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ANALYSIS ON SOUND ABSORPTION OF NATURAL COIR FIBER USING DELANY-BAZLEY MODEL

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ABSTRACT

This paper explores the sound absorption capacity of natural coir fiber. Absorption coefficient of coir fiber is calculated using Delany-Bazley model. Experiments are conducted in impedance tube to validate the analytical outcomes for three samples having different thickness. Increasing the thickness of coir fiber enhances sound absorption and shifts noise absorption peak towards low frequency. Moreover, effect of air gap on sound absorption performance of coir fiber has also been investigated. Increasing air gap thickness usually shifts the peak of absorption coefficient towards lower frequency. Then, the noise absorption of coir fibers with and without air gap is compared and shows that earlier one has greater absorption at low frequency than the later one. However, resonances can not be predicted using this technique. Results also indicate that Delany-Bazley equations can justify the overall trend of absorption coefficient of coir fiber perfectly as demonstrated in this study.

Keywords: Noise absorption, Natural coir fiber, Delany-Bazley equation.

1. INTRODUCTION

At present, green technology is widely used to replace the agricultural waste with synthetic fiber for noise absorption purposes. Natural fibers such as coir fiber can be used as a potential acoustic porous material since they are easily obtained from the nature. Coir fiber is a natural organic resource which is the seed-hair fiber obtained from the outer shell (endocarp) or husk of coconut.

It is well known that the absorption characteristics of porous material vary with type of porous materials. Numerous models were proposed to study the sound propagation in porous materials. Delany and Bazley [1] studied the impedance and wave propagation properties of fibrous materials. They proposed a normalized model based on dimensionless groups and developed an empirical formula to estimate the characteristics impedance and propagation constant of fibrous absorbent material. Their method was very simple and considered as the fast approximation to the solution as this method used only flow resistivity parameter which is an intrinsic property of the material. Dunn and Davern [2] studied on acoustic impedance of multilayer absorbers using Delany-Bazley method. Qunli [3] made an empirical relation for acoustical impedance of foam materials using a large amount of experimental data with a wider range of flow resistivity. It was observed that the Delany-Bazley model can sometimes predict non-physical results for low frequencies and layered media. Hence, Miki [4] suggested an improved relationship based on the same model for wider range frequency with respect to porosity, tortuosity and the pore shape factor ratio.

Equivalent electrical circuit approach (EECA) [5, 6] is an usual method to analyze the multilayer panel, in which surface acoustic impedance of back air gap is assumed as the acoustic impedance of rigid wall even when the air space were actually backed with perforated plates. Jinkyo *et al.* [5] studied the assembly with two layers of perforated plates backed with air spaces by EECA. Lee and Chen [7] further studied the transmission analysis for multilayer absorbers consisting of several layer of porous material, air gap and perforated plate using a new technique named ATA (Acoustic-Transmission Approach) . The effects of the back air gap and porous material was considered in ATA method. Results showed that ATA method can give the better result than the conventional EECA method for multilayer absorber.

However, the microscopic model of sound propagation is more complicated. More sophisticated models like Biot Model [8], Zwikker and Koston Model [9], Allard Model [10], Johnson-Allard Model [10] will not be considered in this analysis because they feature a large number of parameters which are rarely available. They require uncommon procedures for their determination and can't be deduced from simple acoustic measurements. Delany-Bazley model is used in this work to predict the absorption coefficient of coir fiber as a preliminary study and as a simple method. However, this model is not suitable for very low and high frequency.

The sound absorption of coir fiber was investigated previously in Automotive Research Group Laboratories, Universiti Kebangsaan Malaysia [11, 12]. Those studies were based on simulation program WinFLAG^{TM} and compared with experimental data obtained in reverberation room using diffuse sound field of noise source. This present study is analytical and compared with experimental data obtained by impedance tube with normal incidence sound field of noise source. The purpose of this current study is to explore the absorption capacity of coir fiber and to establish an analytical technique which can be able to describe the acoustic characteristics of coir fiber. A panel composed of coir fiber layer and air gap backed by rigid wall was used to analyze the acoustic absorption performance of coir fiber. This paper is just the preliminary study based on Delany-Bazley model to make an analytical technique for coir fiber. For further improvement, sound propagation of coir fiber can be analyzed more accurately based on Biot model [8], Jhonson-Allard model [10].

2. ANALYTICAL MODEL OF THE PANEL

According to Delaney-Bazley empirical model, for a homogenous and isotropic fibrous material, complex wave propagation constant γ_f and characteristic impedance Z_f of porous material can be expressed by flow resistivity σ as [2, 7] ,

$$\gamma_f = 2\pi f/c_a\,[0.189\, b^{-0.595} + i\,(1+0.0978\, b^{-0.7})] \qquad (1)$$

$$Z_f = \rho_a c_a\,[1+0.057\, b^{-0.754} - i\,(0.087\, b^{-0.732})] \qquad (2)$$

$$b = \rho_a f/\sigma \qquad (3)$$

If the porous material is backed with a rigid wall, the surface acoustic impedance of the porous material can be expressed as [2, 7],

$$\Gamma_f = Z_f \coth(\gamma_f L_f) \qquad (4)$$

If the air gap is backed with a rigid wall, the surface acoustic impedance of the air space can be expressed as [7],

$$\Gamma_a = Z_a \coth(\gamma_a L_a) \qquad (5)$$

Where, Z_a (= $\rho_a c_a$) and γ_a (= $i(2\pi f/c_a)$) are wave propagation constant and characteristic impedance of air.

Considering the geometry of Fig. 1, that illustrates a cross section of the panel consisting porous layer and air gap backed by rigid wall, the resultant surface acoustic impedance of the panel can be expressed as [2, 7],

$$\Gamma_p = Z_f\,[\cosh(\gamma_f L_f) + (Z_f / \Gamma_a)\sinh(\gamma_f L_f)] \,/\, [\sinh(\gamma_f L_f) + (Z_f / \Gamma_a)\cosh(\gamma_f L_f)] \qquad (6)$$

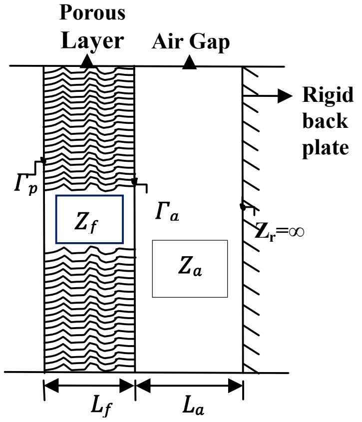


Fig 1. Schematic of the cross-section of absorber panel.

Where, γ_f, Z_f and Γ_a are calculated according to equation (1), (2) and (5) respectively.

The surface acoustic impedance of panel without air gap Γ_f and that of with air gap Γ_p, is calculated from equations (4) and (6) respectively. This result can be expressed as,

$$\Gamma_f \text{ or } \Gamma_p = R + iX \qquad (7)$$

For a normal incident plane sound wave, the absorption co-efficient of the absorption panel is expressed as,

$$\alpha = [4\,\rho_a c_a R] / [(\rho_a c_a + R)^2 + X^2] \qquad (8)$$

3. MATERIALS

In this study two types of coir fiber (CF) sample were used for experimental validation. These two samples are named as fresh CF and industrial CF. Fresh CF was collected from fresh coconut husk available in local wet market and then compressed it to make the sample using molds and punches with an average pressure of 20 kg/cm^2. Industrial CF was prepared industrially using binder as a mixer with the fiber to keep it in shape.

Raw fiber thickness of the material was measured by dial thickness gauge meter in the scale of one hundredth of millimeter. Fifteen randomly selected fibers were used to measure the average thickness and weight of the fiber. Average diameter of the fiber was taken as 273 μm and 248.22 μm for fresh and industrial coir fiber respectively as found from the experimental measurements. The shape of the fiber was considered as cylindrical shape. Bulk density of the material was measured from mass and volume of the sample. Flow resistivity of the material was estimated using the empirical equation (9) based on mass, thickness and fiber diameter of each sample [13],

$$\sigma = 490\,\rho_{bulk}^{1.61} / d_{fiber} \qquad (9)$$

4. EXPERIMENTS FOR ANLYTICAL VALIDATION

Experimental measurements were conducted in impedance tube according to ISO 10534-2 [14] standard to validate the analytical analysis. The components of the measurement system mainly include two impedance tubes with diameters 28 mm and 100 mm each contains ½" microphones type GRAS-40BP, plane wave source, two channel data acquisition system and 01dB software package. Small tube of diameter 28 mm was used to measure the absorption coefficient in high frequency range 1600 Hz - 6300 Hz and large tube of diameter 100 mm was used in low frequency range 31.5 Hz - 1600 Hz. One calibrator type GRAS-42AB was used for microphone sensitivity calibration at 114 dB and 1 KHz frequency.

Before starting the measurement, two microphones used in the impedance tube were calibrated relatively to each other using the standard switching technique by mounting a sample in the sample holder to make sure that the sound field inside the tube is well defined. The measurements were done with 3 Hz frequency resolution and sample records of finite duration about 10 s.

5. RESULTS AND OBSERVATIONS

Fig. 2 and 3 represent the analytical analysis of sound absorption of coir fiber (CF) for different layer thickness with and without air gap. Additionally, Fig. 4 represents the analysis of absorption with bulk density of the material. This analysis will give an overall knowledge of sound absorption capacity of coir fiber which can be designed further to form an optimal sound band absorber.

5.1 Coir Fiber Thickness

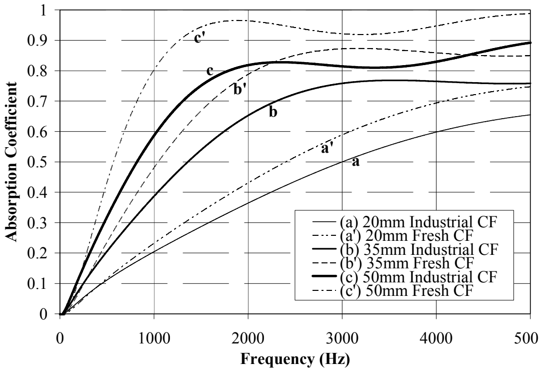


Fig 2. Numerical simulations of absorption coefficient of industrial and fresh coir fiber layer having thickness 20mm, 35mm and 50mm.

In this section, the effect of material layer thickness on sound absorption of coir fiber is investigated as shown in Fig. 2. It shows that increasing coir fiber layer thickness increases the absorption and moves absorption peak towards low frequency. In case of 20 mm layer (Industrial CF) thickness, maximum absorption occurs above 5000 Hz frequency at 6704 Hz with coefficient 0.68. When the layer thickness becomes 35 mm, the absorption peak moves towards lower frequency 3554 Hz with the increased coefficient of 0.76 from 0.68 and so on for 50mm. It indicates that the absorption increases as impinged wave has to go long way through the material and losses its energy. According to absorption phenomena inside a porous material, long dissipative process of viscosity and thermal conductions in the fluid inside the material due to increased thickness, improves the absorption.

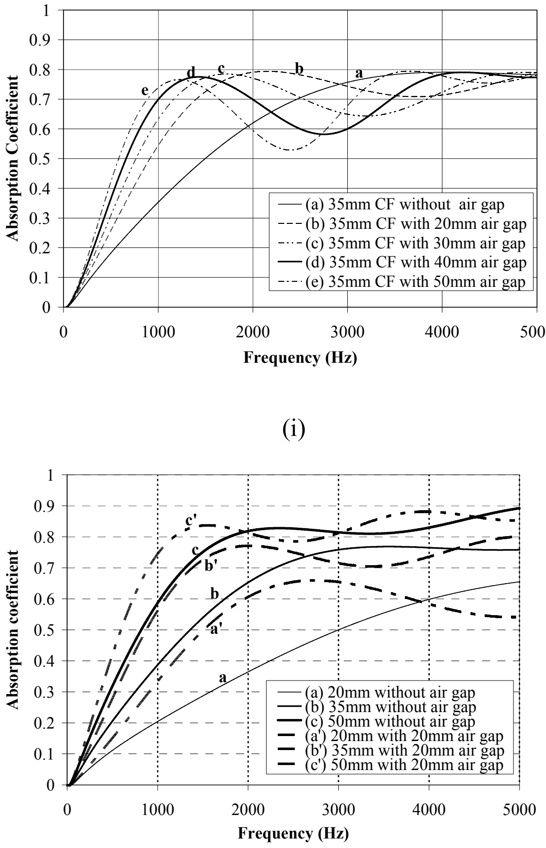
If it is closely observed in Fig. 2, it seems that fresh coir fiber has better absorption for the same thickness of the material. This is because of the increased flow resistivity of fresh coir fiber comparatively that of industrial fiber for the same thickness of material. The main factors influencing the flow resistivity of fibrous material are the fiber size and the bulk density [1]. During the preparation of fresh coir fiber it was found that coir fiber contains some matrix material with the fiber which increased the bulk density of the material, as a result flow resistivity also increased. However, fresh coir fiber without any treatment (or binder) can not be used regularly as an absorber for long time period because of the moisture and stiffness effect [15] of the fiber which may decrease the thickness of the porous material later on and change the absorption characteristics.

5.2 Air Gap Thickness

Fig. 3(i), represents the effect of addition of air gap with coir fiber layer on sound absorption. Addition of 20mm air gap with coir fiber layer increases absorption towards low frequency compare to coir fiber without air gap. As shown in Fig 3(i), 20 mm coir fiber layer with 20 mm air gap moves the absorption peak towards 2740 Hz frequency with almost same coefficient 0.66 from 6704 Hz frequency that of fiber layer without air gap. In case of 35 mm thickness, it moves to 2019 Hz frequency from 3554 Hz with coefficient 0.77 and for 50 mm thickness, it moves to 1556 Hz frequency from 2344 Hz with coefficient 0.84. These results indicate that absorption can be increased in low frequency region with the addition of air gap between the layer of coir fiber and rigid wall.

Fig. 3(ii), illustrates the effect of increasing air gap thickness on sound absorption for particular CF layer thickness of 35mm. It shows that increasing air gap shifts the absorption peak further towards low frequency. This is due the fact that air gap between porous layer and back plate creates resonance, which moves the absorption peaks towards low frequency and increasing air gap thickness moves further towards low frequency.

It can also be observed from Fig. 3(i), that the noise absorption at a particular region of the low frequency end can be achieved with coir fiber by either increasing the coir fiber layer thickness without air gap or increasing the air gap keeping the coir fiber layer thickness in a minimum value. As shown in Fig. 3(i), it can be seen that almost same trend of absorption line up to 2000 Hz frequency can be achieved using 20 mm coir fiber layer with 20 mm air gap instead of 35 mm coir fiber without air gap. Further, same trend of absorption line up to 1700 Hz frequency can be achieved using 35 mm coir fiber layer with 20 mm air gap instead of 50 mm coir fiber without air gap. It indicates that absorption can be enhanced almost the same amount at a particular region by the addition of air gap instead of increasing fiber layer thickness.



(i)

(ii)

Fig 3. Numerical simulations of absorption coefficient of industrial coir fiber (i) with 20 mm air gap and without air gap having CF thickness 20 mm, 35 mm and 50 mm. (ii) 35 mm CF with 20 mm,30 mm, 40 mm, 50 mm air gap and without air gap.

5.3 Effect of Bulk Density

Absorption coefficient of 35mm coir fiber layer with different bulk density is presented in Fig. 4. Four sample mass of 20, 25, 30 and 35 gm were considered for coir fiber sample of 100 mm diameter to change the bulk density of the material. Fig.4 shows that increasing bulk density of the porous material enhances the absorption property of coir fiber from 0.7 to 0.87. Enhancement of absorption occurs due to increased flow resistivity with increased bulk density.

It can also be observed from Fig. 4 that the profile of the graphs is same, though the additional bulk density increases the absorption. It means that increasing bulk density does not change the position of absorption peak. As long as there is no additional layer (porous or air) with the existing layer, absorption peak does not change its position.

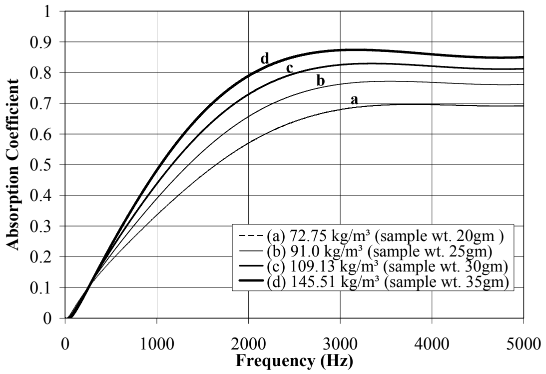
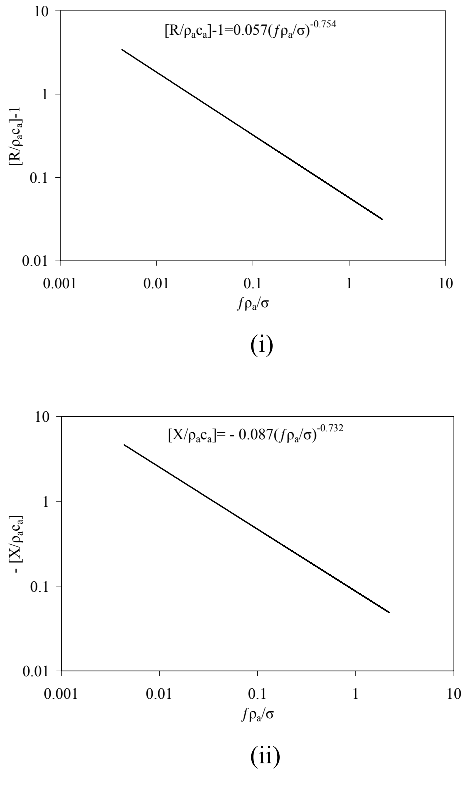


Fig 4. Numerical simulations of absorption coefficient of 35 mm industrial coir fiber with different bulk density.

These results denote that porous absorber prepared with larger bulk density will increase the absorption of the material. However, increased bulk density should be within a limit which will allow the sound wave to go through the material. Otherwise, there will be a probability of sound wave to be reflected by congested material surface rather than absorption.

6. LIMITATIONS OF DELANY-BAZLEY MODEL



(i)

(ii)

Fig 5. Normalization of real and imaginary component of characteristics impedance Z_f. (i) Real component and (ii) Imaginary component.

Delany-Bazley is considered to give good agreement between the theoretical and experimental results for the following limitations as explained in Ref. [1],

$$0.01<\rho_a f/\sigma<1.0 \qquad (10)$$

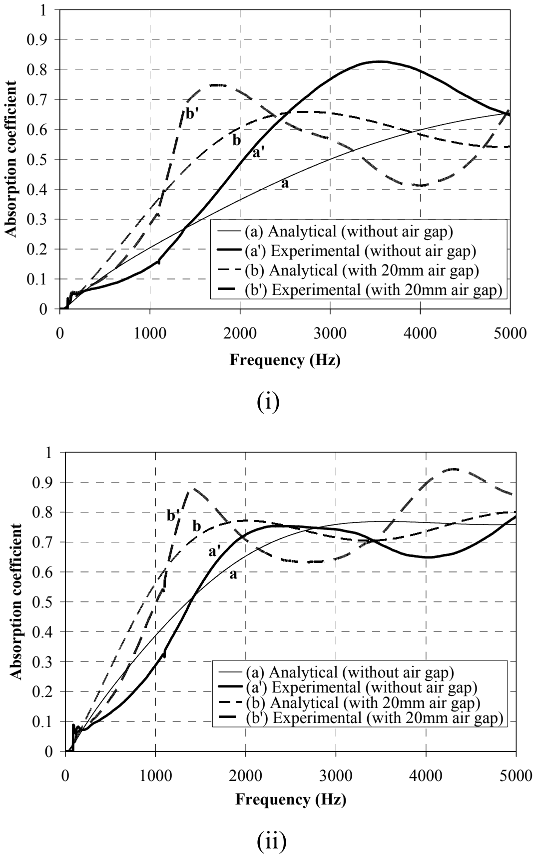
To verify the validity of this model for coir fiber, real and imaginary component of characteristics impedance (Z_f) is normalized into two dimensionless group with free field wave impedance $\rho_a c_a$ and plotted against normalized dimensionless frequency group $\rho_a f/\sigma$ as shown in Fig. 5. It can be seen that the frequency range ($\rho_a f/\sigma$) is within the given dimensionless limit 0.01 to 1.0 for the majority of the normalized real and imaginary components of Z_f. However, beyond this range this model can not be able to predict the material property as good as it can within the approximate frequency range of equation (5). Sometimes in the case of multilayer, real part of the surface impedance (when computed using this model) becomes negative at low frequencies as Miki [4] mentioned it as a non-physical result.

7. VERIFICATION OF THE ANALYTICAL MODEL

Verification of Delany-Bazley Model was done for three samples of industrial coir fiber with and without air gap, as shown in Fig. 6 (here shown for two samples 20 mm and 35 mm). Experimental results for 20 mm and 35 mm fresh coir fiber layer with and without air gap is also plotted in Fig. 7. The measured plots agree fairly well with analytical prediction. The profiles of the graphs are the same. However, the results also show that analytical model can not be able to predict the resonance peak. This resonance may be for frame resonance and Delany-Bazley model did not consider bulk modulus of elasticity which has been considered in Biot-Allard elastic model [10].

The graph in Fig. 6, also shows that analytical plot gives better agreement with experimental measurements at larger thickness of the sample increases from 20 mm to 50 mm. It may be due to one reason was addressed by Delany-Bazley [1] to show this type of behavior,, at lower value of $\rho_a f/\sigma$ many materials exhibit significant structural non-rigidity and under these circumstances simple normalization is not possible as shown in Fig. 5.

In case of these three samples, it is found that increasing coir fiber layer (sample) thickness, decreases flow resistivity from 3206 Nsm^{-4} to 2613 Nsm^{-4} and those samples maintain almost equal thickness to mass ratio (TMR) between 1.3~1.45. Although, flow resistivity should be increased with increased thickness, but in this case flow resistivity is decreased because of bulk density. Bulk density is a factor of both mass and thickness, which is also decreased with increased layer thickness due to constant TMR. As a result, for larger thickness with the same TMR, gives a higher value of $\rho_a f/\sigma$ ratio compare to smaller thickness of the same material, which produces a better agreement of analytical model with experimental results.



(i)

(ii)

Fig 6. Experimental data compared to numerical simulations of the absorption coefficient of industrial CF with and without air gap having CF thickness (i) 20 mm (ii) 35 mm.

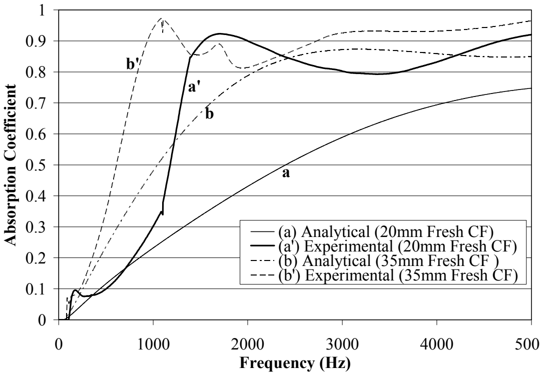


Fig 7. Experimental data compared to numerical simulations of the absorption coefficient of fresh CF having thickness 20 mm and 35 mm without air gap.

8. CONCLUSION

In this study, it is shown that, coir fiber has the potential to be replaced with the common synthetic fibrous material such as glass, mineral wool, felts or polyester fibers.

Analyses from this study give an overall idea about the factors that are able to enhance the absorption of coir fiber. Increasing coir fiber layer thickness will increase absorption and move the absorption peak towards low frequency. Increasing air gap thickness will increase the absorption at low frequencies, though it will increase absorption only at resonance frequencies. Absorption characteristics of coir fiber can also be increased by increasing bulk density of the material. Fresh coir fiber seems to give better absorption characteristics because of increased bulk density due to extra matrix material and moisture content with fiber. These results demonstrate that more strategically designed layers and configurations of coir fiber could increase the noise reduction.

An analytical model for theoretical prediction has been obtained. It can justify the overall trend of the absorption spectrum. For accurate prediction of overall absorption including the frame resonance, more sophisticated model like Johnson-Allard [10] or Biot-Allard model [10] can be used. Application of perforated plate and making multilayer structure are necessary to improve the absorption in low frequency. They may help to reduce the thickness of the panel which is a very important factor for limited space structure.

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10. NOMENCLATURE

Symbol	Meaning	Unit
f	Frequency	(Hz)
c_a	Sound speed	(ms^{-1})
ρ_a	Air density	(Kgm^{-3})
σ	Flow resistivity	(Nsm^{-4})
L_f	Thickness of Coir fiber layer	(m)
L_a	Thickness of air gap	(m)
α	Absorption coefficient	(%)
d_{fiber}	Diameter of fiber	μm
ρ_{bulk}	Bulk density of material	(Kgm^{-3})
γ_f	Propagation constant of CF	
Z_f	Characteristic impedance of CF	
Γ_f	Surface acoustic impedance of CF backed by rigid wall	
γ_a	Propagation constant of air gap	
Z_a	Characteristic impedance of air gap	
Γ_a	Surface acoustic impedance of air gap backed by rigid wall	
Γ_p	Resultant surface acoustic impedance of panel composed of CF, air gap and rigid wall.	
R	Real part of surface impedance Γ_f or Γ_p.	
X	Imaginary part of surface impedance Γ_f or Γ_p .	

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