**Enhancement of Coir Fiber Normal Incidence Sound Absorption Coefficient**

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**Abstract**

Coir fiber from coconut husk is an important agricultural waste in Malaysia. The porous structure of fiber makes it an eligible material for acoustical absorption. In previous studies at Universiti Kebangsaan Malaysia, single layer coir fiber showed low acoustical absorption in medium and low frequencies; e.g., absorption coefficient of a 20 mm industrial prepared coir fiber sample was below 0.3 for frequencies less than 1.5 kHz. Current research was initiated to improve the shortcoming by mixing industrial prepared coir fiber with air gap layers. Analyses were based on two approaches, namely; Delany-Bazley with Acoustic Transmission Analysis (ATA) and Allard elastic model with transfer matrix analysis. Experimental measurements were conducted in impedance tube to validate the analytical results. Outcomes described that Delany-Bazley-ATA technique was an approximate solution showing overall absorption path without giving any accurate information about the peaks and resonances. Allard method took the elasticity of material into account and transfer matrices were able to characterize the whole structure as a combination of single layers. Results were close to
experimental values and predicted the path and resonances very well. Further analyses were conducted by Allard method and derived that having a fiber layer backed by an air gap was better than leaving the same gap in between that layer. The explanation was that, in the first arrangement, the sound field impacted a solid layer with higher thickness and followed a longer transmission path which caused a higher acoustical absorption. Furthermore, it was noticed that a reasonable thickness of backing air gap improved the overall sound absorption. Increase in the gap thickness produced more peaks and moved them to lower frequencies which caused better absorption in low frequencies. The cause of this phenomenon was increase in impedance of the panel due to rise in the air-gap thickness. This moved the acoustical resonances to lower frequencies and improved the sound absorption in this frequency span. Finally it was concluded that other acoustic absorption techniques such as adding perforated plate may be combined with coir fiber-air gap structure to improve the low frequency acoustic absorption coefficient without any need to highly increase the air gap thickness.

**Keywords:** coir fiber; acoustic absorption coefficient; porous material; Delany-Bazley; Acoustic Transmission Analysis (ATA); Allard elastic model.

1. Introduction

Multilayer sound absorption panels consisting of porous material, perforated plate and air gap are broadly used to improve room acoustics. Acoustic absorption of materials has spectral characteristic; they have different absorption abilities throughout the frequency spectrum. None of them are a good wideband sound absorber and they have spectral strength and weaknesses. Addition of extra layers is generally utilized to overcome these shortcomings, enhance the noise attenuation or isolation and satisfy the human comfort. Brekhovskikh [1] introduced modeling of sound propagation in layered media using transfer matrices. Allard
[2] extended his approach for sound propagation in porous materials having elastic frames. This technique was generalized by Brouard et al. [3] to model sound propagation in stratified media. The solution needed sufficient information about the acoustic field at the boundaries and different configurations of plates, impervious screens, air gap and porous media where analyzed. Lauriks et al. [4] also implemented transfer matrices to model plane wave propagation in layered media using three Biot waves. Lafarge et al. [5] estimated the dynamic compressibility of air in reticulated foams and glass wool using static thermal permeability and thermal characteristic dimension. Their model was analogous to Johnson et al. [6] model of dynamic viscous permeability and obtained predictions closer to experimental results.

Chen et al. [7] studied the effects of different surface shapes and perforated plates on the acoustic absorption of panels. They used a finite element system that was derived from the Galerkin residual method and Helmholtz wave propagation equation. Bolton et al. [8] utilized the Biot theory to calculate transmission loss of lined double panels at arbitrary angles of incidence. For a greater transmission loss, it was generally better not to attach the lining materials directly to the facing panels. Attenborough et al. [9] modeled a multilayer medium consisting of granular surface and porous substrate. The granular media was characterized by uniform slit-pores within a rigid solid matrix and boundary conditions were applied at interfaces. Rebillard et al. [10] studied the effects of bounded and un-bounded facings to the acoustic impedance of isotropic porous materials. Such facings were consisted of porous plates and porous elastic membranes and the whole layer was represented in the form of a matrix.

Lee and Chen [11] established a new method to calculate surface acoustic impedance of multilayer absorbers. Equivalent Electrical Circuit Approach (EECA) assumed the acoustic impedance of every back layer as that of rigid wall even if it was constructed of perforated plate or air gap. Outcomes of EECA were deviated from experimental values and
considered as poor resolution. Acoustic Transmission Analysis (ATA) approach assumed the
effect of back surface acoustic impedance of every layer according to the back layer material.
Results showed that ATA technique was more accurate than EECA method. Moreover, they
[12] studied the effects of inner structure of multilayer absorbers on their acoustic
characteristic. Results described that having more materials in front or behind the perforated
plate enhanced the acoustic absorption at higher and lower frequencies, respectively. Besides,
longer transmission path of the incident sound improved the acoustic absorption.

Noise control engineering is enhanced recently by using natural acoustic absorbers.
Coir fiber is an agricultural waste obtained from coconut husk. The high amount of lignin has
put it among the hardest natural fibers available today [13]. Study on acoustic characteristics
of coir fiber was initiated in vibration and acoustics laboratories of Universiti Kebangsaan
Malaysia. Acoustic absorption of coir fiber for single and multilayer panels was simulated by
software WinFlag™. Experimental validation was also obtained through the measurements in
reverberation room [14, 15, 16]. Recently, analytical analysis of coir fiber acoustical
characteristics was conducted and validated by impedance tube measurements. An example is
shown in Fig. 1 which indicates that coir fiber has absorption below 50% for frequencies less
than 1 kHz. This weakness necessitates the utilization of an approach such as adding air gap
to improve the low to medium frequency sound absorption. Current paper deals with
analytical analysis of multilayer panels consisting of coir fiber and air gap. Experiments in
impedance tube also supported the outcomes.

2. Methodology

Two approaches were proceeded to calculate the sound absorption coefficient of multilayer
panels. Firstly, the well-known Delany-Bazley technique was used to calculate surface
impedance of porous material. Impedances of other layers were also calculated and results added together to construct the surface impedance of panel using ATA method. Secondly, Allard [2] formulation based on wave equation and transfer matrix representation of every layer was utilized to estimate the acoustic absorption of panel.

2.1 Delany-Bazley together with ATA approach

The characteristic impedance $Z_m$ and propagation constant $\gamma_m$ of a layer of homogeneous porous material is obtained as [17, 18]:

\[
Z_m = \rho_0 c_0 \left[1 + c_1 \left(\frac{f \rho_0}{\sigma}\right)^{c_2}\right] - i \left[c_3 \left(\frac{f \rho_0}{\sigma}\right)^{c_4}\right] \quad (1)
\]

\[
\gamma_m = k_0 \left[c_5 \left(\frac{f \rho_0}{\sigma}\right)^{c_6} + i \left[1 + c_7 \left(\frac{f \rho_0}{\sigma}\right)^{c_8}\right]\right] \quad (2)
\]

where $f$ and $c_0$ are frequency and speed of sound, respectively, $\sigma$ flow resistivity, $c_1$ to $c_8$ are the Delany-Bazley regression constants, $\rho_0$ and $k_0 = \frac{2\pi f}{c_0}$ are the density and wave number of air, respectively. Based on these equations, $Z_m$ and $\gamma_m$ depend mainly on frequency of analysis and flow resistivity of the porous media. Characteristic impedance and complex wave number of air are also defined as $\rho_0 c_0$ and $ik_0$, respectively. For an isotropic and homogeneous multilayer material, the surface acoustic impedance $\Gamma_j$ of $j^{th}$ layer with thickness $t_j$ is calculated using Eq. (3) as below [18]:

\[
\Gamma_j = \frac{Z_j}{Z_{jm}} \Gamma_{jm} \quad j = 1, 2, \ldots, n
\]
\[ I_j = Z_j \frac{Z_{back} \cosh(\gamma_j t_j) + Z_j \sinh(\gamma_j t_j)}{Z_{back} \sinh(\gamma_j t_j) + Z_j \cosh(\gamma_j t_j)} \]  

(3)

where \( Z_j \) and \( \gamma_j \) are characteristic impedance and complex wave number of \( j^{th} \) layer, respectively, and \( Z_{back} \) is the back surface acoustic impedance. Finally, acoustic absorption coefficient \( \alpha \) of the multilayer material can be calculated as [19]:

\[
\alpha = \frac{4R_r/\rho_0 c_0}{(R_r/\rho_0 c_0 + 1)^2 + (X_r/\rho_0 c_0)^2}
\]

(4)

where \( R_r \) and \( X_r \) are real and imaginary components of the surface acoustic impedance of the layer, respectively, that is impinged by air. Kidner and Hansen [20] mentioned that although Delany-Bazley is an old; 40 years old, empirical model but still it is satisfactory for many studies of sound absorption of porous materials where \( 10^3 < \sigma < 5 \times 10^4 \) Ns/m\(^4\). However, this model cannot describe the dynamics of materials and accuracy of outcomes is limited.

### 2.2 Allard multilayer transfer matrix approach

Allard elastic model [2] is the source of all formulations in this section. Firstly, his technique for single-layer elastic porous material is implemented to model coir fiber. Eqs. (5) to (7) are based on his model and modified for industrial prepared coir fiber. The industrial prepared coir fiber is normally mixed with binder to increase the stiffness. It is simulated as elastic cylindrical fibers and viscous characteristic length is defined as:

\[
\Lambda = \frac{1}{2\pi r l \varphi_c}
\]

(5)
where \( r \) is radius of fiber mixed with binder, \( l_t \) total length of fiber per unit volume of material and \( \varphi_c \) is porosity of material. Parameters \( r \) and \( l_t \) for industrial coir fiber are defined as Eqs. (6) and (7): 

\[
\begin{align*}
    r &= r_{fiber} + (r_{fiber} \varphi_c) \quad (6) \\
    l_t &= \frac{1}{\pi r^2} 
\end{align*}
\]

This formulation easily assists in calculation of wave numbers and velocity ratios of compressional waves transmitting in porous layer.

The above-mentioned layer can be presented by a single transfer matrix. Allard [2] proposed an approach to model the surface impedance of multilayer materials consisting of infinite porous layers. Based on this method, each porous layer is defined by a transfer matrix. Consider Fig. 2 as a porous layer with thickness \( l \). The acoustic field vectors \( V(M) \) and \( V(M') \) at two \( M \) and \( M' \) points close to front and back surface of the layer can be related by transfer matrix \([T]\). This matrix depends on \( l \) and physical properties of the layer as follows:

\[
V(M) = [T]V(M') \quad (8)
\]

where matrix \([T]\) can be calculated by Eq. (9) [21]:

\[
[T] = [\Gamma(0)][\Gamma(l)]^{-1} \quad (9)
\]
Matrix $\Gamma(x)$ is evaluated from the velocity components and stress tensors of the fluid and frame constructing the acoustic field vectors $V(M)$ and $V(M')$. The components of matrix $\Gamma(x)$ are given by Allard [2]. Now consider a material consists of several porous layers. The transition between the first two adjacent layers $a$ and $b$ with porosities $\varphi_a$ and $\varphi_b$ is estimated by transfer matrix $[T]$ as follows:

$$[T] = [T_a][T_{interface,ab}][T_b]$$  \hspace{1cm} (10)

where $[T_a]$ and $[T_b]$ are transfer matrices of layers $a$ and $b$, respectively, and $[T_{interface,ab}]$ is the interface matrix relating stresses and velocities for the two porous layers. Let $a$ equals the first layer impinged by the acoustic field, then matrix $[T_{interface,ab}]$ is defined as [2]:

$$[T_{interface,ab}] = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 - (\varphi_b/\varphi_a) & \varphi_b/\varphi_a & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 - (\varphi_a/\varphi_b) \\
0 & 0 & 0 & 1 & 0 & (\varphi_a/\varphi_b) \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$ \hspace{1cm} (11)

The transfer matrix $[T]$ in Eq. (10) is again related to transfer matrix of the next layer by an interface matrix and so on. This process continues for the rest of layers to calculate the resultant transfer matrix representing the whole material. The surface impedance at normal incidence of multilayer porous material $Z$ is calculated using $T_{ij}$ components of the resultant
transfer matrix $[T]$. Relating the velocities and stresses in the front and back surfaces of material, produce a system of equations having coefficients $\Delta_i$ as follows:

\[
\begin{align*}
\Delta_1 &= T_{24} T_{55} - T_{25} T_{54} \\
\Delta_2 &= T_{26} T_{55} - T_{25} T_{56} \\
\Delta_3 &= T_{34} T_{55} - T_{35} T_{54} \\
\Delta_4 &= T_{36} T_{55} - T_{35} T_{56} \\
\Delta_5 &= T_{44} T_{55} - T_{45} T_{54} \\
\Delta_6 &= T_{46} T_{55} - T_{45} T_{56} \\
\Delta_7 &= T_{64} T_{55} - T_{65} T_{54} \\
\Delta_8 &= T_{66} T_{55} - T_{65} T_{56}
\end{align*}
\] 

(12)

Note that, $T_{ij}$ should not be misunderstood with $[T_{interface,ab}]$ elements that will cause most of the $\Delta_i$ terms to be zero. Thereafter, $Z$ is estimated by using the above coefficients:

\[
Z = \frac{\Delta_6 \Delta_7 - \Delta_5 \Delta_8}{D}
\]

(13)

Considering $\varphi$ as the porosity of the layer in contact with air, $D$ is equal to:

\[
D = \{(1 - \varphi)\Delta_1 + \varphi \Delta_3\}\{(1 - \varphi)\Delta_8 - \varphi \Delta_6\} - \{(1 - \varphi)\Delta_2 + \varphi \Delta_4\}\{(1 - \varphi)\Delta_7 - \varphi \Delta_5\}
\]

(14)

Although this formulation is complicated compared to Delany-Bazley-ATA approach, but resonances within the frame of multilayer material can be detected very well using this method.
3. Results and observations

A number of 15 strings, having cylindrical shape, were selected to obtain an average for density and diameter of coir fiber. The diameter and weight of each string were measured by caliper and precision balance, respectively. Samples having too high or low diameters were put aside and the rest averaged to find the average diameter of fibers. Densities of fibers were measured by dividing the volume of each cylindrical string by its mass. Average density and fiber diameter $d_{fiber}$ of the industrial prepared coir fiber (mixed with binder) that was utilized in this research were measured as 821 kg/m$^3$ and 252 µm, respectively. Bulk density $\rho_{bulk}$ was obtained from the mass and volume of each sample separately. Flow resistivity was the only parameter needed to proceed using the Delany-Bazley approach. It was estimated empirically using the following equation [22]:

$$\sigma = 490 \frac{\rho_{bulk}^{1.64}}{d_{fiber}}$$  \hspace{1cm} (15)

Flow resistivity of industrial prepared coir fiber was measured experimentally for two samples having typical small and large thicknesses of 20 and 50 mm. The experimental apparatus was AMTEC C522 air flow resistance test system which operates in compliance with the ASTM C522 specifications as “Test method for Airflow Resistance of Acoustical Material” [23]. It comprises of sample holder, data acquisition system including vacuum pump and software package C522. This system may be used for airflow and differential pressure measurements ranges between 0 to 15 lpm and 0 to 294.1 Pa, respectively. Measurements were set up for four flow point 1 to 4 lpm with three sequential repeated tests.
for every sample to get an average flow resistivity data. Experimental and predicted flow resistivity values were 1618 and 1680 Nsm$^{-4}$ for 20 mm samples also 1395 and 1359 Nsm$^{-4}$ for 50 mm samples, respectively. It proved that Eq. (15) may be used to predict flow resistivity of coir fiber.

Characteristic impedance and propagation constant of coir fiber were obtained by Eqs. (1) and (2). Starting from the first layer in contact with the rigid wall, surface impedance of layers was calculated having the characteristic impedance of the back layer as shown in Eq. (3).

In Allard approach, viscous characteristic length was calculated according to physical properties of industrial coir fiber that were defined in Eqs. (5), (6) and (7). Allard stated that for highly porous material, thermal characteristic length $\Lambda'$ is double of $\Lambda$. Based on these parameters, single layer coir fiber was modeled as an elastic porous material. This model was applied in Eq. (9) to obtain the transfer matrix representing a single layer coir fiber. Air gap was considered as a porous material with 100 percent porosity, tortuosity $\alpha_{\infty} = 1$ and very low flow resistivity and shear modulus. Therefore, viscous characteristic length of air was estimated by Eq. (16) as below [2]:

$$\Lambda = \left( \frac{8\alpha_{\infty} \eta}{\varphi \sigma} \right)^{1/2}$$  \hspace{1cm} (16)

where $\eta$ is dynamic viscosity of air. Further, layers of air and coir fiber were added together by Eqs. (10) and (11). Finally, the resultant transfer matrix was utilized to calculate the surface acoustic impedance of material using Eqs. (12) to (14).
3.1 Arrangement of fiber-air gap

The acoustic absorption coefficient of 20, 35 and 50 mm coir fiber samples having typical small, medium and large thicknesses backed with air gap are presented in Figs. 3 to 5, respectively. The 20 mm air gap was arbitrary and kept constant in the experiments to make it possible to compare the results. Graphs that are corresponded to impedance tube show the real experimental outcomes that were measured directly. The Allard elastic model had the nearest prediction to the measured values. It followed the same pattern and exhibited resonances that were close to the experimental graph. Figures show that utilization of Delany-Bazley technique together with ATA approach was a rough approximation to the solution. It was a good implement to obtain the overall absorption pattern, however, the real positions of structural resonances were not observed. EECA is also shown as an example just in Fig. 3 and did not conduced to meaningful values.

For 20 mm coir fiber in Fig. 3, the addition of air gap enhanced sound absorption between 1000-3000 Hz. The resonance peak was moved from 4000 Hz in single layer coir fiber (data “Allard without air gap”) to 2100 Hz in the multilayer (data “Allard”). In Fig. 4, the 2300 Hz resonance of 35 mm coir fiber (data “Allard without air gap”) was diminished a bit but another two peaks rose for the multilayer structure (data “Allard”). Resonances around 1400 and 4300 Hz improved the overall absorption in medium to high frequencies. Fig. 5 shows the same enhancement, the resonances of single layer fiber at 1600 and 4600 Hz were replaced by three peaks at 1150, 3000 and 4800 Hz for coir fiber backed with air gap. Evidently, application of air gap improved the acoustic absorption of coir fiber in medium to high frequencies as it absorbed energy of the incident wave in this frequency span. The
experimental results measured in impedance tube and shown in Figs. 3 to 5 are summarized in Table 1 for one-third octave band center frequencies.

Another interesting point was the arrangement of porous layer and air gap. They were two possibilities; leave an air gap between two layers of fiber or place the coir fiber in one side backed by an air gap. A schematic plan of the assembly is shown in Fig. 6. Both conditions were analyzed using Allard approach and outputs together with absorption coefficient of single layer coir fiber are shown in Fig. 7. Results show that both arrangements enhanced the acoustic absorption of fiber at medium and high frequencies. The two peaks of single layer fiber were moved to lower frequencies and another one was added in high frequency around 4500 Hz. However, it is obvious that arrangement (b) had higher absorption while arrangement (a) shows diminish in medium frequencies between 600 Hz and 2500 Hz. Note that mass and thickness (then volume) of coir fiber that is located in front of sound field are doubled from condition (a) to (b). Then bulk modulus is constant; porosity and flow resistivity are the same in both conditions. The difference is that having a thick unified fiber layer as Fig. 6.b better isolated the sound field from entering the structure because longer transmission path for the incident sound will improve the acoustic absorption. Thereafter absorption was enhanced further by adding an air gap. Besides, incident wave reflects as hits each solid medium. So in condition (a), it reflected back again as hit the secondary fiber layer and recombined with the primary reflections which caused in lower absorption.

3.2 Compression Effect

Fig. 8 illustrates the acoustic absorption response of coir fiber during 1D compression. In this analysis, initial thickness of coir fiber was 50 mm and compression is defined by a ratio named as compression rate \((n)\) [24]:

\[ \text{absorption} = \frac{\text{power} - \text{loss}}{\text{incident power}} \]

...
Compression affected the physical parameters of porous material like porosity, tortuosity, flow resistivity and the two characteristic lengths. These variations follow a simple law that was explained by Castegnate et al. [24] and Wang et al. [25]. For a given homogenous layer, compression is pursued by reduction in porosity and two characteristic lengths and at the same time by an increase in flow resistivity and tortuosity [24]. Such variations in the characteristics of physical parameters were observed for coir fiber during compression. The physical properties of a 50 mm coir fiber sample under various compression rates are addressed in Table 2 and their acoustic absorptions were investigated in Fig. 8. This figure shows that increasing the compression rate (n=1 to 1.6) moved the absorption peak towards higher frequencies which can be described as thickness effect [24, 25]. Reason is the drop in thickness of the porous material which usually shifts the absorption peak towards high frequencies. At the same time, higher compression rate resulted in higher acoustic absorption due to increased density and flow resistivity of the material. Moreover, compression made the pores of the compressed media smaller and caused frictional effect on sound energy while transmitting in the fluid part of the porous media. In contrast to current outcomes it was shown [24, 25] that there is degradation in acoustic absorption characteristic as compression rate increases. This can be described by the very low flow resistivity of coir fiber. Flow resistivity enhances as the compression rate increases but it is still not too high (lower than 5000 Nm$^{-4}$s) and cannot affect the sound transmission 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 layer.
3.3 Effects of increasing the backing air gap

The industrial coir fiber has low absorption in low and medium frequencies due to dryness and effect of binder in increasing its stiffness. A reasonable combination of fiber and air gap layers can improve this shortcoming to some extents. Definitely, space limitations constrain the thickness of isolator structure. Designer has to compromise between the amount of sound absorption and space occupation according to the attenuation target. Moreover, one should be careful about reduction in medium and high frequency acoustical absorption caused by increase in the air gap thickness. An example is shown in Fig. 9 which a 50 mm fiber layer was backed by an air gap with thickness starting from 20 mm to 160 mm. The combination with 20 mm air gap had a reasonable absorption mostly around or higher than 70% for $f > 800$ Hz. Increasing the air gap by eight times up to 160 mm improved the low frequency absorption and moved the absorption peak to lower frequencies. Unfortunately, the absorption coefficient for 40 mm air gap layer was less than the 20 mm one for the frequency span of 1000-2200 Hz. The data regarding 160 mm air gap also showed a major reduction of absorption between 600-1900 Hz in comparison with the 20 mm air gap layer. The declining was also steeper as the air gap increased. The reason is that increase in the air-gap thickness will increase the impedance of the panel and moves the acoustical resonance to lower frequencies which causes a better absorption in this region. It may be derived that other techniques such as adding perforated plate can be mixed with coir fiber-air gap structure to further improve the low frequency absorption without any need to highly increase the air gap thickness. A reason for low acoustic absorption is the large diameter of coir fiber. Further enhancement may be achieved by mixing the coir fibers with other ones having smaller
diameter. That is out of the scope of the current study and will be investigated in another research. This cheap natural fiber may have the potential to rectify the current NVH problems in industries [26], possibility of its commercialization and probable shortcomings should be investigated in future.

4. Conclusion

This research was conducted to enhance acoustic absorption characteristics of coir fiber as an agricultural waste material in Malaysia. Previous studies showed that coir fiber has low acoustical absorption; e.g., the absorption coefficient for 20 mm industrial prepared coir fiber sample was below 0.3 for frequencies less than 1.5 kHz. Therefore addition of air gap layer as a potential technique was proceeded to improve the weakness. Two procedures were considered for the analyses, Delany-Bazley empirical technique followed by ATA method and Allard elastic model based on wave equations. The first one was about estimating the acoustic absorption of coir fiber using Delany-Bazley formulae and then calculating the surface acoustic impedance of structure according to back surface impedance of each layer. Second one was to represent each layer with a transfer function using the velocity components and stress tensors on front and back surfaces of that layer. Thereafter these transfer matrices were added together by interface matrices to characterize the whole structure. Results showed that Delany-Bazley-ATA approach was suitable in giving the overall absorption pattern without any accurate information about peaks and resonances of structure. Outcomes of the Allard model were close to experimental values; truly showed both pattern and resonances of structure. Therefore, this model was used further to analyze two coir fiber-air gap arrangements. They included having a layer of fiber backed by an air
gap or leaving the layer of air gap in between the fiber layer. Analyses derived that later condition had lower sound absorption coefficient as transfer path in front of incident sound was shorter and also material exhibited more reflections. At the end, influences of the thickness of backing air gap on sound absorption were investigated. Combining reasonable thickness of fiber and air gap layers improved the sound absorption to some extents. Increase in the gap had positive effect on low frequency sound absorption having more peaks. But at the same time it was noticed that medium and high frequency absorptions were reduced by moving the peaks to lower frequencies. The reason of such behavior is increase in the panel’s impedance which moves the acoustical resonance to lower frequencies and enhances the absorption in this region. Hence, it was concluded that other acoustic material such as perforated plate may be added to the coir fiber-air gap structure to enhance to low frequency absorption without any need to excessively increase the thickness of air gap layer.

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Figure 1. Acoustic absorption coefficient of a type of industrial prepared coir fiber, thickness=50 mm, mass=34.13 g, $\rho_{\text{fiber}}$=821 kg/m$^3$, $\rho_{\text{bulk}}$=86.9 kg/m$^3$, $d_{\text{fiber}}$=252 µm, $\Lambda$=133 µm, $\Lambda'$=266 µm, porosity=89%, tortuosity=1.06, $\sigma$=1359 Nsm$^{-4}$. 

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Null
Figure 2. Normal incidence acoustic field impinging a porous layer.
Figure 3. Acoustic absorption coefficient of 20 mm coir fiber backed with 20 mm air gap. Fiber characteristics: mass=15.5 g, ρ_{fiber}=821 kg/m$^3$, ρ_{bulk}=98.7 kg/m$^3$, d_{fiber}=252 µm, Λ=135 µm, Λ'=269 µm, porosity=88%, tortuosity=1.07, σ=1680 Nsm$^{-4}$. 
Figure 4. Acoustic absorption coefficient of 35 mm coir fiber backed with 20 mm air gap. Fiber characteristics: mass=24.73 g, $\rho_{\text{fiber}}=821$ kg/m$^3$, $\rho_{\text{bulk}}=90$ kg/m$^3$, $d_{\text{fiber}}=252$ µm, $\Lambda=134$ µm, $\Lambda'=267$ µm, porosity=89%, tortuosity=1.06, $\sigma=1440$ Nsm$^{-4}$. 
Figure 5. Acoustic absorption coefficient of 50 mm coir fiber backed with 20 mm air gap. Fiber characteristics: mass=34.13 g, $\rho_{\text{fiber}}=821$ kg/m$^3$, $\rho_{\text{bulk}}=87$ kg/m$^3$, $d_{\text{fiber}}=252$ µm, $\Lambda=133$ µm, $\Lambda'=267$ µm, porosity=89%, tortuosity=1.06, $\sigma=1359$ Nsm$^{-4}$. 
Figure 6. Two possible arrangements for coir fiber-air gap assembly: a) leaving an air gap in between two coir fiber layers; b) a single layer coir fiber backed by an air gap.
Figure 7. Acoustic absorption coefficient of coir fiber in three conditions; Dashed line: 35 mm coir fiber backed with 20 mm air-gap and again 35 mm coir fiber, Solid line: 70 mm coir fiber backed with 20 mm air-gap, Thick line: single layer 70 mm coir fiber. Fiber characteristics: $\rho_{\text{bulk}}=89.96$ kg/m$^3$, porosity=89%, $\sigma=1440$ Nsm$^{-4}$. 

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Figure 8. Simulations of the absorption coefficient of 50 mm coir fiber sample for varying compression rates.
Figure 9. Effects of increasing the backing air gap of 50 mm thickness coir fiber layer.
Table 1. Impedance tube measurement of acoustic absorption coefficient of 20, 35 and 50 mm coir fiber samples backed with 20 mm air gap at different one-third octave band center frequencies.

<table>
<thead>
<tr>
<th>One-Third Octave Band Center Frequency (Hz)</th>
<th>20 mm thickness</th>
<th>35 mm thickness</th>
<th>50 mm thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.026</td>
<td>0.033</td>
<td>0.015</td>
</tr>
<tr>
<td>125</td>
<td>0.053</td>
<td>0.061</td>
<td>0.067</td>
</tr>
<tr>
<td>160</td>
<td>0.056</td>
<td>0.070</td>
<td>0.095</td>
</tr>
<tr>
<td>200</td>
<td>0.055</td>
<td>0.076</td>
<td>0.114</td>
</tr>
<tr>
<td>250</td>
<td>0.063</td>
<td>0.090</td>
<td>0.145</td>
</tr>
<tr>
<td>315</td>
<td>0.076</td>
<td>0.109</td>
<td>0.190</td>
</tr>
<tr>
<td>400</td>
<td>0.087</td>
<td>0.137</td>
<td>0.256</td>
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<td>500</td>
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<td>0.177</td>
<td>0.349</td>
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<td>630</td>
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<td>0.241</td>
<td>0.485</td>
</tr>
<tr>
<td>800</td>
<td>0.197</td>
<td>0.349</td>
<td>0.658</td>
</tr>
<tr>
<td>1000</td>
<td>0.282</td>
<td>0.493</td>
<td>0.772</td>
</tr>
<tr>
<td>1250</td>
<td>0.508</td>
<td>0.761</td>
<td>0.814</td>
</tr>
<tr>
<td>1600</td>
<td>0.738</td>
<td>0.833</td>
<td>0.724</td>
</tr>
<tr>
<td>2000</td>
<td>0.725</td>
<td>0.707</td>
<td>0.690</td>
</tr>
<tr>
<td>2500</td>
<td>0.624</td>
<td>0.636</td>
<td>0.827</td>
</tr>
<tr>
<td>3150</td>
<td>0.546</td>
<td>0.661</td>
<td>0.958</td>
</tr>
<tr>
<td>4000</td>
<td>0.412</td>
<td>0.895</td>
<td>0.840</td>
</tr>
<tr>
<td>5000</td>
<td>0.673</td>
<td>0.853</td>
<td>0.987</td>
</tr>
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</table>
Table 2. Properties of 50 mm coir fiber sample under different compression rate $n$.

<table>
<thead>
<tr>
<th></th>
<th>$n = 1$ (Uncompressed)</th>
<th>$n = 1.2$</th>
<th>$n = 1.4$</th>
<th>$n = 1.6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>50</td>
<td>41.67</td>
<td>35.71</td>
<td>31.25</td>
</tr>
<tr>
<td>flow resistivity, $\sigma$ (Nm$^{-4}$s)</td>
<td>1359</td>
<td>1631</td>
<td>1903</td>
<td>2175</td>
</tr>
<tr>
<td>Porosity, $\varphi_c$ (%)</td>
<td>89</td>
<td>87</td>
<td>85</td>
<td>83</td>
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<tr>
<td>Tortuosity, $\alpha_\infty$</td>
<td>1.05</td>
<td>1.07</td>
<td>1.08</td>
<td>1.09</td>
</tr>
<tr>
<td>Viscous characteristics length, $\Lambda$ (μm)</td>
<td>133</td>
<td>101</td>
<td>76</td>
<td>55</td>
</tr>
<tr>
<td>Thermal characteristics length, $\Lambda'$ (μm)</td>
<td>266</td>
<td>222</td>
<td>189</td>
<td>161</td>
</tr>
</tbody>
</table>
Figure 1. Acoustic absorption coefficient of a type of industrial prepared coir fiber, thickness= 50 mm, mass=34.13 g, $\rho_{\text{fiber}}=821$ kg/m$^3$, $\rho_{\text{bulk}}=86.9$ kg/m$^3$, $d_{\text{fiber}}=252$ µm, $\Lambda=133$ µm, $\Lambda'=266$ µm, porosity=89%, tortuosity=1.06, $\sigma=1359$ Nsm$^{-4}$.

Figure 2. Normal incidence acoustic field impinging a porous layer.

Figure 3. Acoustic absorption coefficient of 20 mm coir fiber backed with 20 mm air gap. Fiber characteristics: mass=15.5 g, $\rho_{\text{fiber}}=821$ kg/m$^3$, $\rho_{\text{bulk}}=98.7$ kg/m$^3$, $d_{\text{fiber}}=252$ µm, $\Lambda=135$ µm, $\Lambda'=269$ µm, porosity=88%, tortuosity=1.07, $\sigma=1680$ Nsm$^{-4}$.

Figure 4. Acoustic absorption coefficient of 35 mm coir fiber backed with 20 mm air gap. Fiber characteristics: mass=24.73 g, $\rho_{\text{fiber}}=821$ kg/m$^3$, $\rho_{\text{bulk}}=90$ kg/m$^3$, $d_{\text{fiber}}=252$ µm, $\Lambda=134$ µm, $\Lambda'=267$ µm, porosity=89%, tortuosity=1.06, $\sigma=1440$ Nsm$^{-4}$.

Figure 5. Acoustic absorption coefficient of 50 mm coir fiber backed with 20 mm air gap. Fiber characteristics: mass=34.13 g, $\rho_{\text{fiber}}=821$ kg/m$^3$, $\rho_{\text{bulk}}=87$ kg/m$^3$, $d_{\text{fiber}}=252$ µm, $\Lambda=133$ µm, $\Lambda'=267$ µm, porosity=89%, tortuosity=1.06, $\sigma=1359$ Nsm$^{-4}$.

Figure 6. Two possible arrangements for coir fiber-air gap assembly: a) leaving an air gap in between two coir fiber layers; b) a single layer coir fiber backed by an air gap.

Figure 7. Acoustic absorption coefficient of coir fiber in three conditions; Dashed line: 35 mm coir fiber backed with 20 mm air-gap and again 35 mm coir fiber, Solid line: 70 mm coir fiber backed with 20 mm air-gap, Thick line: single layer 70 mm coir fiber. Fiber characteristics: $\rho_{\text{bulk}}=89.96$ kg/m$^3$, porosity=89%, $\sigma=1439$ Nsm$^{-4}$.

Figure 8. Simulations of the absorption coefficient of 50 mm coir fiber sample for varying compression rates.

Figure 9. Effects of increasing the backing air gap of 50 mm thickness coir fiber layer.

Table 1. Impedance tube measurement of acoustic absorption coefficient of 20, 35 and 50 mm coir fiber samples backed with 20 mm air gap at different one-third octave band center frequencies.

Table 2. Properties of 50 mm coir fiber sample under different compression rate $n$. 