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Effect of Compression on the Acoustic Absorption of Coir Fiber

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Abstract: Problem statement: The absorption characteristics of coir fiber were analyzed previously. Analytical method to predict the acoustical behavior of coir fiber has already been developed. However, compression effects of coir fiber were not explored which might significant for acoustics absorption during seat padding. In this study, compression effect on the sound absorption characteristics of coir fiber are demonstrated based on the previous analytical approach such as rigid frame method with the modification in the physical parameters. **Approach:** The verification of the estimated acoustical absorption coefficient in uncompressed condition using rigid frame Johnson-Allard Model are shown for three different thicknesses of industrially processed coir fiber mixed with binder latex. Measurements were conducted in impedance tube on normal incidence sound absorption of coir fiber. It is well known that the absorption behavior of a porous material varies during compression and affects the physical parameters. In these analyses, formulas proposed by Castagnede are employed to predict the compression effect on the absorption of coir fiber which takes into account the modifications of the physical parameters during compression. **Results:** The agreement between the analytical and measured results is justified for all three sample thicknesses in uncompressed condition. Analyses on the acoustic behavior of material during compressed condition show that compression has a substantial effect on the absorption of coir fiber. It also indicates that the absorption of coir fiber can be enhanced by compressing the material. In addition, the absorption performances are compared by varying the compression rate on material at uncompressed and compressed condition. **Conclusion:** From overall analyses, it is evident that compression of coir fiber can significantly change the absorption behavior of coir fiber from the actual acoustical characteristics as estimated at normal condition. Moreover, compressing the material might be considered as a possible approach to improve the absorption coefficient of coir fiber. An additional example is presented to show a potential way of enhancing absorption coefficient of coir fiber utilizing compression effect.

Key words: Coir fiber, rigid frame model, compression effect, acoustic absorption

INTRODUCTION

Porous media filled with air are used intensively in the automobile, aeronautical and building industries to attenuate sound waves. Coir fibers from coconut husk have high potential to be used as porous material for noise control purposes. Utilizing coir fiber as an effective porous material will be a great contribution in

building acoustics, since it can be collected as agricultural waste.

Malaysia has plenty of agricultural waste such as coconut fiber (*Cocos nucifera*), rice fiber (*Oryza sativa*) and oil palm frond fiber (*Elaeis guineensis*) which are abundant and usually burned or used as agricultural by-products (Zulkifli *et al.*, 2009a; 2009b). These natural fibers, such as coir fiber, are suitable as a substitute for

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synthetic fibers and wood-based materials for acoustic absorption purposes. The advantages of these fibers are cheaper, renewable, nonabrasive and do not give rise to health and safety issues during processing and handling (Lee and Swenson, 1992; Joshi *et al.*, 2004).

The sound absorption attribute of coir fiber was investigated previously in Automotive Research Group laboratories, University Kebangsaan Malaysia (Nor *et al.*, 2004; Zulkifli *et al.*, 2008; 2009a; 2009b). Those studies covered simulation approach with program WinFLAG™ and experimental observations in reverberation room. Studies conducted on coir fiber showed that they can be very useful for various usages in many structural and non-structural applications. Based on those studies, it was initiated to implement analytical techniques for illuminating the acoustical characteristics of coir fiber in order to optimize the performance of coir fiber absorber panel (Fouladi *et al.*, 2010; Ayub *et al.*, 2009; 2010; Ballagh, 1996). This current study is also a part of that initiative to explore the possible approaches for enhancing the absorption coefficient. As a result, it was believed that the compression would have a significant effect on the absorption of coir fiber, since the flow resistivity of the material is considerably low. This study presents the analysis of compression effect of the porous layer on absorption feature of coir fiber. Moreover, the comparison between the absorption performance of uncompressed and compressed material is illustrated; and the effect is described as a possible way to improve the absorption property.

MATERIALS AND METHODS

In these analyses, acoustic characteristics impedance of coir fiber was estimated by Johnson-Allard equivalent fluid model (Allard, 1993) as the solid structure of the coir fiber was considered as rigid. Compression of the material is presented by the ratio known as compression rate as introduced by Castagnede *et al.* (2000). In addition, during compression, the variation of physical parameters such as porosity, tortuosity, flow resistivity and two characteristics length was evaluated using the formulas developed by Castagnede *et al.* (2000).

Rigid frame method: Johnson-Allard model: This model assumes that the solid phase of porous material remains motionless. In this research, it was sought that rigid frame condition could be considered for solid structure of coir fiber, as the flow resistivity of coir fiber found to be very low (less than 10,000 Nsm⁻⁴) (Wang *et al.*, 2008). As a result, a rigid frame model was assumed to be applicable for analytical prediction of absorption characteristics of coir fiber.

According to the Johnson-Allard Model (Allard, 1993), the equation for effective density and bulk modulus of the rigid framed porous material can be expressed by Eq. 1-4, which involves five non-acoustical parameters flow resistivity, tortuosity, porosity and two characteristics lengths (thermal and viscous characteristics length) (Allard, 1993; Kino *et al.*, 2009).

Equation of the Effective density:

$$\rho(\omega) = \rho_0 \alpha_\infty \left(1 + \frac{\sigma \phi}{i \alpha_\infty \rho_0 \omega} G_j(\omega) \right) \quad (1)$$

With:

$$G_j(\omega) = \left(1 + \frac{4i \alpha_\infty^2 \eta \rho_0 \omega}{\sigma^2 \Lambda^2 \phi^2} \right)^{\frac{1}{2}} \quad (2)$$

Equation of the Bulk Modulus:

$$K(\omega) = \frac{\gamma P_0}{\left[\gamma - (\gamma - 1) \left[1 + \frac{8\eta}{i \Lambda'^2 \rho_0 \text{Pr}(\omega)} G'_j(\text{Pr} \omega) \right]^{-1} \right]} \quad (3)$$

With:

$$G'_j(\omega) = \left(1 + \frac{i \rho_0 \Lambda'^2 \text{Pr} \omega}{16\eta} \right)^{\frac{1}{2}} \quad (4)$$

Where:

- ρ_0 = The density of the air
- α_∞ = The tortuosity
- σ = The flow resistivity
- ϕ = The porosity of porous material
- ω = The angular frequency
- f = The frequency of sound
- i = An imaginary number
- Λ = The viscous characteristics length,
- Λ' = The thermal characteristics length
- η = The viscosity of the air
- γ = The specific heat ratio of the air
- P_0 = The atmospheric pressure

The characteristics impedance of the porous material Z_f can be derived from the effective density $\rho(\omega)$ and bulk modulus $K(\omega)$ using Eq. 5 and the propagation constant Γ_f can be derived from the effective velocity $c(\omega)$ using Eq. 6. Relationship

between all those parameters can be expressed as (Allard, 1993; Kino *et al.*, 2009):

$$Z_f = \rho(\omega)c(\omega) = \sqrt{K(\omega)\rho(\omega)} \quad (5)$$

$$\Gamma_f = i \left[\frac{\omega}{c(\omega)} \right] = i\omega \sqrt{\frac{\rho(\omega)}{k(\omega)}} \quad (6)$$

Variation of the physical parameters versus the compression rate: As shown in Fig. 1, the porous fibrous layer has an initial thickness L_f . If the porous layer goes under compression, then the material layer will be compressed and the new compressed thickness is L_f' . The compression rate is defined as:

$$n = \frac{L_f}{L_f'} \quad (7)$$

Compressing the material affects the physical parameters of porous material like porosity, tortuosity, flow resistivity, two characteristics length. These all parameters are related with the acoustic impedance of porous material. Castagnede *et al.* (2000) had shown that the variation in those parameters follow a simple law. The new porosity, tortuosity, flow resistivity, thermal characteristics length, Viscous Characteristics length caused by the 1D compression are defined as (Castagnede *et al.*, 2000; Wang *et al.*, 2008):

- Porosity, ϕ :

$$\phi^{(n)} = 1 - n(1 - \phi^{(0)}) \quad (8)$$

- Tortuosity, α_∞ :

$$\alpha_\infty^{(n)} = 1 - n(1 - \alpha_\infty^{(0)}) \quad (9)$$

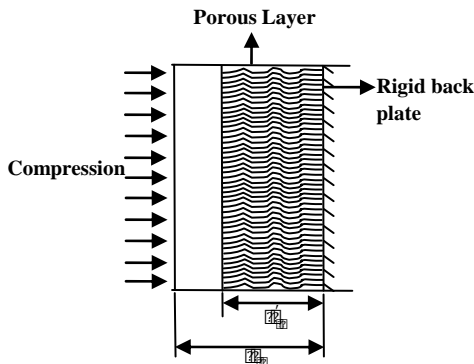


Fig. 1: The illustration of compression rate

- Flow resistivity, σ :

$$\sigma^{(n)} = n\sigma^{(0)} \quad (10)$$

- The Viscous Characteristics length, Λ :

$$\Lambda^{(n)} = \frac{\Lambda^{(0)}}{\sqrt{n}} + \frac{Q}{2} \left(\frac{1}{\sqrt{n}} - 1 \right) \quad (11)$$

- The thermal characteristics length, Λ :

$$\Lambda^{(n)} = \frac{\Lambda^{(0)}}{\sqrt{n}} + \frac{Q}{2} \left(\frac{1}{\sqrt{n}} - 1 \right) \quad (12)$$

Where:

(0) = The initial value without compression and superscript

(n) = The changing value due to the compression effect with compression rate and 'a' represents the mean fiber radius

According to the description in Castagnede *et al.* (2000) and Wang *et al.* (2008), above Eq. 8-12 generally apply in many cases for small compression rate 'n', but those equations cannot be rigorously true for all cases. The compression rate 'n' should be kept lower and no more than 2 (i.e., $n \leq 2$). It should be better to keep the compression rate within the limit for obtaining the best result using those equations.

RESULTS

Experiments were conducted in impedance tube according to ISO 10534-2 (1998) standard to validate the analytical analysis. The measurement system included two impedance tubes with diameters 28 mm and 100 mm each contains two 1/4" microphones type GRAS-40BP, plane wave source, dual channel Symphonie (01 dB model) real time data acquisition unit and 01dB software package. Calibrator type GRAS-42AB was used for microphone sensitivity calibration at 114 dB and 1 KHz frequency. Before starting the measurement, the two impedance tube microphones were calibrated relatively to each other using the standard switching technique, to make sure that the sound field inside the tube is well defined. Measurements were done with 3 Hz frequency resolution and sample records of finite duration about 10 sec. Coir fiber sample was collected industrially as a large rectangular sheet and then cut into suitable circular shape for impedance tube. Numbers of 15 fiber samples were selected randomly to obtain an average value for density and fiber diameter. Raw fiber thickness of the material is measured by dial thickness gauge meter in the scale of one hundredth of millimeter. Average diameter and density of the fiber was taken as 252 μm

and 821 kg m^{-3} respectively for industrial coir fiber as found from the experimental measurements. The shape of the fiber was considered as cylindrical shape. Bulk density of the material was measured from the mass and volume of each sample thickness separately.

Figure 2-4 shows the absorption performances of the 20, 35 and 50 mm single layer coir fiber backed with rigid wall, respectively. The absorption coefficient was estimated by rigid frame model and then compared with measured results. The agreement between the measured absorption coefficient and the rigid frame prediction is favorable. It seems that this rigid frame model can predict the position of the peak with their absorption coefficient almost evenly.

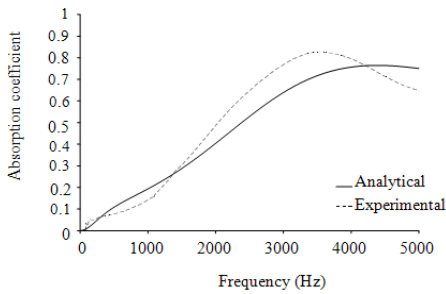


Fig. 2: Acoustic absorption coefficient of 20 mm coir fiber layer backed with rigid wall

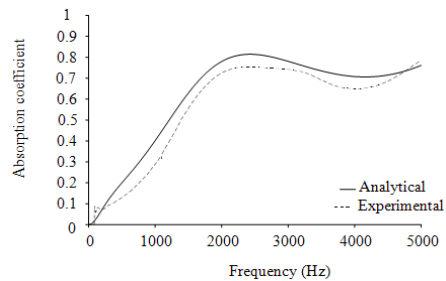


Fig. 3: Acoustic absorption coefficient of 35 mm coir fiber layer backed with rigid wall

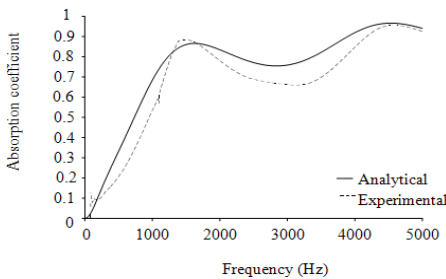


Fig. 4: Acoustic absorption coefficient of 50 mm coir fiber layer backed with rigid wall

Above mentioned results indicate that equivalent fluid model is amply adequate for modeling coir fiber with low flow resistivity. Apparently, it can be conceded that the rigid frame model can be accepted as an accurate and reliable analytical procedure for single layer assembly. Therefore, the rigid frame modeling approach is implemented for further analysis to investigate the other properties such as compression effect.

DISCUSSION

Compression effect: Figure 5 illustrates the acoustic absorption response of coir fiber during 1D compression. In this analysis, initial thickness of coir fiber is 50 mm and compression is defined by a ratio named as compression rate (n). It can be estimated as (Castagnede *et al.*, 2000):

$$n = \frac{L_f}{L'_f} = \frac{\text{initial thickness}}{\text{compressed thickness}}; (n \leq 2) \quad (13)$$

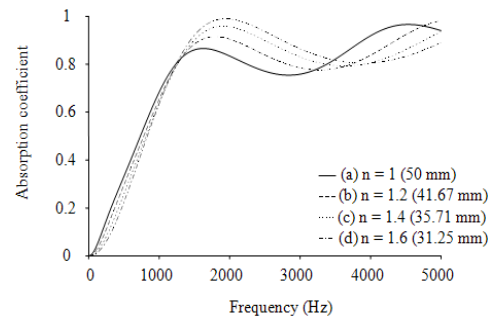


Fig. 5: Simulations of the absorption coefficient of 50 mm (Original thickness) coir fiber for varying compression rate. (a) Uncompressed, Compression rate $n = \frac{50}{50} = 1$ Thickness = 50

mm, flow resistivity (σ) = $1359.2 \text{ Nm}^{-4}\text{s}$, Porosity (ϕ_c) = 0.8941, Tortuosity (α_∞) = 1.0575, Viscous characteristics length (Λ) = $133.46 \mu\text{m}$, Thermal characteristics length (Λ') = $266.92 \mu\text{m}$; (b) $n = \frac{50}{41.67} = 1.2$, Thickness = 41.67 mm, $\sigma = 1631.1 \text{ Nm}^{-4}\text{s}$, $\phi_c = 0.87297$, $\alpha_\infty = 1.069$, $\Lambda = 101.04 \mu\text{m}$, $\Lambda' = 222.87 \mu\text{m}$; (c) $n = \frac{50}{35.71} = 1.4$ Thickness = 35.71 mm, $\sigma = 1902.9 \text{ Nm}^{-4}\text{s}$, $\phi_c = 0.8518$, $\alpha_\infty = 1.0806$, $\Lambda = 75.84 \mu\text{m}$, $\Lambda' = 188.63 \mu\text{m}$; (d) $n = \frac{50}{31.25} = 1.6$ Thickness = 31.25 mm, $\sigma = 2174.8 \text{ Nm}^{-4}\text{s}$, $\phi_c = 0.83062$, $\alpha_\infty = 1.0921$, $\Lambda = 55.25 \mu\text{m}$, $\Lambda' = 161.03$

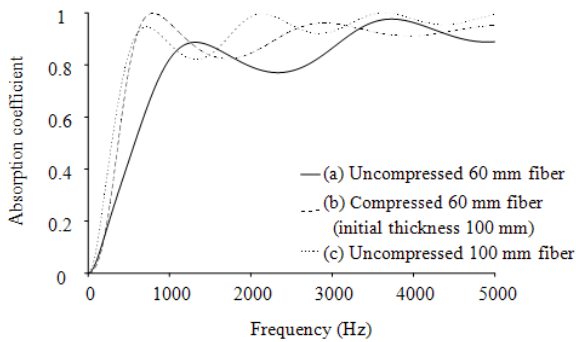


Fig. 6: Simulations results for the comparison of absorption coefficient for 60 mm coir fiber in uncompressed and compressed condition. (a) Uncompressed, Thickness = 60 mm (b) Compressed 60 mm coir fiber (initial thickness 100 mm) with compression rate, $n = \frac{100}{60} = 1.666$ (c) Uncompressed 100 mm coir fiber

Compressing the material affects the physical parameters of porous material like porosity, tortuosity, flow resistivity and two characteristics length and the variation follows a simple law as explained by Castagnede *et al.* (2000) and Wang *et al.* (2008). For a given homogenous layer, compression is followed by a reduction in porosity and two characteristics length; and at the same time by an increase in flow resistivity and tortuosity (Castagnede *et al.*, 2000). The same variation in the characteristics of physical parameters is observed for coir fiber during compression as the data indicated with the Fig. 5.

Figure 5 shows that increasing the compression rate ($n = 1$ to 1.6) moves the absorption peak towards higher frequency which can be described as thickness effect as mentioned in previous works (Castagnede *et al.*, 2000; Wang *et al.*, 2008). Drop in thickness of the porous material usually shift the absorption peak towards high frequency. At the same time, higher compression rate corresponds to the strong acoustic absorption which is greater than the uncompressed coir fiber. This effect may be due to increased density and flow resistivity of the material with the increasing compression rate. Moreover, compression makes the pore of the compressed media small that causes the large frictional effect on sound energy when sound is transmitted in the fluid part of the porous media (Wang *et al.*, 2008). However, in the previous analysis on compression, it was shown that porous materials usually show degradation in the absorption with the increased compression rate, which is the opposite behavior of the present analysis. This can be adopted by the very low

flow resistivity of coir fiber. In this case, if the compression rate increases, the flow resistivity of coir fiber also increases. But it is not too high (still lower than $5000 \text{ Nm}^{-4} \text{ sec}$) those sound waves face difficulty to be transmitted within the porous media. Therefore, increased flow resistivity seems to show positive effect on the absorption rather than the occurrence of the sound reflection due to congested inner structure.

These results of compression can be powerfully exploited in designing models of sound absorption. Compressing the material can be useful to enhance the absorption, at the same time reducing the thickness of fiber layer which is an important factor for limited space structure. Figure 6 shows an example regarding the comparison of absorption for 60 mm coir fiber in compressed and uncompressed (normal condition) condition. Solid line concerns the absorption for 60 mm coir fiber in uncompressed condition which shows good absorption at mid and high frequency but poor absorption at low frequency. Dotted line represents absorption for 100 mm coir fiber in uncompressed condition. Dashed line demonstrated the absorption for 60 mm coir fiber which compressed from initial thickness of 100 mm. Figure 6 exhibits that low frequency absorption beyond 1000 Hz frequency can be improved by increasing the coir fiber layer thickness to 100 mm. However, 100 mm thickness is too large for a porous acoustic absorber. But, this 100 mm coir fiber can be made more useful if the material compressed to 60 mm thickness (dashed line), at the same time maintaining similar absorption. It depicts how the absorption can be improved substantially for the same thickness of coir fiber by compressing the material.

CONCLUSION

Analyses have been conducted to explore the compression factors that can affect the absorption coefficient of coir fiber based on the analytical method demonstrated in this study. In these analyses, Johnson-Allard model together with compensation in physical parameters were implemented to estimate the surface impedance of coir fiber. Castagnede formulas were utilized to evaluate the changes of physical parameters of material during compression. Variations of acoustic behavior of coir fiber with the change of compression rate are illustrated. It has been revealed that compressed coir fiber can improve the absorption considerably. Moreover, analysis on compression effect has shown that low frequency absorption as well as wide span absorption can be improved significantly by compressing the material without any increase of extra layer. Compression effect of the porous layer on

absorption feature demonstrated in this study can be useful for the application of automotive acoustics, since they go under compression during seat padding.

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