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Jute and Luffa Fiber-Reinforced Biocomposites: Effects of Sample Thickness and Fiber/Resin Ratio on Sound Absorption and Transmission Loss Performance

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ABSTRACT
The acoustic properties of natural fiber-reinforced composites should be identified before using these materials in various engineering applications including sound and vibration isolation. This study investigates the effects of sample thickness and fiber/resin ratio on the acoustic performance of jute and luffa fiber-reinforced biocomposites. For this purpose, jute and luffa composite samples with different thicknesses and fiber/epoxy ratios are manufactured and their sound absorption coefficients (SACs) and transmission losses (TLs) are determined using impedance tube method. Thickness-dependent tendencies of the SACs and TLs of jute and luffa composites for low-, medium-, and high-frequency ranges are identified. The effect of fiber/epoxy ratio on the acoustic properties of jute and luffa composites as a function of frequency are determined. Furthermore, the SACs and TLs of some natural fiber-based samples with different thicknesses are predicted using mathematical models and the theoretical and experimental results are compared and evaluated.

摘要
在将天然纤维增强复合材料用于各种工程应用（包括隔声和隔振）之前，应确定其声学特性. 研究了样品厚度和纤维树脂比对黄麻和丝瓜纤维增强生物复合材料声学性能的影响. 为此，制备了不同厚度和纤维/环氧树脂比的黄麻和丝瓜复合材料样品，并用阻抗管法测定了它们的吸声系数（SACs）和传输损耗（TLs）. 确定了黄麻和丝瓜复合材料在低频、中频和高频范围的SACs和TLs随厚度的变化趋势. 研究了纤维/环氧树脂比对黄麻和丝瓜复合材料声学性能的影响. 利用数学模型预测了不同厚度天然纤维样品的SACs和TLs, 并对理论和实验结果进行了比较和评价.

KEYWORDS
Jute; luffa; biocomposites; fiber/resin ratio; sound absorption; transmission loss

关键词
黄麻丝瓜; 生物复合材料; 纤维/树脂比; 吸声; 传输损耗

Introduction

Natural fiber-reinforced composite structures are used in many industrial areas including aerospace, automotive, marine, biomedical, and architecture (Zhang et al. 2020). Synthetic materials such as carbon fibers are used widely in these areas due to their superior mechanical properties (Fu et al. 2000; Li et al. 2019). On the other hand, natural fiber-reinforced biocomposites are less harmful to human health, more nature-friendly, sustainable and low-cost compared to synthetic materials (Asdrubali, Schiavoni, and Horoshenkov 2012; Ho et al. 2012; Joshi et al. 2004; Li et al. 2020).

Natural fiber-based composites can be utilized for different purposes, including acoustic applications (Asdrubali, Schiavoni, and Horoshenkov 2012; Berardi and Iannace 2015; Liao, Zhang, and Tang 2020). For example, it is noted that the conventional natural plant materials including flax and ramie (Yang and Li 2012), sisal (Asdrubali, Schiavoni, and Horoshenkov 2012), kapok (Xiang et al. 2013),

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coconut and kenaf (Berardi and Iannace 2015), and hemp (Liao, Zhang, and Tang 2020) can show good sound absorbing performance. It is seen that the sound absorption properties of these materials can be similar or better than those of conventional materials such as glass wool. In addition to these conventional natural fibers, the sound absorbing properties of some other plant fibers such as broom fiber (Berardi, Iannace, and Di Gabriele 2017) and esparto grass (Arenas et al. 2020) have also been investigated recently, and it has been shown that they can have promising sound absorbing properties. Although there have been many studies on the sound absorption of natural cellulose materials, limited number of studies have investigated the sound insulation property of these materials. It is seen that the sound insulation property of these porous materials without any resin such as cotton and ramie generally is not good, compared to structural materials such as metals (Chen and Jiang 2009).

Among many natural fibers, the natural material jute is the most produced one worldwide (Perumal et al. 2018). Another natural material, luffa, which is grown in many regions in the world, has attracted considerable attention from engineers and researchers in recent years (Alhijazi et al. 2020; Koruk and Genc 2019). It is noted that jute has superior mechanical properties, high sound absorption coefficients (SACs), and transmission losses (TLs) (Bansod, Mittal, and Mohanty 2016; Ramesh, Palanikumar, and Reddy 2013), while luffa has high damping and SACs (Koruk and Genc 2015). Therefore, in order to utilize these two materials in practical engineering applications effectively, the acoustic performance of the composites of these two fibers with different thicknesses and fiber/epoxy ratios needs to be thoroughly investigated.

Acoustic properties of the jute and luffa fiber and their composite forms have been determined experimentally in some works (Fatima and Mohanty 2011; Genc and Koruk 2017; Raj, Fatima, and Tandon 2020; Saygili et al. 2020; Tang and Yan 2017; Tanobe et al. 2005; Thilagavathi et al. 2018; Zakriya and Ramakrishnan 2019). For example, the acoustic properties of the jute and luffa fibers-reinforced composites for a single thickness and a single fiber/epoxy ratio have been experimentally determined before (Saygili et al. 2020). There have been some studies to investigate the effects of density, sample thickness, and volume fraction on the acoustic properties of various natural plant-based materials. For example, the effects of density and thickness on the acoustic properties of some green fiber samples (specimens without any resin) such as kapok and kenaf have been investigated before (Lim et al. 2018; Mat Tahir et al. 2018; Or, Putra, and Selamet 2017; Sengupta et al. 2020). The influence of the starch/hemp ratio on the SACs is investigated (Le et al. 2015). The effects of fiber volume fraction and panel thickness on the acoustic and mechanical properties of coconut fibers have been determined (Suardana, Sugita, and Wardana 2020). To the best knowledge of the authors, the effects of sample thickness and fiber/resin ratio on the SACs and TLs of luffa fiber-reinforced composite structures have not been investigated in the literature before. In addition, there is a need to determine the thickness-dependent tendencies of the SACs and TLs of the jute and luffa epoxy composites for different frequency ranges. The work presented here aims to fill this gap in the literature. Furthermore, the difficulties related to manufacturing and testing biocomposites are presented and discussed in this study.

In addition to the experimental studies in the literature, there are also some mathematical models to predict the SACs of porous samples (Allard and Champoux, 1992; Fouladi, Ayub, and Mohd Nor 2011). For example, Liu et al. (2015) used the Delany-Bazley (DB) model to understand the sound absorbing properties of kapok fiber samples. Berardi and Iannace (2017) exploited a least-square fit procedure based on the Nelder–Mead method to calculate the coefficients that best describe the acoustic impedance and propagation constant for different natural fiber samples including coconut, hemp, and kenaf. Da Silva et al. (2019) used the DB and Johnson–Champoux–Allard (JCA) models to predict the SACs of various natural fiber samples including sisal. There are also some mathematical models to predict the TLs of test samples (Prascevic, Cvetkovic, and Mihajlov 2012; Tadeu and Mateus 2001; Wang et al. 2011). In this study, the DB and JCA models and the mass law for sound insulation are used to predict the SACs and TLs of some natural fiber-based samples, respectively.

The outline of the paper is as follows. (i) Jute and luffa fiber-reinforced samples with different thicknesses and fiber/epoxy ratios are prepared and their SACs and TLs are measured using impedance tube method. (ii) The effect of sample thickness on the acoustic performances of the jute and luffa composites as a function of frequency is presented. (iii) The thickness-dependent tendencies of the SACs and TLs of the jute and luffa composites for low, medium, and high-frequency ranges are revealed. (iv) The effect of fiber/resin ratio on the acoustic performances of the jute and luffa composites as a function of frequency is determined. (v) The SACs and TLs of some natural fiber-based samples are predicted using mathematical models and the theoretical and experimental results are compared and evaluated. (vi) The difficulties related to manufacturing and testing epoxy biocomposites are presented and discussed. It should be noted that the measured acoustic properties, the trend curves as a function of thickness and fiber/epoxy ratio for different frequency ranges, and the theoretical models exploited in this study can be used to design jute and luffa fiber-reinforced composites in many applications.

Materials and methods

Jute and luffa fibers are used as reinforcement and epoxy is used as a resin for production of the composite plates. The origins of the jute and luffa fibers used in this work are Bangladesh and Turkey, respectively. After the dry fibers are arranged, they are put in the mold and epoxy resin is added. The mold is pressed using a hydraulic press under $p = 5$ bar at $T = 120$°C temperature for $t = 2$ h. After the curing process, the mold is left at room temperature to cool. The manufacturing process for biocomposites is illustrated in Figure 1a. By cutting the manufactured composite plates, the specimens for acoustic tests are obtained. The so-called acoustic samples have a nominal diameter of 29 mm which is equal to the inner diameter of the impedance tube. The manufactured sample jute and luffa fiber-reinforced epoxy composite test specimens are shown in Figure 1b and c, respectively. In order to investigate the effects of sample thickness and fiber/resin ratio on the acoustic properties, samples with different fiber/epoxy mass ratios (0.5, 0.6, and 1.0 for jute composites and 0.45, 0.7, and 1.0 for luffa composites) and thicknesses (5, 10, 12.5, 15, and 20 mm) are manufactured. The SACs and TLs of the samples are determined by using impedance tube method (ASTM E1050–12 2012; ASTM E2611-17 2017; Jung et al. 2008; Koruk 2014). Readers can refer to the references (ASTM E1050–12 2012; ASTM

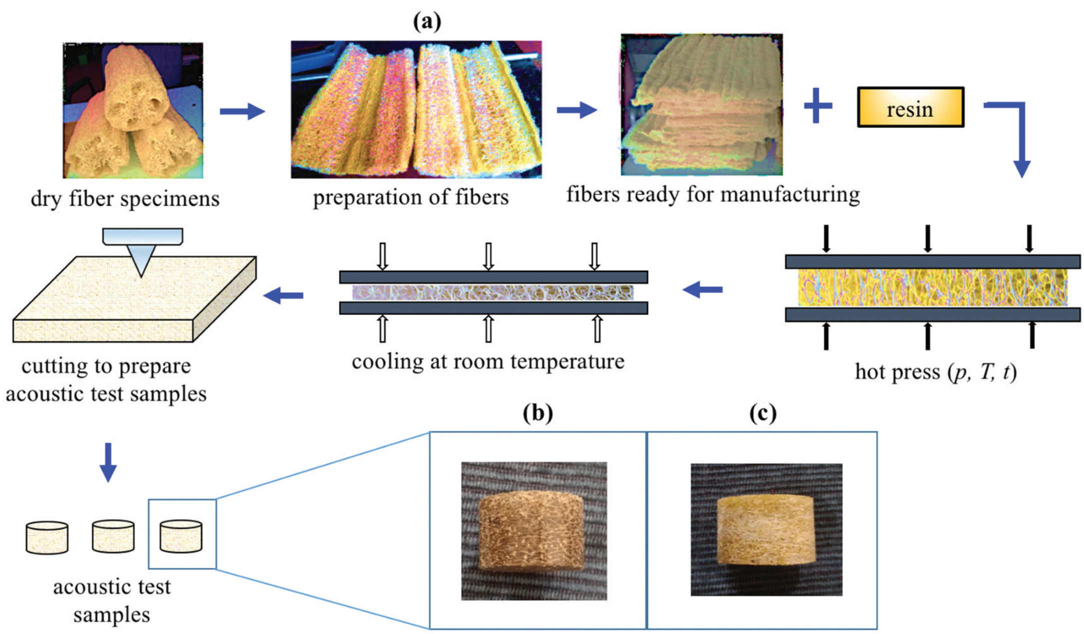

Figure 1. Manufacturing process for biocomposites (a) and manufactured sample jute (b) and luffa (c) composite test specimens.

E2611-17 2017; Jung et al. 2008; Koruk 2014) for information on impedance tube tests and the experimental calculation of acoustic properties. It should be noted that the difficulties related to manufacturing and testing natural fiber-reinforced biocomposites and variations in their acoustic properties are discussed in this study.

Effect of thickness

General trends as a function of frequency

The measured SACs and TLs of the jute and luffa composite samples with different thicknesses are presented in Figures 2 and 3. The SACs and TLs of these jute and luffa epoxy composite samples in Octave bands are listed in Table 1. It is seen that the SACs are quite low and there are no considerable variations in the SACs of these jute and luffa composites as sample thickness changes. On the other hand, the TLs of both the jute and luffa composites significantly increase with thickness. It is seen that, in general, excluding the lower frequency range, the TLs of the jute and luffa composites increase almost linearly with frequency.

Analysis of the acoustic performances at low-, medium-, and high-frequency ranges

The average SACs and TLs of the jute and luffa composite samples with different thicknesses for low (100–500 Hz), medium (500–2000 Hz), and high (2000–6300 Hz for α and 2000–5000 Hz for TL) frequency ranges are plotted in Figures 4 and 5. It is seen that both the SACs and TLs of these samples with different thicknesses increase from the low-frequency range to the high-frequency range.

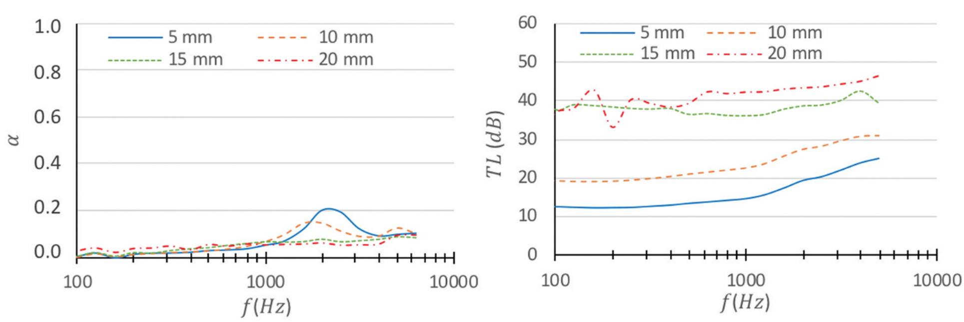

Figure 2. The SACs (left) and TLs (right) of the jute composite samples with different thicknesses (density: 997.6 kg/m^3, fiber/epoxy ratio: 0.6).

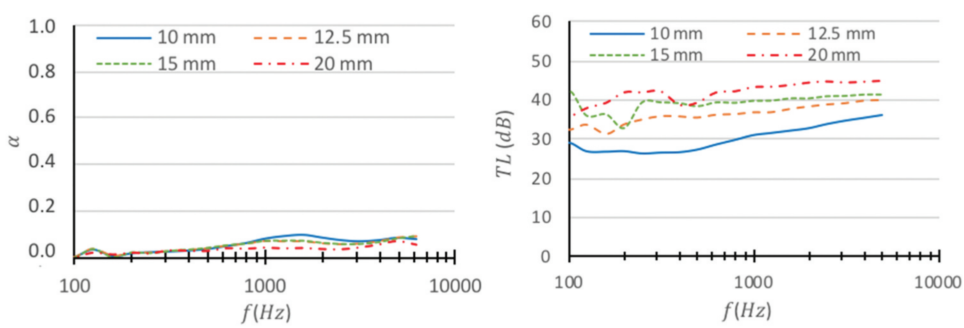

Figure 3. The SACs (left) and TLs (right) of the luffa composite samples with different thicknesses (density: 829.9 kg/m^3, fiber/epoxy ratio: 0.45).

Table 1. The SACs and TLs of the jute (density: 997.6 kg/m^3, fiber/epoxy ratio: 0.6) and luffa (density: 829.9 kg/m^3, fiber/epoxy ratio: 0.45) composite samples with different thicknesses.

Frequency	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Thickness (mm)			SAC, α for jute composites			
5	0.021	0.020	0.031	0.054	0.203	0.094
10	0.015	0.016	0.028	0.068	0.148	0.091
15	0.021	0.018	0.042	0.067	0.078	0.077
20	0.038	0.038	0.053	0.051	0.060	0.055
Thickness (mm)			TL for jute composites (dB)			
5	12.3	12.3	13.3	14.6	19.3	23.9
10	19.2	19.5	21.1	22.7	27.6	31.0
15	38.9	37.9	36.4	36.0	38.5	42.4
20	38.0	40.2	39.3	42.3	43.4	45.1
Thickness (mm)			SAC, α for luffa composites			
10	0.033	0.021	0.036	0.083	0.089	0.077
12.5	0.034	0.019	0.036	0.068	0.058	0.066
15	0.035	0.018	0.039	0.068	0.060	0.062
20	0.021	0.018	0.028	0.043	0.037	0.056
Thickness (mm)			TL for luffa composites (dB)			
10	26.7	26.1	27.1	30.8	32.6	35.3
12.5	33.9	35.2	35.7	37.1	38.5	40.1
15	35.9	39.2	38.3	39.6	40.3	41.2
20	37.8	41.9	39.3	43.3	44.4	44.6

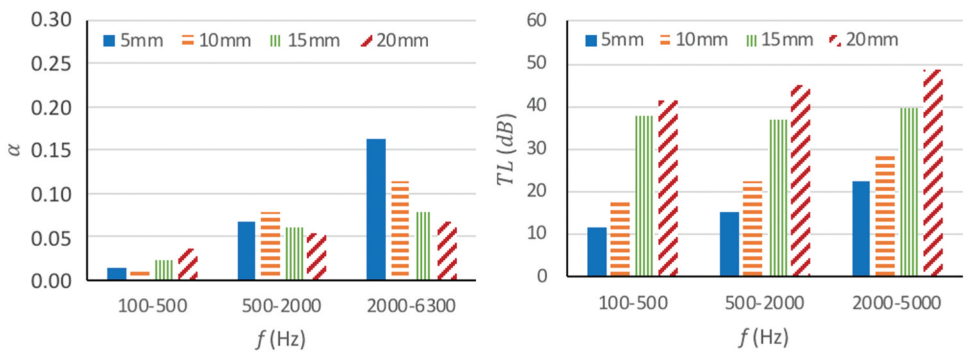

Figure 4. The SACs (left) and TLs (right) of the jute composite samples with different thicknesses for different frequency ranges (density = 997.6, fiber/epoxy ratio = 0.60).

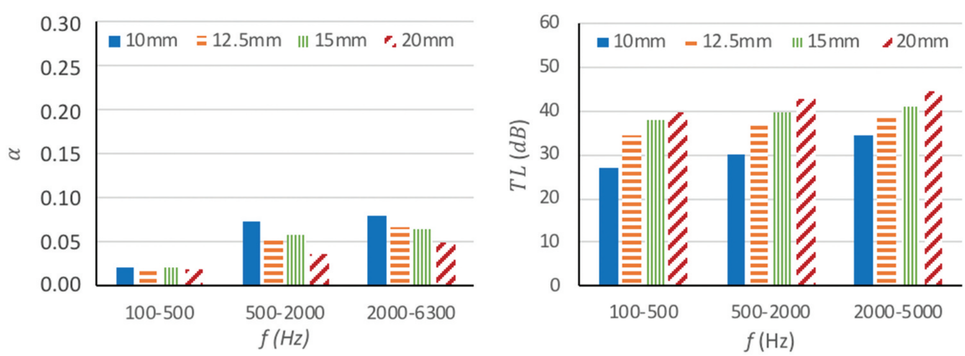

Figure 5. The SACs (left) and TLs (right) of the luffa composite samples with different thicknesses for different frequency ranges (density = 829.9, luffa fiber/epoxy ratio = 0.45).

In order to clarify the thickness-dependent tendencies of the SACs and TLs of the jute and luffa composites for different frequency ranges, the averaged results of the jute and luffa composites for different thicknesses at low-, medium-, and high-frequency ranges and the first-order curves (lines) fitted to the measured data together with the correlation coefficient *R* are shown in Figures 6 and 7. It is seen that the SACs of the jute sample increase slightly with thickness, and the SACs of the luffa sample remain constant as thickness increases at low-frequency range. At medium- and high-frequency ranges, the SACs decrease slightly for both the jute and luffa composite samples as thickness increases. On the other hand, the TLs tend to increase linearly with thickness for all frequency ranges for both the jute and luffa composite samples. The results show that, although there are some small variations in the SACs as sample thickness changes, the amount of epoxy in these samples is so high so that quite reflective materials are obtained and thus the SACs of these structures are low. The shifts of the peaks in the SAC curves between 1000 and 3000 Hz (Figures 2 and 3) and the changes in their amplitudes and the accuracy of the experimental methods discussed in detail later are the reasons for the slight decreases in the SACs at medium- and high-frequency ranges.

Effect of fiber/resin ratio

The acoustic properties of the jute composite samples with different fiber/epoxy ratios (0.5, 0.6 and 1.0) are shown in Figure 8. The thickness of the samples is about 10 mm and the densities of the samples with the fiber/epoxy ratio of 1.0, 0.6, and 0.5 are around 420, 998, and 1020 kg/m^3, respectively. The SACs and TLs of these jute samples in Octave bands are listed in Table 2. It is seen in Figure 8 that the jute fiber-reinforced epoxy composite samples have much lower SACs than the jute fiber samples without epoxy. On the other hand, the jute fiber samples without epoxy have the lowest TLs due to their porous structure. The averaged acoustic properties of the jute samples for different fiber/epoxy ratios at low-, medium-, and high-frequency ranges are shown in Figure 9. It is seen that the SACs increase and the TL decrease as fiber/epoxy ratio increases for all frequency ranges.

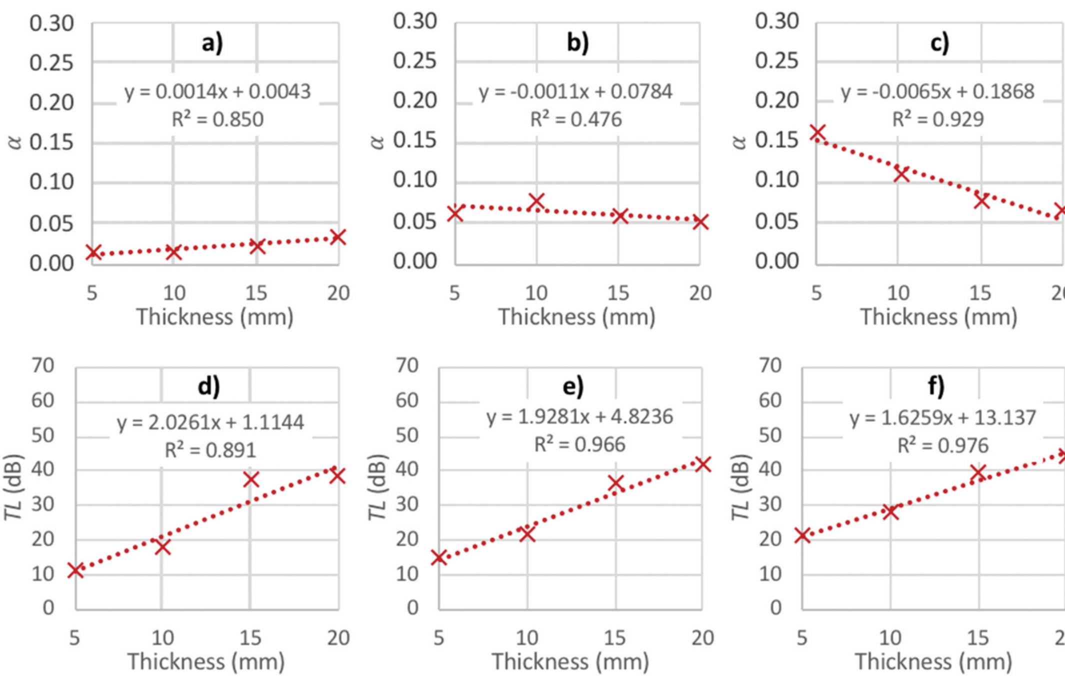

Figure 6. The average SACs and TLs of the jute composite samples with different thicknesses for low (a and d), medium (b and e) and high (c and f) frequency ranges (density = 997.6, fiber/epoxy ratio = 0.6).

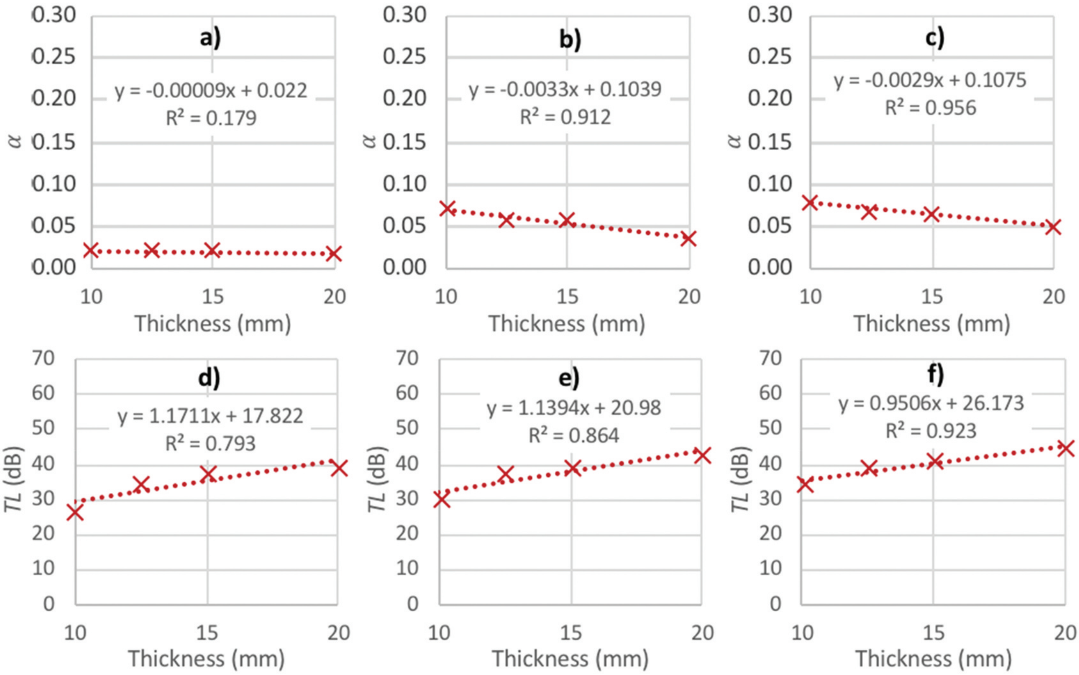

Figure 7. The average SACs and TLs of the luffa composite samples with different thicknesses for low (a and d), medium (b and e) and high (c and f) frequency ranges (density = 829.9, luffa fiber/epoxy ratio = 0.45).

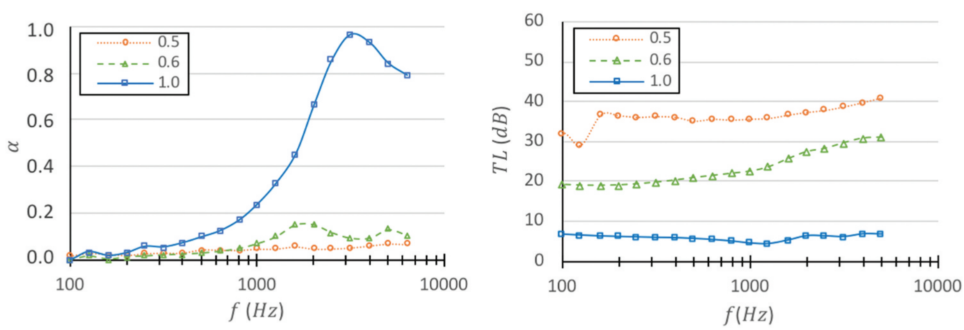

Figure 8. The SACs (left) and TLs (right) of the jute composite samples with different fiber/epoxy ratios.

The acoustic properties of the luffa composite samples with different fiber/epoxy ratios (0.45, 0.7 and 1.0) are shown in Figure 10. The thickness of the samples is about 10 mm again and the densities of the samples with the fiber/epoxy ratio of 1.0, 0.7, and 0.45 are around 74, 830, and 670 kg/m^3, respectively. The SACs and TLs of these luffa samples in Octave bands are included in Table 2. The averaged acoustic results of the luffa samples for different fiber/epoxy ratios at low, medium and high-frequency ranges are shown in Figure 11. It is seen that the SACs increase with increasing fiber/epoxy ratio for low and high-frequency ranges and the TLs increase with decreasing fiber/epoxy ratio at almost all frequency ranges. There are slight decreases in the SACs as fiber/epoxy ratio increases at medium-frequency range. The reasons (the shifts of the peaks, etc.) for the decreases in the SACs are explained before. As expected, the TLs of the fiber samples without epoxy are low due to their porous structure.

Table 2. The SACs and TLs of the 10 mm jute and luffa samples with different fiber/epoxy ratios.

Frequency	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Fiber/epoxy ratio			SAC, *α* for jute samples			
0.5	0.027	0.026	0.043	0.047	0.046	0.061
0.6	0.015	0.016	0.028	0.068	0.148	0.091
1.0	0.033	0.055	0.096	0.237	0.660	0.928
Fiber/epoxy ratio			TL for jute samples (dB)			
0.5	29.2	36.2	35.3	35.8	37.5	39.9
0.6	19.2	19.5	21.1	22.7	27.6	31.0
1.0	6.6	6.2	5.8	4.7	6.5	7.0
Fiber/epoxy ratio			SAC, *α* for luffa samples			
0.45	0.033	0.021	0.036	0.083	0.089	0.077
0.70	0.030	0.030	0.063	0.133	0.135	0.144
1.0	0.027	0.048	0.053	0.072	0.101	0.232
Fiber/epoxy ratio			TL for luffa samples (dB)			
0.45	26.7	26.1	27.1	30.8	32.6	35.3
0.70	20.1	20.5	22.0	24.2	27.8	32.2
1.0	0.23	0.25	0.31	0.25	0.35	0.54

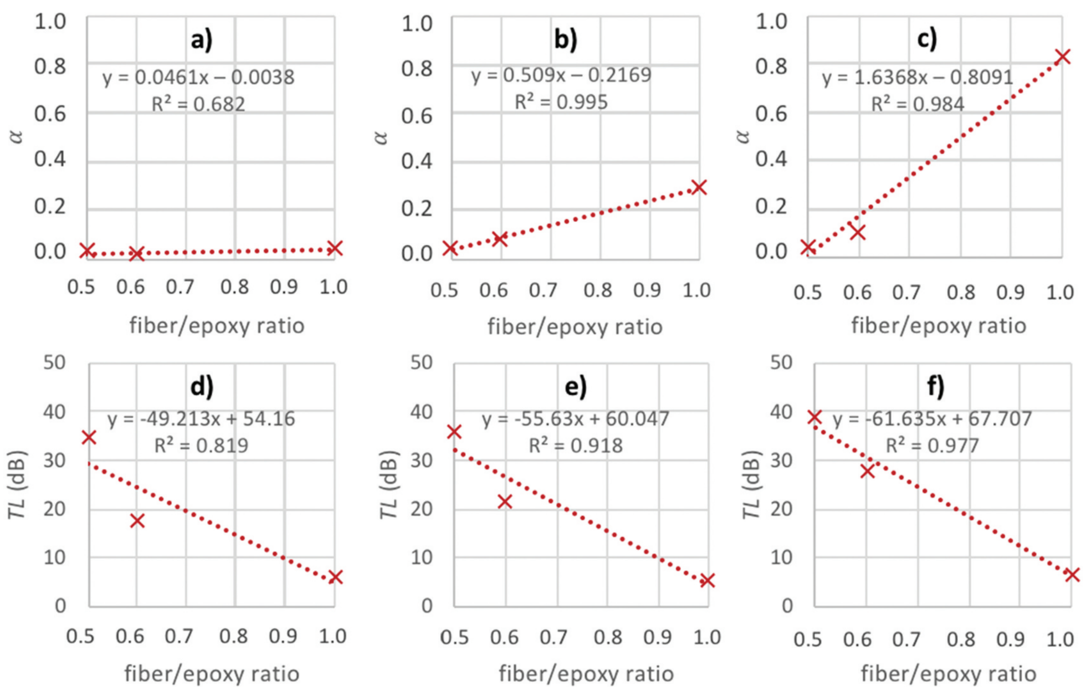

Figure 9. The average SACs and TLs of the jute composite samples with different fiber/epoxy ratios for low (a and d), medium (b and e) and high (c and f) frequency ranges.

Theoretical predictions

The first-order curves in Figures 6, 7, 9, and 11 can be used to estimate the acoustic properties of the jute and luffa composites at different thicknesses and fiber/epoxy ratios. Here, in addition to these simple empirical models, mathematical models are used to predict the acoustic properties of some natural fiber-based samples and the experimental and theoretical results are compared and evaluated. The Delany–Bazley (DB) model is an uncomplicated method to predict the acoustic parameters of a porous material (Fouladi, Ayub, and Mohd Nor 2011). Delany and Bazley measured the complex wave number k and the characteristic impedance Z_c for a large range of frequencies in many fibrous materials with porosity close to one (Delany and Bazley 1970; Miki 1990). Based on their

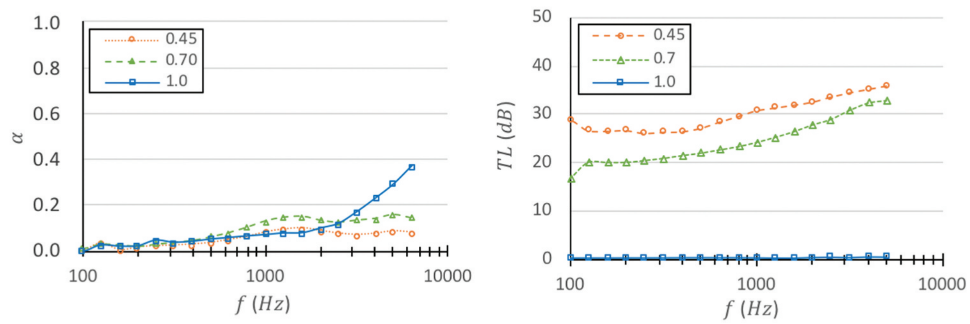

Figure 10. The SACs (left) and TLs (right) of the luffa composite samples different fiber/epoxy ratios.

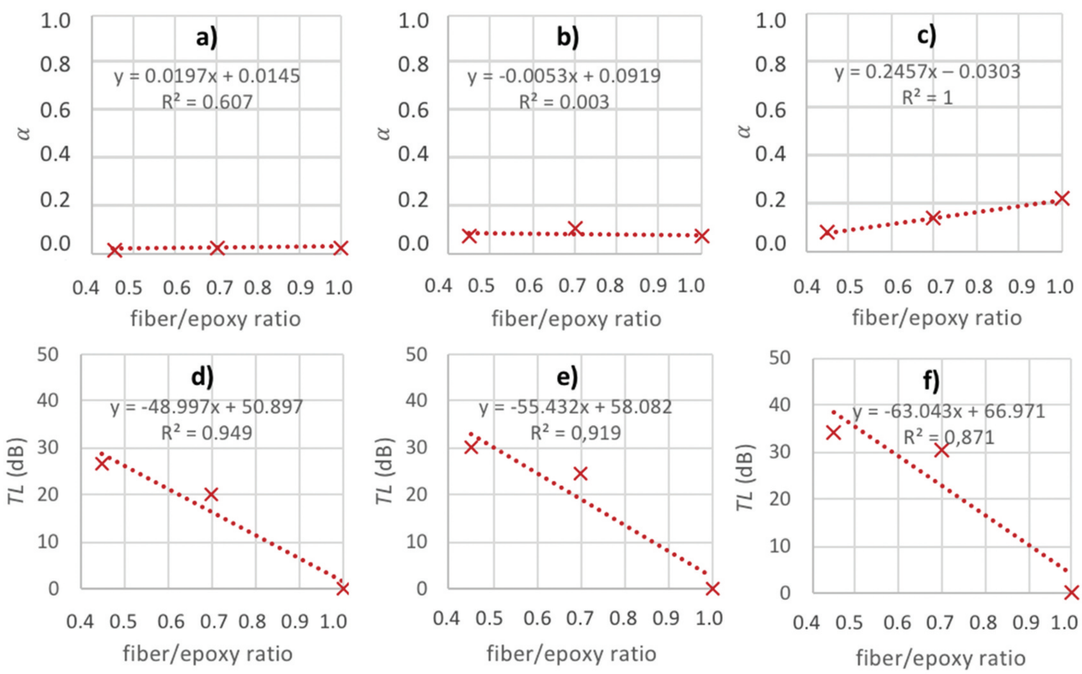

Figure 11. The average SACs and TLs of the luffa composite samples with different fiber/epoxy ratios for low (a and d), medium (b and e) and high (c and f) frequency ranges.

measurements, it was seen that the angular frequency ω, and the flow resistivity σ of the porous media mainly affected k and Z_c. The following two equations were used to obtain a fit of the measured values of k and Z_c (Delany and Bazley 1970; Fouladi, Ayub, and Mohd Nor 2011; Miki 1990):

$$Z_c(\omega) = Z_0\left\{\left[1 + c_1\left(\frac{f}{\sigma}\right)^{c_2}\right] - jc_3\left(\frac{f}{\sigma}\right)^{c_4}\right\} \tag{1}$$

$$k(\omega) = k_0\left\{\left[1 + c_5\left(\frac{f}{\sigma}\right)^{c_6}\right] - jc_7\left(\frac{f}{\sigma}\right)^{c_8}\right\} \tag{2}$$

Here, f and c_0 show the frequency and speed of sound, σ is the flow resistivity, $c_1 - c_8$ are the so-called Delany–Bazley regression constants and ρ_0, $k_0 = \frac{2\pi f}{c_0}$ and $Z_0 = \rho_0 c_0$ are the density, wave number, and impedance of air, respectively.

The geometric properties of fibrous samples was not considered in the DB model (Delany and Bazley 1970) and its improved versions (Dunn and Davern 1986; Miki 1990). Johnson, Koplik, and Dashen (1987) conducted a noteworthy improvement in the explanation of the viscous forces. From the geometry of the samples, Allard and Champoux (1992) derived new equations that give similar results in the range of validity of the equations of the DB model and are based on a physical representation of the acoustical event associated with the different physical properties of porous test samples. This model is called JCA model. The equations for this improved model are not presented here for brevity and the interested readers may refer to the references (Johnson, Koplik, and Dashen 1987; Kino 2015; Kino and Ueno 2008; Koruk 2021) for the mathematical expressions of the model.

The temperature and air pressure during the acoustic experiments were 25°C and 101 kPa, respectively, and the universal gas constant is taken as 287 JK^{-1} kg^{-1}. It is worth stating here that the average diameter of the jute fibers is around 100 μm (Bansod, Mittal, and Mohanty 2016; Bevitori et al. 2010). Hence, using these numerical values, the expressions above, and in the references (Allard and Champoux, 1992; Fouladi, Ayub, and Mohd Nor 2011; Johnson, Koplik, and Dashen 1987; Kino 2015; Kino and Ueno 2008), the SACs for the samples with 20 and 30 mm thicknesses are predicted using the DB and JCA models, and they are compared with the experimental results in Figure 12. It is seen that, although there are some differences between the experimental and theoretical results, in general, they are close to each other. Hence, these models can be used for design purposes before manufacturing the natural fibers-based structures.

For the prediction of TLs, there is a need for determining the so-called critical frequency of the samples which is defined as (Norton and Karczub 2003)

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{\rho_s}{B}} \tag{3}$$

where c is the speed of sound in air and ρ_s is the surface density of the sample. The other term, the bending stiffness modulus B, is defined as

$$B = \frac{Et^3}{12(1-\nu^2)} \tag{4}$$

where E is the elasticity modulus, t is the thickness of the sample and ν is the Poisson's ratio. The transmission loss between the resonance region and the critical frequency can be calculated as (Norton and Karczub 2003)

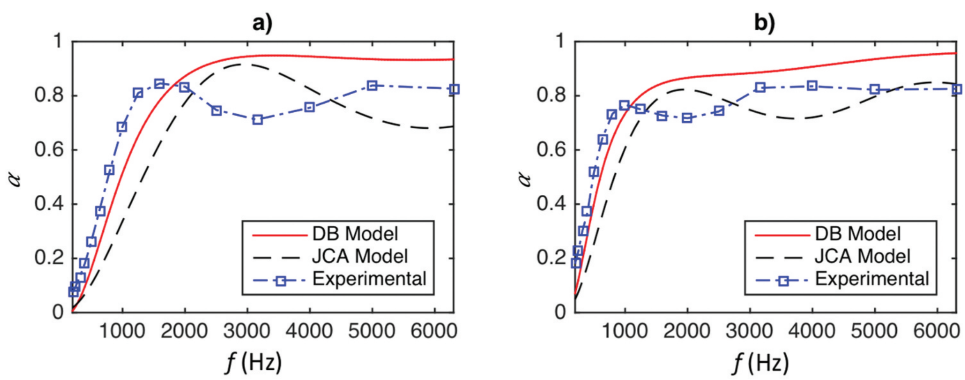

Figure 12. Comparison of the experimental and predicted SACs using the DB and JCA models for the jute samples with (a) 20 and (b) 30 mm thicknesses.

$$TL = 10\log\left\{1 + \left(\frac{\rho_s \pi f}{\rho_0 c}\right)^2\right\} - 5dB \quad (5)$$

where ρ_0 is the air density and f shows the frequency.

The Young's modulus of the luffa composite plates with similar fiber/epoxy ratios is around 2 GPa (Koruk and Genc 2019; Saygili et al. 2020). Hence, the critical frequencies for the 15–20 mm thick luffa plates using Eqs. (3) and (4) are calculated to be around 2700–2000 Hz. It should be noted that the experimentally measured TLs presented above show that the resonances are below 500 Hz for the luffa composites (Figure 3). Hence, the experimental and theoretical TLs of the 15 and 20 mm thick luffa (fiber/epoxy ratio: 0.45, sample density: 829.9 kg/m^3) composite samples predicted using Equation (5) for 500–2000 Hz are shown in Figure 13. It is seen that the experimental and theoretical TLs of the luffa composite samples are in general close to each other. It should be stated that the structures of natural fiber-reinforced composites are different than those of typical materials such as steel plates, hence the basic mathematical model used here is not expected to predict the transmission loss levels of biocomposite samples with high accuracy. Furthermore, although the acoustic properties of the samples have been determined based on some standards (ASTM E1050–12 2012; ASTM E2611-17 2017), there are still some problems preventing the accurate identification of the acoustic properties of biocomposite structures as explained in detail in the next section.

Difficulties related to manufacturing and testing biocomposites

The acoustic properties of even some nominally identical natural fiber-reinforced composite samples made of the same natural material can be quite different. The results for two cases are shown in Figure 14. Results show that the average deviations in the SACs and TLs for the three samples in Figure 14a are about 0.015 and 3 dB, respectively. On the other hand, the deviations in the SACs and TLs of the three samples in Figure 14b are 0.017 and 10 dB, respectively. The acoustic results for the three nominally identical samples in Figure 14a are close to each other while the variations in the TLs of the samples in Figure 14b are huge. It is worth stating that it is quite possible to obtain samples that may exhibit huge deviations from nominal properties. Three main reasons for the deviations are considered to be the variability of the properties of fibers, the accuracy of the manufacturing process, and the mismatch between the diameter of the test samples and the inner diameter of the impedance tube. These are explained below.

It is known that, in contrast to chemical-based fibers, each natural fiber in a batch/plant can have different individual mechanical and physical properties, thus some variations in the acoustic properties of natural fiber-reinforced composites should be expected. Furthermore, manufacturing methods for natural fiber-based structures are not very precise today. For example, epoxy can accumulate in

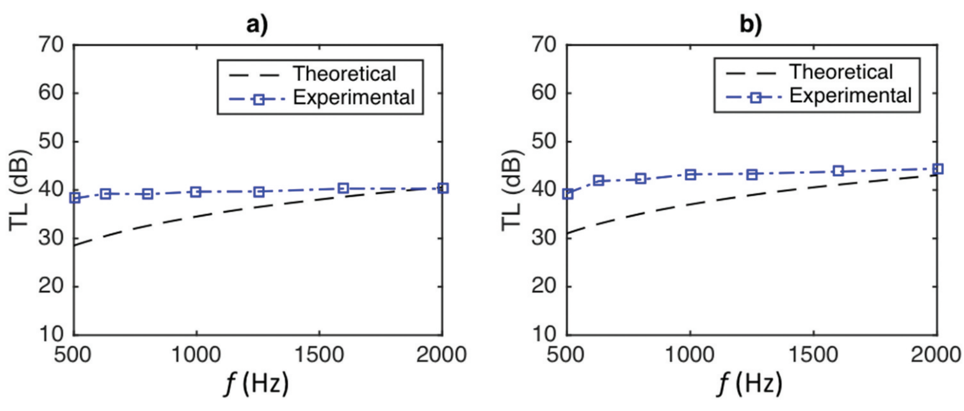

Figure 13. Comparison of the experimental and predicted TLs for the luffa composite samples with (a) 15 and (c) 20 mm thicknesses.

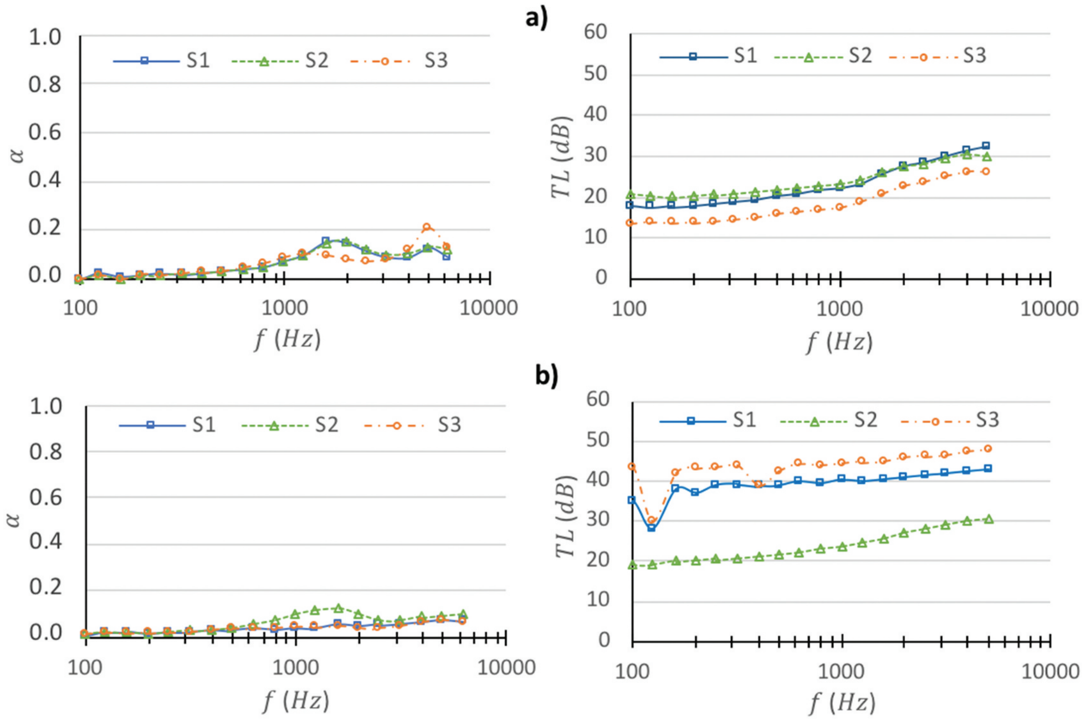

Figure 14. (a) The SACs (left) and TLs (right) of the three nominally identical jute composite samples with fiber/epoxy ratio of 0.6, density of 997.6 kg/m^3, and thickness of 10 mm. (b) The SACs (left) and TLs (right) of the three nominally identical jute composite samples with fiber/epoxy ratio of 0.5, density of 1019.8 kg/m^3, and thickness of 13 mm.

some regions of the composite plate during manufacturing. It should be noted that, because of this problem, samples with lower epoxy ratios than the ones presented in the previous sections could not be manufactured in this study. Moreover, some voids may be present in the various regions of the sample during manufacturing. Therefore, even the nominally identical samples can have variations in their measured acoustic properties due to epoxy accumulation and the voids in different parts of the manufactured composite plates.

Another important point is that the test sample should fit properly to the impedance tube in order to measure reliable acoustic properties (ASTM E1050–12 2012; ASTM E2611-17 2017). However, in practice, the diameter of the test sample can be a bit lower and higher than the inner diameter of the tube. A lower sample diameter results in higher SACs and lower TLs. A sample with a higher diameter will be compressed and pushed to fit into the tube, hence its acoustic properties will change and mostly some undesirable peaks occur in the measured data. Therefore, samples with somewhat smaller diameters are prepared and they are covered with materials such as petroleum jelly to fit the samples in the tube in practice, as recommended in the standards (ASTM E1050–12 2012; ASTM E2611-17 2017). In this study, the same procedure is applied. However, as one might expect, a perfect fit is hardly possible, hence the mounting conditions always lead to some uncertainty in the measured acoustic properties. It should be noted that the three problems mentioned in this section are inherent to the natural fiber-reinforced composites, and they are almost always encountered in practice.

Discussion

The results presented in this manuscript show that reflective jute and luffa composite samples with low SACs (<0.15) are obtained when the ratio of fiber to epoxy is less than 0.6 (Figures 2 and 4). On the other hand, the SACs increase with increasing fiber/epoxy ratio for both the jute and luffa composites (Figures 8 and 10). It is seen that samples with high SACs (>0.7) can be obtained when the fiber/epoxy ratio is high or no epoxy is used even for a thickness of 10–20 mm (Figures 8, 10 and 12). For example, the noise reduction coefficient, or NRC (a measure of the sound absorption between 250 and 2000 Hz), of a jute fiber sample with a thickness of 20 mm is around 0.4. It should be noted that the NRCs of the natural coconut (bulk density: 110 kg/m^3) and kenaf (bulk density: 150 kg/m^3) fiber samples with a thickness of 20 mm are around 0.25 (Bhingare and Prakash 2020) and 0.3 (Taban et al. 2020), respectively.

Although the SACs of the jute and luffa composite samples with a fiber/epoxy ratio less than 0.6 can be low, the TLs of these samples are quite high. For example, the average TL of the 10 mm jute sample with a fiber/epoxy ratio of 0.6 (and the 10 mm luffa sample with a fiber/epoxy ratio of 0.7) is around 25 dB. It should be noted that the TLs of the structural panels such as gypsum and plywood boards used in practice are around 20–25 dB for a thickness of 10 mm (Rudder 1985). On the other hand, the TLs of the jute and luffa composites decrease with increasing fiber/epoxy ratio (Figures 8 and 10).

It is clear that the increase of epoxy in the composite sample fills the pores and sound could not pass through the barrier, hence the TLs increase with increasing epoxy in the composite sample. On the other hand, a small amount of epoxy in the composite sample can reduce the diameters of large pores, hence this results in more dissipation of sound waves to heat through refraction within the porous sample. However, after a certain value, the epoxy fills the voids and disturbs the networks of interconnected pores in the sample, which decreases the sound absorption (Cuthbertson et al. 2019).

Utilizing the fact that the SACs increase and the TLs decrease with increasing fiber/epoxy ratio, better hybrid composites can be designed for optimized acoustic performance. For example, a composite structure consisting of a jute (or luffa) fiber layer without any resin and a jute (or luffa) epoxy composite layer would have quite high sound absorption and insulation property, even for a sample thickness of a few centimeters. It should be noted that such structures can be used in various sound and vibration isolation applications including in architectural designs. The design and experimental evaluation of such structures as well as theoretical model development for such hybrid structures is considered as topics for a future study.

Conclusion

The sound absorption coefficients (SACs) and transmission losses (TLs) of the jute and luffa composites are thoroughly investigated in this study. It is seen that the SACs increase and the TLs decrease with increasing fiber/epoxy ratio at almost all frequency ranges for both the jute and luffa composites. A fiber/epoxy ratio less than 0.5–0.6 produces reflective jute and luffa composite samples with low SACs and the SACs do not change significantly with thickness. On the other hand, the TLs increase almost linearly with thickness for all frequency ranges for both jute and luffa composites. The acoustic properties of even some nominally identical composite samples of the same natural material can be quite different. Three main reasons for the deviations are the variability of fibers, the accuracy of the manufacturing process, and the mismatch between the diameter of the test samples and the inner diameter of the impedance tube. The measured acoustic properties of the jute and luffa composites for a variety of thicknesses and fiber/epoxy ratios, the trend curves fitted to the measured data as a function of thickness and fiber/epoxy ratios for different frequency ranges, and the theoretical models exploited in this study can be used to design jute and luffa composite structures in many engineering applications.

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