3]. Another soft fiber is the pineapple fibers with average sound absorption coefficient of 0.9 with the same thickness [4].

Santoni et al. [5] investigated the absorption performance of hemp fibers according to the manufacturing process of the samples, such as the alkali treatment and combing method. The sample with 40 mm thick and density of 88 kg/m^3 shows absorption coefficient above 0.8 at 1–4 kHz. The acoustical properties were calculated for different manufacturing processes and validated with good agreement with experimental data. Borrell et al. [6] studied the fruit stone wastes from olive, cherry, apricot and peach as sound absorbers. Those stones were arranged in such a way to form a cylinder with 100 mm diameter and various thicknesses from 20 to 98 mm.

Cherradi et al. [7] combined the fibers from alfa plant and sawdust wood into a composite absorber and found that the added alfa fibers improved the porosity and thus increased the absorption coefficient. This is better compared to the performance of the absorbers made from pure sawdust wood fibers. The absorption coefficient of the composite can reach average of 0.8 above 2 kHz with sample thickness of 20 mm.

Boubel et al. [8] worked on the loose wood chips as sound absorbers dividing them based on the particle sizes. As expected, the small particles provided better sound absorption due to better porosity and tortuosity. Prediction using mathematical model was also presented for one class of sample for different thicknesses with good agreement.

Various farm residues namely, coconut leaf, sugarcane leaf, maize, urad dhal, and lobia shell were grinned and turned into cylinders with thickness of 5 to 20 mm for impedance tube test [9]. All the natural wastes revealed absorption coefficient above 0.5 at above 2 kHz only for thickness 20 mm. Only lobia shell showed good absorption coefficient from thickness 5 mm.

Another bio waste material as acoustic absorber was published by Yun et al. [10] by utilising coffee wastes from coffee shops. Sample absorbers for various particle sizes were tested and the measured results were simulated through architectural acoustics software to present reduction of reverberation time in a room when the coffee waste absorber is applied as the room ceiling.

Sing and Mohanty [11] applied the jute felt and waste cotton to reduce the noise level from HVAC unit of a motor vehicle. The outcome was the reduction of noise level by 4 dB(A) and loudness level by 7 sones. Subjective data from passengers were also collected and revealed that application of the natural materials successfully reduced the annoyance caused by the HVAC noise. Most recently, Abdi et al. [12] revealed the absorption performance of composite fibers made of wasted coffee silver skin and chrome shave which showed average absorption coefficient of 0.9 above 1 kHz for thickness of 50 mm.

In this study, we report use of durian husk fibers as acoustic absorber. The measurement data of sound absorption coefficient and the prediction using the optimized macroscopic parameters are presented.

2. Methodology

2.1. About Durian

Durian (*Durio zibethinus Murray*) is a fruit with thorn-covered husk and is well known for its strong odour, but sweet flavour (Figure 1a). Thailand is still ranked number one as producer of durian with 700,000 tonnes a year, followed by Malaysia and Indonesia of around 250,000 tonnes each [13]. The fruit has 40% of flesh and 60% of husk. Unfortunately, the husk is usually ended up on landfill as waste (Figure 1b). With the projection of each country to increase production of durian every year, the amount of waste from durian husk will be increased.

Some works regarding the use of durian husk include its utilisation as adsorbent for removal in aquoeus solution [14], as bio-briquette [15], as insulating particle boards [16] and for composite [17]. Fibers from durian husk has also been shown to have good tensile and impact strength [18]. However based on the literature study, research work has yet been published on utilising the fibers from the durian husk as acoustic absorber.

Figure 1. (**a**) Durian fruit and (**b**) bio waste from durian husk.

2.2. Preparation of Test Samples

The primary raw materials are the durian husk, which was collected from the local area. The husk was first chopped using a coconut cracker machine and was washed thoroughly with water for 48 h to remove any adhering particles and dusk. It was then dried in an oven at 60 °C for almost 24 h. Next, the dried husk was milled by using ultra centrifugal mill and the dried fibers were obtained.

These fibers were first weighted and were mixed with 2% NaOH solution for 4 h at 100 °C under mechanical stirring. The mixed samples were then placed into a square mould and were hot compressed at temperature 170 °C to the desired thickness. Figure 2 shows the fiber preparation processes. After cooling it down, the sample was cut with round shape of diameter 34.5 mm for the impedance tube test. The example of the test sample is shown in Figure 3. Table 1 list the mass of the fibers, the thickness and the density of the fabricated test samples. The bulk density is calculated as $\rho = m/(0.25\pi D^2 t)$, where m is the fiber mass, t is the sample thickness and D is the diameter of the sample.

Table 1. Parameters of the test samples of durian husk fibres.

Mass of Fibers, m (g)	Thickness, t (mm)	Bulk Density, ρ (kg/m^3)
2	10	214
3	20	160
4	20	214
6	20	321
5	30	178
6	30	214
7	30	250
8	30	285
8	40	214

2.3. Measurement Setup

The measurement of the sound absorption coefficient was conducted by using the impedance tube method with two microphones in accordance with ISO 10534-2. The diagram of the setup is shown in Figure 4. Before the experiment, the microphones were first calibrated using the calibrator at 114 dB and 1 kHz. The loudspeaker was turned on for 10 min prior to the measurement to stabilise the temperature in the tube. To ensure the validity of the results, the measurement was repeated three times for each sample. After one experiment was done, the sample was taken out and re-inserted back into the sample holder and the measurement was repeated. The variability were found to be negligible and this ensures the unwanted errors during the installation of the sample, such as the presence of air leakage around the sample edges due to the sample which might not properly be fitted in the tube, were eliminated. The frequency range for this experiment is valid for 500 Hz to 4.5 kHz.

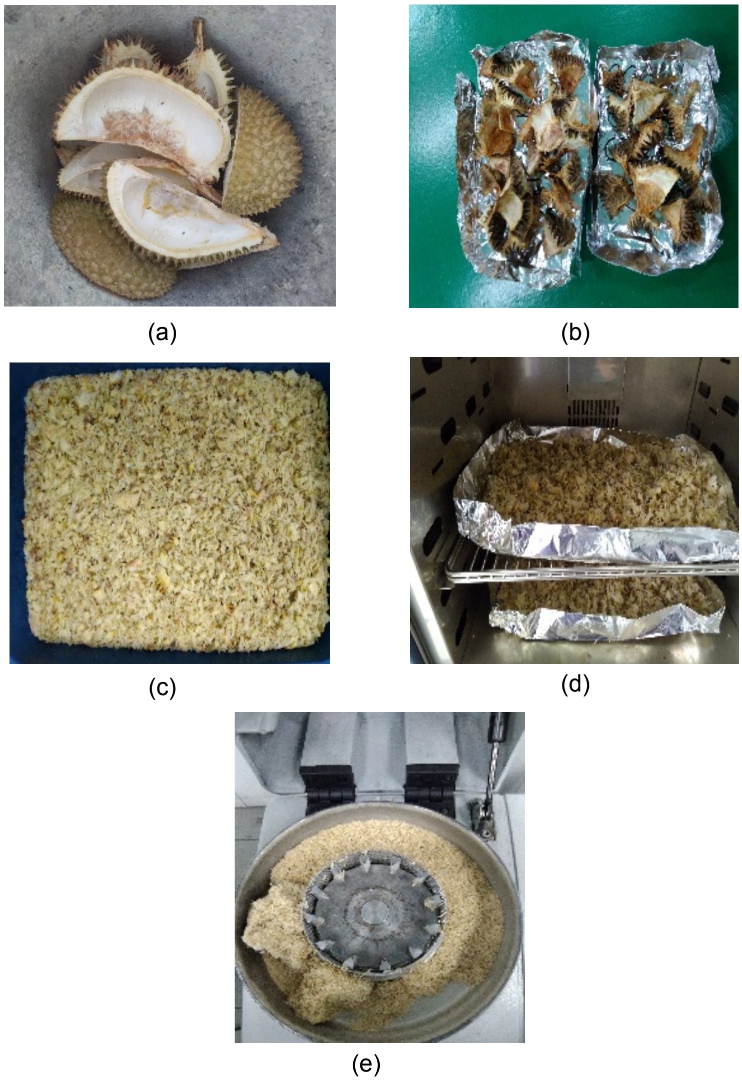

Figure 2. Preparation of durian husk fibers: (**a**) durian husk, (**b**) cut into pieces, (**c**) the husk soaked in water, (**d**) drying process and (**e**) the milling process.

Figure 3. Example of fabricated test sample.

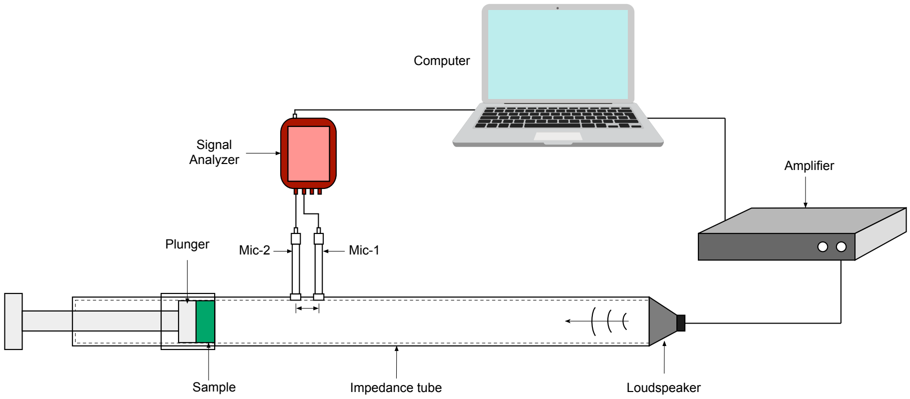

Figure 4. Setup of sound absorption measurement using the impedance tube method.

3. Measured Results and Analysis

3.1. Absorption Performance with Thickness

Figure 5 shows the results of the sound absorption coefficient for various thicknesses with density of 214 kg/m^3. Considering the half-power absorption to indicate a good sound absorption performance (where $\alpha \geq 0.5$, denoted as $\alpha_{0.5}$), the sample with thickness 10 mm can be observed to not perform well up to 4 kHz. The performance increases significantly when the thickness is doubled to 20 mm, where the $\alpha_{0.5}$ now starts at 1.25 kHz. The peak frequency is at 2.5 kHz and this resonant frequency shifts to lower frequency as the thickness is increased. The peak can strongly depends on the tortuosity and flow resistivity of the sample, where the performance can be improved towards the lower frequency by increasing the tortuosity and flow resistivity [19]. This can be achieved by increasing the fiber density.

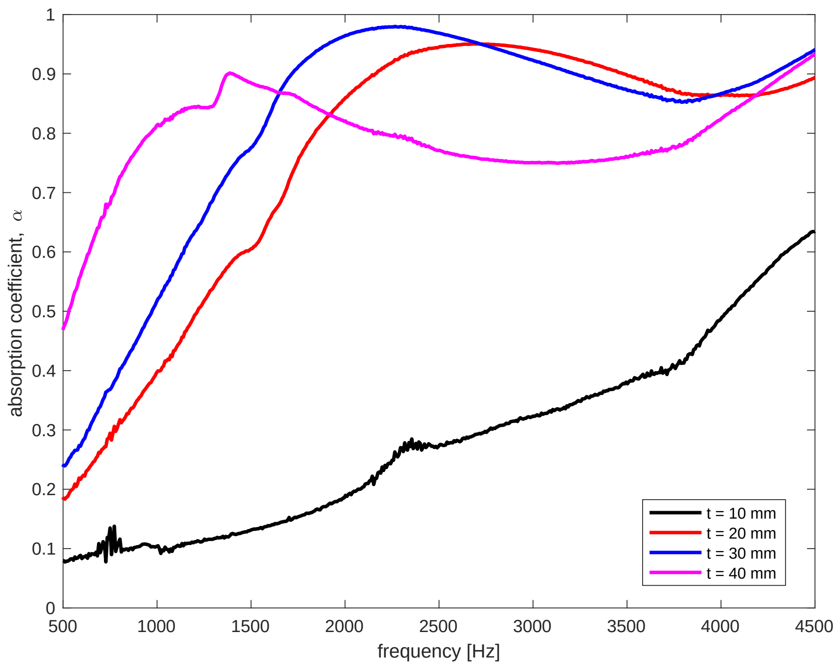

Figure 5. Measured absorption coefficient of durian husk fibers for different thicknesses ($\rho = 214$ kg/m^3).

Figure 6 shows the absorption coefficient for the same variation of sample thicknesses, but with increased fiber density to 285 kg/m^3. Here the peaks can be seen to shift to lower frequency compared to those for density of 214 kg/m^3 in Figure 5. For sample with 10 mm thick, the $\alpha_{0.5}$ now starts at around 3 kHz. For thickness 40 mm, the durian husk fiber can perform with average absorption coefficient of 0.8 above 800 Hz.

From Figures 5 and 6, the peak frequencies are not at the equivalent half-quarter-wavelength frequency (of the sample thickness) as usually used in practice (here the peak appears at much lower frequency). This depends on the nature of the fibers. This quarter wavelength rule is valid for softer fibers, such as pineapple fibers as presented in Ref. [4].

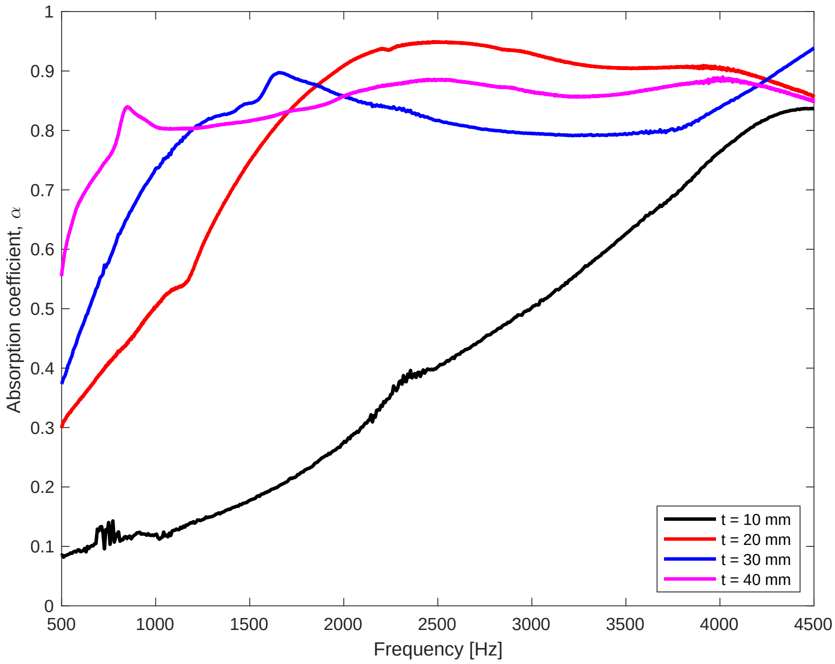

Figure 6. Measured absorption coefficient of durian husk fibers for different thicknesses ($\rho = 285$ kg/m^3).

3.2. Absorption Performance with Density

Figure 7 shows the measured results of constant sample thickness of 20 mm with different fiber densities. It can be seen that the frequency of absorption is improved at low frequency, although it is not so significant. The starting frequency of $\alpha_{0.5}$ improves from 1.3 kHz for 160 kg/m^3 to only 1.1 kHz for 321 kg/m^3, which is after doubling the amount of the density. Improving the low frequency region can be done effectively by introducing an air gap behind the panel.

The same phenomenon can also be observed for thickness 30 mm in Figure 8. Here, an improvement of from $\alpha_{0.5} = 1.2$ kHz to 600 Hz is demonstrated when the density is increased from 178 kg/m^3 to 285 kg/m^3. However this ends up with the reduction in amplitude, which has also been highlighted in Ref. [2].

The change of thickness (t) is limited by the flow resistivity (σ) of the material, bounded by the product of σt. If σt is too high, there will be high reflection on the free surface of the material which prevents optimum absorption of sound energy [20]. For density of 285 kg/m^3 in Figure 8 for example, possible of high flow resistivity and large thickness deteriorates the absorption coefficient especially above the peak (>1.5 kHz) compared to other densities with the same thickness.

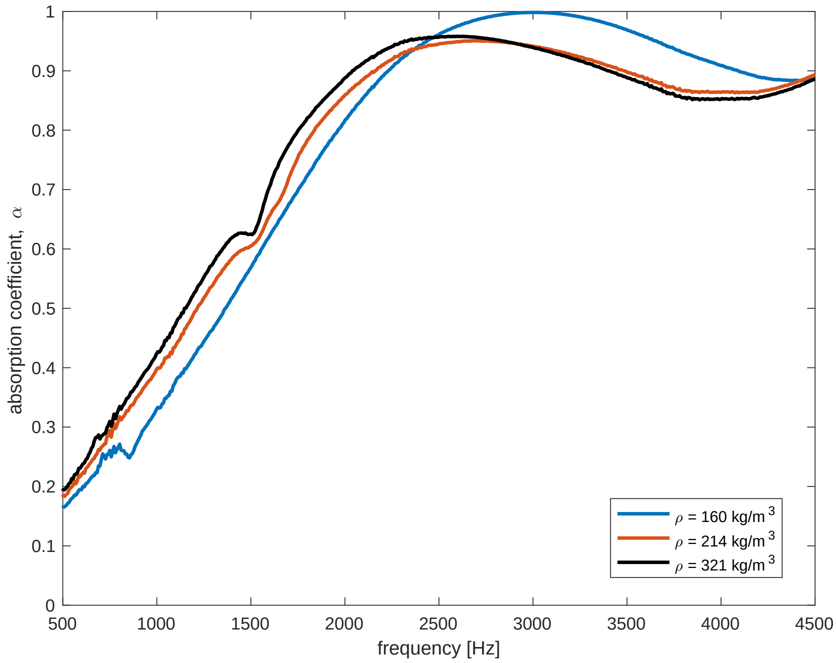

Figure 7. Measured absorption coefficient of durian husk fibers for different densities ($t = 20$ mm).

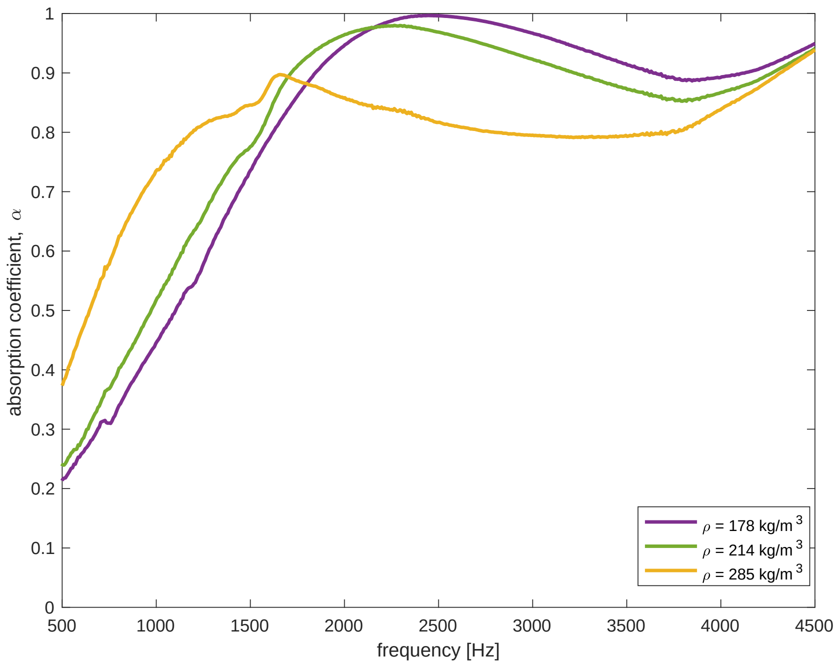

Figure 8. Measured absorption coefficient of durian husk fibers for different densities ($t = 30$ mm).

4. Determination of Acoustical Properties

The identification of macroscopic parameters of porous materials is important for material characterization and mathematical modelling [21,22]. These are usually used as the input parameters to predict the sound absorption and sound transmission to determine the flow of noise and vibration energy in a complex vibroacoustic structure. In this scenario, one of the methodologies is based on the curve-fitting technique with the measured data from the impedance tube. The measured surface impedance or the absorption coefficient from the test specimen can be used as the parameter to determine the objective function.

The chosen mathematical model to predict the surface acoustic impedance of the absorbent material and the cost of the used function in the optimization algorithm will affect the accuracy of the method. It is important to consider that the model should represent well the acoustic properties being sufficiently sensitive to variations of the parameters. Some classical phenomenological alternatives for modeling porous media consider the sample having a solid rigid frame and five macroscopic properties characterizing an equivalent fluid part, namely:

- Porosity, ϕ
- Tortuosity, α_∞
- Flow resistivity, σ
- Viscous characteristic length, Λ
- Thermal characteristic length, Λ'

4.1. Propagation Model

From the equivalent fluid theory proposed by Zwicker and Kosten [23], the characteristic impedance $\tilde{Z}_c$ and a complex wavenumber $\tilde{k}_c$ which governs the wave propagation into a dissipative fluid medium can be defined as

$$\tilde{Z}_c = \frac{\sqrt{\rho_{\text{eff}} K_{\text{eff}}}}{\phi} \tag{1}$$

and

$$\tilde{k}_c = \frac{\omega\sqrt{\rho_{\text{eff}}/K_{\text{eff}}}}{\phi} \tag{2}$$

where K_{eff} represents the effective bulk modulus and ρ_{eff} the effective density of the material. The macroscopic properties presented in Section 4 composes the Johnson-Champoux-Allard (JCA) equations for determining the bulk and density parameters to characterize the equivalent fluid. Johnson in 1987 [24] suggested an effective fluid density ρ_{eff} given by

$$\rho_{\text{eff}} = \rho_0 \left[\alpha_\infty + \frac{\nu\phi}{\mathrm{j}\,\omega q_0}\left(1 + \frac{4\,\alpha_\infty^2 q_0^2}{\Lambda^2\phi^2\nu}\,\mathrm{j}\,\omega\right)^{1/2}\right] \tag{3}$$

being ρ_0 the density of the air, $\nu = \eta/\rho_0$ its kinematic viscosity, $\eta = 1.84 \times 10^{-5}$ [Pa $\cdot$ s] the air static viscosity, and q_0 the viscous permeability referenced as $q_0 = \eta/\sigma$. An alternative for obtaining the effective bulk modulus K_{eff} was presented by Champoux and Allard [25] computed as

$$K_{\text{eff}} = \gamma P_0 \left[\gamma - \frac{\gamma - 1}{1 + \dfrac{\nu'\phi}{\mathrm{j}\,\omega q_0'}\left(1 + \dfrac{\mathrm{j}\,\omega(\Lambda')^2}{16\nu'}\right)^{1/2}} \right]^{-1} \tag{4}$$

where $\nu' = \nu/\mathrm{Pr}$ is the thermal viscosity of the air with the Prandtl number of $\mathrm{Pr} = 0.77$, q_0' is the thermal permeability computed as $q_0' = \phi(\Lambda')^2/8$ under the hypothesis that the pores can be approximated by circular cross-shaped tubes [22].

If considering a sample with thickness t backed by a rigid wall and excited by normal incidence plane waves, the surface impedance $\tilde{Z}_s$ of the system is [22,26]

$$\tilde{Z}_s = -\mathrm{j}\,\tilde{Z}_c \coth(\tilde{k}_c t) \tag{5}$$

The sound absorption coefficient α is then determined by

$$\alpha = \frac{4\mathrm{Re}(\tilde{z}_s)}{[1 + \mathrm{Re}(\tilde{z}_s)]^2 + [\mathrm{Im}(\tilde{z}_s)]^2} \tag{6}$$

where $\tilde{z}_s = \tilde{Z}_s/\rho_0 c_0$.

4.2. Optimization Function

The genetic algorithm considered in this paper uses an optimization function based on the comparison between the experimental absorption coefficient $\alpha^{(\mathrm{exp})}$ and the theoretical absorption coefficient $\alpha^{(\mathrm{teo})}$ from Equation (6). The target criterion was set as [26]

$$\beta = \sum_{n=1}^{N} \left| \frac{\alpha_n^{(\mathrm{exp})} - \alpha_n^{(\mathrm{teo})}}{\alpha_n^{(\mathrm{exp})}} \right|^2 \tag{7}$$

where n is the index and N is the total number of discrete points of frequency considered in the experiment. A similar methodology was previously considered by Pereira et al. [27] for porous concrete materials, where the Horoshenkov-Swift model [28] was used for modeling the theoretical absorption.

A MATLAB/OCTAVE routine was used on the computational composition of the genetic algorithm. The function *ga* calculates the minimum error of the objective function β in Equation (7). These optimized parameters can be useful to characterize dissipative materials to be considered in energy based simulations available in many ordinary commercial codes on building acoustics and vibroacoustics, although the direct measurement of macroscopic properties can be beneficial for improving the reliability of the results.

4.3. Computational Results

Simulation of the acoustical performance for the Durian husk fibers was conducted by utilizing the measured data from the impedance tube measurement presented in Section 3. The predicted acoustical parameters should change for different densities of fibers, as the optimization process considers the porous materials as equivalent fluids in a solid frame.

Figure 9 shows the comparison of the simulated sound absorption coefficient with the expriment for various densities for 30 mm thick samples. The approximated values of the absorption coefficient was calculated by following the optimization steps. Table 2 shows the optimized macroscopic values derived from the equivalent fluid model.

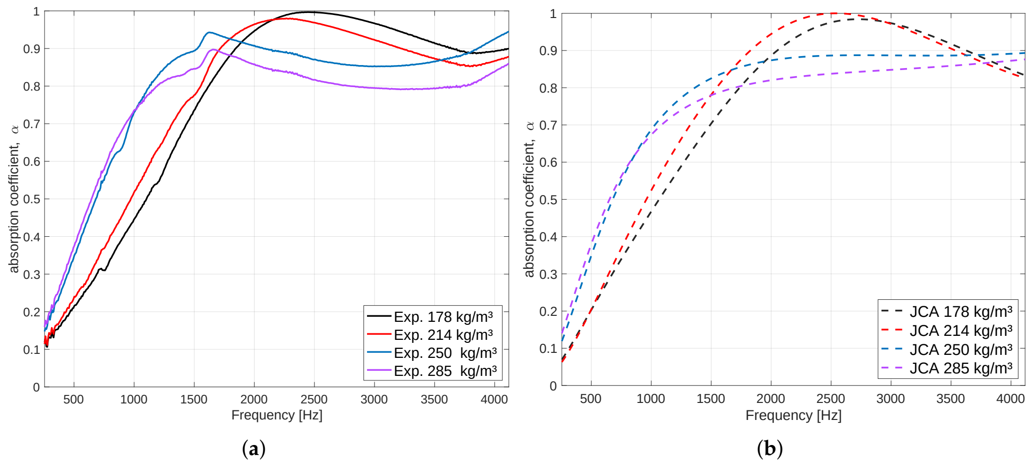

Figure 9. Comparison of sound absorption coefficient of Durian husk fibers from measurement and numerical simulation with different fiber densities: (**a**) Experimental, (**b**) Numerical.

Table 2. Optimized macroscopic parameters for the Durian husk fibers.

Density [kg/m^3]	σ [kN/m^4]	ϕ [-]	α_∞ [-]	Λ [μm]	Λ' [μm]
178	17.1	0.73	1.03	118	176
214	23.1	0.68	1.06	94	142
250	56.9	0.77	1.05	53	54
285	70.1	0.76	1.06	48	50

It can be observed in Figure 9 that the rigid model allows to capture the trend of the absorption curves of the Durian fibers, although there are small differences between the experimental and numerical results. For example in Figure 9a, it is shown that for the high density sample (285 kg/m^3), the resonance occurs at about 1.6 kHz which is not well captured by the numerical result (Figure 9b). A possible cause of this occurrence could be due to structural elastic effects that cannot be represented by equivalent fluids.

Table 2 shows that increasing the fiber density increases the flow resistivity and decreases the characteristic lengths. To validate these values for each density, they are applied back to the JCA model to predict the sound absorption for different thickness of Durian samples. The parameters for the 214 and 285 kg/m^3 density are used as the example to to simulate for the 10 mm thick. The comparison with the experimental data is as shown in Figure 10.

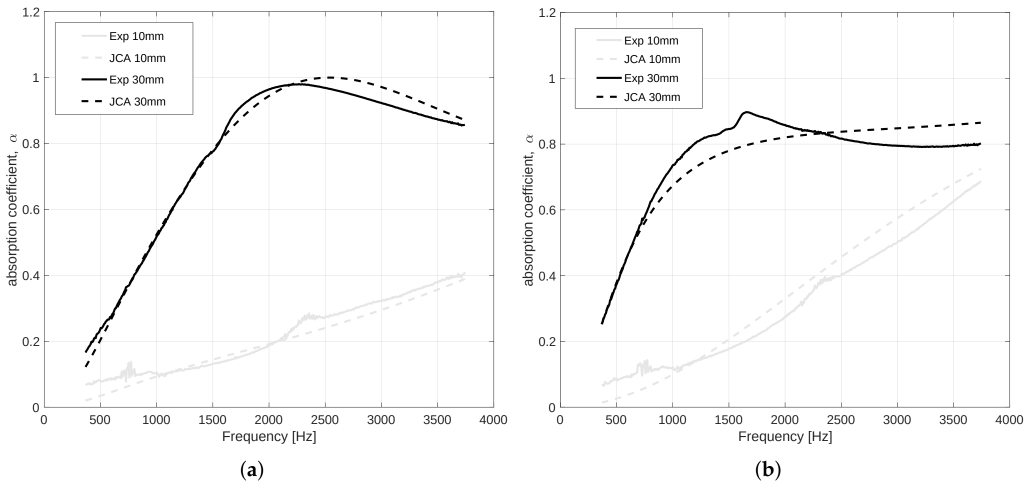

Figure 10. Sound absorption coefficient of Durian husk fibers calculated using the optimized macroscopic parameters obtained from the numerical calculation for each density: (**a**) Durian 214 kg/m^3, (**b**) Durian 285 kg/m^3.

It can be seen in Figure 10a that the 214 kg/m^3 fiber was well represented in most of the spectrum. However the frame influence in the absorption for 285 kg/m^3 sample is greater, which causes slightly underestimation of the numerical simulation to the experimental data as shown in Figure 10b. However the general trend of absorption coefficient is consistent over the frequency. Table 3 presents the global error between measurement and numerical values given in Figure 10 which are all under 5%. This parameter was calculated as

$$\text{Error} = \frac{1}{N}\sum_{n=1}^{N} \alpha_n^{(\text{exp})} - \alpha_n^{(\text{teo})} \quad (8)$$

where N is the total number of samples.

Table 3. Error between numerical and experimental results.

Density (kg/m^3)	10 mm	30 mm
214	2.36%	2.32%
285	4.77%	4.62%

Although here it is shown that prediction for different thickness can be used, in practical situation consideration must be taken on the consistency during the fabrication of the absorber panel, for example change of compression temperature or pressure, and the amount of binder used can create variation of porosity and flow resistivity for each sample thickness, and these can be sensitive to the sound absorption coefficient. For the calculated macroscopic parameters to have a greater accuracy in prediction for other thicknesses, it would be a good practice, for a thicker absorber, to use a multi-layer absorber panels. This has been shown for kenaf fibers with thicknesses from 10 to 40 mm, with careful control of parameters during the fabrication for 10 mm and 20 mm thick samples, density of 178 kg/m^3 [26]. The thicker samples (30 mm and 40 mm) are the combinations of these layers. The calculated macroscopic parameters can predict the sound absorption coefficient across these different sample thicknesses with good agreement.

5. Conclusions

The sound absorption coefficient of sound absorbers made from durian husk fibers have been presented. The measurement results show that the durian fibers can have good absorption coefficient, $\alpha > 0.5$ above 1.3 kHz for 20 mm thick sample, and above 1 kHz for 30 mm thick sample, with density of 214 kg/m^3. Above 1 kHz, this performance overcomes that of the commercial rockwool with a thicker sample of 45 mm (although with lower density of 120 kg/m^3). Improvement to the lower frequency can be achieved by increasing the density to 285 kg/m^3 for thickness 30 mm with the consequence of reducing the performance at higher frequency due to the flow resistivity-thickness relation. Overall, the measured results demonstrate that the starting frequency of $\alpha_{0.5}$ below 1.5 kHz is achieved for minimum thickness of 20 mm and density of 160 kg/m^3. The inverse method utilising the JCA model has been used to obtain the macroscopic parameters from the measured absorption coefficient for various fiber densities and has been shown to give good agreement between the predicted and measured absorption coefficient. Durian husk fibers can therefore be considered to be the alternative natural sound absorber. Although like other natural materials, further study on the fiber durability over time, its resistance to fungus and additional fire retardant is important as a measure of its feasibility to be applied in practice.

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