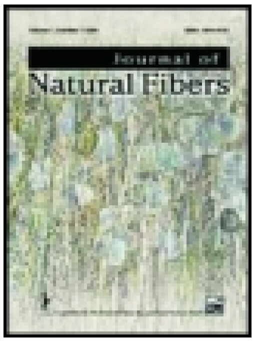

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Investigation of the Acoustic and Mechanical Properties of Homogenous and Hybrid Jute and Luffa Bio Composites

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ABSTRACT

Design and development of new biomaterials has become a necessity due to adverse effects of chemical materials on people and nature. As the mechanical properties of biomaterials are not as good as those of chemical materials, their different configurations should be developed and tested before considering them for practical applications. Acoustic and mechanical properties of homogenous and hybrid jute and luffa biocomposites are investigated here. Homogenous and hybrid composites using jute and luffa fibers and epoxy are designed and manufactured and methods for identification of the acoustic and mechanical properties are summarized. Acoustic and structural frequency response functions are measured using homogenous and hybrid composite plates to determine their natural frequencies and loss factors. Using the experimental modal parameters of the plates and their theoretical models, elasticity moduli of biomaterials are determined. The acoustic absorption properties and transmission losses of homogeneous and hybrid composites are determined using impedance tube method. Results show that homogenous and hybrid jute and luffa composites can have moderate absorption coefficients (0.1 for a thickness of 4 mm) and superior damping performance of luffa and stiffness property of jute can be used together to produce hybrid composites with high damping (2.2–2.6%) and elasticity modulus (3–5 GPa).

KEYWORDS

Jute; luffa; sound absorption; elastic properties; damping; transmission loss

摘要

由于化学物质对人和自然的不利影响，设计和开发新的生物材料已成为必要. 由于生物材料的力学性能不如化学材料，在考虑其实际应用之前，需要对其不同的构型进行开发和测试. 本文研究了均质和杂化黄麻和丝瓜生物复合材料的声学和力学性能. 设计和制造了以黄麻、丝瓜纤维和环氧树脂为原料的均质复合材料和混合复合材料，并总结了其声学和力学性能的识别方法. 利用均质复合材料板和混合复合材料板测量结构和声学频响函数，确定其固有频率和损耗因子. 利用板的实验模态参数及其理论模型，确定了生物材料的弹性模量. 采用阻抗管法测定了均质复合材料和混杂复合材料的吸声性能和传输损耗. 结果表明，均匀混合黄麻与丝瓜复合材料具有中等的吸收系数(厚度4mm为0.1)，可以同时利用丝瓜的优良阻尼性能和黄麻的刚度特性，制备出高阻尼(2.2-2.6%)、弹性模量(3-5 GPa)的复合材料.

关键词

黄麻; 丝瓜; 吸声; 弹性性质; 阻尼; 传输损耗

Introduction

Design and development of new biomaterials as an alternative to chemical-based materials such as glass and carbon fibers has become a necessity due to the adverse effects of chemical materials on people and nature (Selonen et al. 2020). Due to their sustainability and low cost (Kalauni and Pawar 2019),

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biomaterials appear to be a very promising alternative to chemical-based materials (Bansod, Mittal, and Mohanty 2016; Berardi, Iannace, and Di Gabriele 2017; Gokulkumar et al. 2019; Koruk and Genc 2019; Takagi 2019). As the mechanical properties of biomaterials are not as good as those of chemical materials (Gurunathan, Mohanty, and Nayak 2015; Taha and Ziegmann 2006), it is necessary to develop, test and optimize different configurations of biomaterials before they are considered for practical applications. In recent years, a huge number of research has been conducted to show how biomaterials can replace chemical-based materials and to reveal the applications of plant-based materials (Taiwo, Yahya, and Haron 2019; Wambua, Ivens, and Verpoest 2003), including their uses as acoustical products (Kalauni and Pawar 2019; Tang and Yan 2017). In the recent years, an attempt has been made to develop and characterize hybrid composites using different fibers such as hemp and flax (Chaudhary, Bajpai, and Maheshwari 2018; Sanjay et al. 2019).

Various methods have been used for mechanical characterization of biomaterials in the literature (Arulmurugan et al. 2019a, 2019b, 2020; Koruk and Genc 2019; Prabu, Rajamurugan, and Thirumurugan 2019). In addition to classical characterization methods such as tensile testing, experimental modal analysis can also be used for the identification of damping and elastic properties of materials (Koruk and Genc 2019). For the determination of the acoustic properties of biomaterials, the impedance tube method is widely used (Berardi and Iannace 2015; Koruk and Genc 2015). In addition to experimental methods, there are some mathematical models for the prediction of acoustic properties such as acoustic impedance, the propagation constant and sound absorption coefficients of porous materials including the plant-based materials in the literature (Allard and Atalla 2009; Allard and Van 1992; Berardi and Iannace 2017; Delany and Bazley 1970). In these models, the acoustic properties are calculated using the mechanical and physical properties of samples such as fiber diameter, flow resistivity and surface density (Allard and Atalla 2009; Berardi and Iannace 2017).

Jute fiber has relatively high strength among plant-based materials (Alves et al. 2010; Liu et al. 2009; Vilaseca et al. 2007) and luffa fiber has taken considerable attention in recent years (Liu et al. 2016; Papanicolaou, Psarra, and Anastasiou 2015; Saw, Ghose, and Sarkhel 2017). As the different manufacturing and testing systems may result in different dynamic properties for biomaterials, there is a need to manufacture and test these materials using the same systems to be able to compare their performances. Although the sound absorption properties (Bansod, Mittal, and Mohanty 2016; Bansod and Mohanty 2016; Koruk and Genc 2015; Thilagavathi et al. 2018) and strength (Bisen et al. 2020; Genc and Koruk 2017) of many biomaterials including jute and luffa are investigated, there is a need for the investigation of the dynamic mechanical properties including modal loss factors of the composites of these materials. Furthermore, the dynamic behaviors of hybrid jute and luffa composites have not been studied in the literature.

The mechanical properties such as damping and Young's moduli and acoustic properties such as sound absorption and sound transmission loss levels of homogenous and hybrid jute and luffa biocomposites are investigated in this study. First, homogenous and hybrid composites using jute and luffa fibers and epoxy matrix are designed and manufactured and the methods for the identification of the acoustic and mechanical behaviors are summarized. Then, acoustic and structural frequency response functions (FRFs) are measured using homogenous and hybrid composite plates to determine their natural frequencies and loss factors (damping levels). Using the experimentally identified natural frequencies and loss factors of the plates and their theoretical models, elasticity moduli of homogenous and hybrid jute and luffa composites are determined. Afterward, the acoustic absorption properties and sound transmission loss levels of homogeneous and hybrid composites are identified using the impedance tube method. The results show that the superior damping performance of luffa and the superior stiffness property of jute can be used together to produce hybrid composite samples with high damping (2.2–2.6%), elasticity modulus (3–5 GPa) and transmission loss levels (24–27 dB for a thickness of 4 mm).

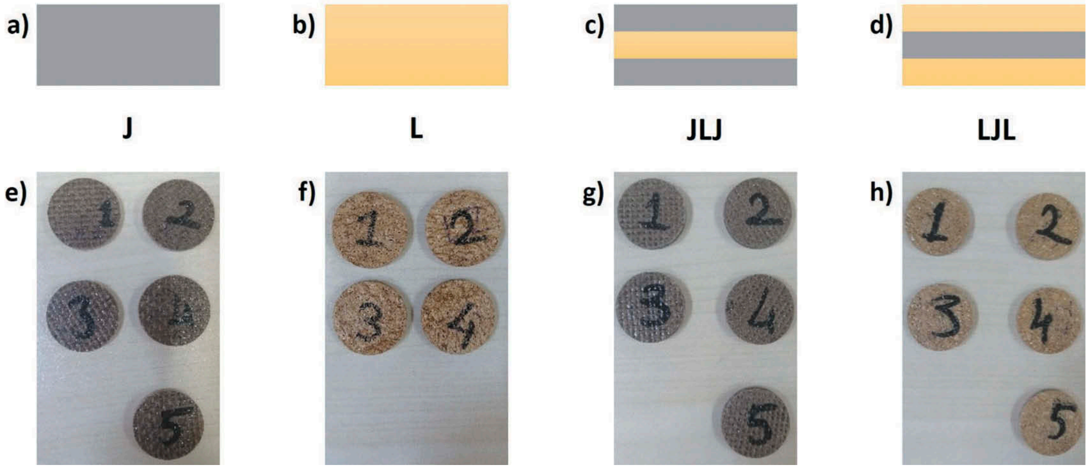

Figure 1. The cross-sections of the designs (a-d) and acoustic test samples (e-h) of the jute, luffa, jute-luffa-jute and luffa-jute-luffa composites.

Materials and methods

Luffa and jute fibers and epoxy as a matrix are used to produce composite plates. The designs of the homogenous jute (J) and luffa (L) and hybrid jute-luffa-jute (JLJ) and luffa-jute-luffa (LJL) composite structures are shown in Figure 1a-d. The plates are cured at 85°C for two hours under a pressure of 5 Bar. The acoustic test samples (diameter: 29 mm) are depicted in Figure 1e-h. Rectangular plates with the dimensions of 110 and 250 mm are used for vibration tests. The thickness and volume faction for the test specimens are around 4 mm and $V_{\text{epoxy}}/V_{\text{fiber}} = 0.45/0.55$, respectively.

As mentioned before, there are various methods for mechanical characterization of materials including biomaterials (Arulmurugan et al. 2019a, 2019b, 2020; Koruk, Dreyer, and Singh 2014; Prabu, Rajamurugan, and Thirumurugan 2019). In this study, the mechanical properties of the composite plates are determined via modal tests. For this purpose, the responses of the composite plates to impact excitation are measured using an accelerometer and a modal hammer and their structural FRFs are determined using:

$$H(\omega) = \frac{S_{fx}(\omega)}{S_{ff}(\omega)} \tag{1}$$

where $S_{ff}(\omega)$ is the auto-spectrum of the excitation (force) signal and $S_{fx}(\omega)$ is the cross-spectrum between response (vibration) and excitation signals. The experiments are performed only under free–free boundary conditions to eliminate any uncertainty due to boundary damping and stiffness. The test plates are divided into 4 × 7 points and more than twenty FRFs for each composite plate are measured. The FRFs are analyzed and modal frequencies and loss factors are determined using the line-fit method (Koruk, Dreyer, and Singh 2014). In the line-fit method, the compliance function H_{ij} for response point i and excitation point j is written as:

$$H_{ij}(\omega)_{\omega \cong \omega_r} = \frac{B_{ij,r}}{\omega_r^2 - \omega^2 + j\eta_r\omega_r^2} + \epsilon_{ij,r} \tag{2}$$

where $B_{ij,r}$ is the modal constant and $\epsilon_{ij,r}$ is the residual term for the rth mode corresponding to i and j. A new form of compliance function, $\bar{H}_{ij}(\omega)$, which is the difference between the actual compliance function and the value of the compliance function at one fixed frequency, Ω, in the frequency range of interest is defined as:

$$\bar{H}_{ij}(\omega) = H_{ij}(\omega) - H_{ij}(\Omega) \tag{3}$$

to cancel the residual term in the compliance function. After that, an inverse parameter (Eq. 4a) is defined using $\bar{H}_{ij}(\omega)$ for modal analysis. The expression in Eq. (4a) can also be expressed as in Eq. (4b).

$$Z(\omega) = \frac{\left(\omega^2 - \Omega^2\right)}{\bar{H}_{ij}(\omega)} \tag{4a}$$

$$Z(\omega) = \frac{\left(\omega_r^2 - \omega^2 + j\eta_r\omega_r^2\right)\left(\omega_r^2 - \Omega^2 + j\eta_r\omega_r^2\right)}{B_{ij,r}} \tag{4b}$$

The inverse parameter in Eq. (4b) is separated into real and imaginary parts which are supposed to fit onto a line when plotted against ω^2. The modal parameters are then estimated by determining the best lines that provide the best fits for the measured data (Ewins 2000; ICATS 2006; Koruk, Dreyer, and Singh 2014).

As the composite plates are lightweight, the mass loading effect of the contact-type sensor (the accelerometer) leads to errors in modal frequencies (Koruk and Genc 2019), hence the natural frequencies of the plates are determined using acoustic FRFs. For this purpose, the acoustic responses of the composite plates to impact excitation are measured using a microphone and the acoustic FRFs are determined using Eq. (1) by replacing $S_{fx}(\omega)$ with $S_{fp}(\omega)$ which shows the cross-spectrum between the response (sound pressure) and excitation signals. Nevertheless, the modal loss factors are estimated using structural FRFs. Following the experimental identification of the modal parameters of the composite plates, the same structures are modeled using finite elements (S4R) in Abaqus software (Dassault Systems, France) to predict the modal frequencies of the structures. The density of each material needed in the finite element model is determined by using the measured dimensions and the mass of the sample. The elasticity modulus of each material, on the other hand, is determined by minimizing the error between experimentally identified modal frequencies and the modal frequencies predicted by varying the value of the elasticity modulus of the material in the finite element model.

The acoustic properties of homogenous and hybrid composite structures are determined using the standard impedance tube method (ASTM E-1050, 1998). The incidence reflection coefficients of the test samples are determined using the transfer function $H_{12}(\omega)$ that is obtained using two microphones (Koruk and Genc 2015):

$$R(f) = \frac{H_{12}(\omega) - e^{-jks}}{e^{jks} - H_{12}(\omega)} e^{2jk(s+L)} \tag{5}$$

where ω, c, $k = \omega/c$, s and L show the frequency, sound speed, wave number, microphone spacing and the distance between the sample and the microphone closest to the sample, respectively. The sound absorption coefficients are then calculated using:

$$\alpha(\omega) = 1 - |R(\omega)|^2 \tag{6}$$

The sound transmission loss levels of the plates are determined using the standard impedance tube with four microphones (ASTM E2611-09 2009).

Results and discussion

Sample acoustic and structural FRFs measured using the four composite plates are shown in Figure 2. It is seen that there are more than five modes between 100 and 1100 Hz. As explained before, the natural frequencies of the plates are determined using acoustic FRFs due to the mass loading effect of the contact-type sensor in modal frequencies seen in structural FRFs (Figure 2) and the modal loss

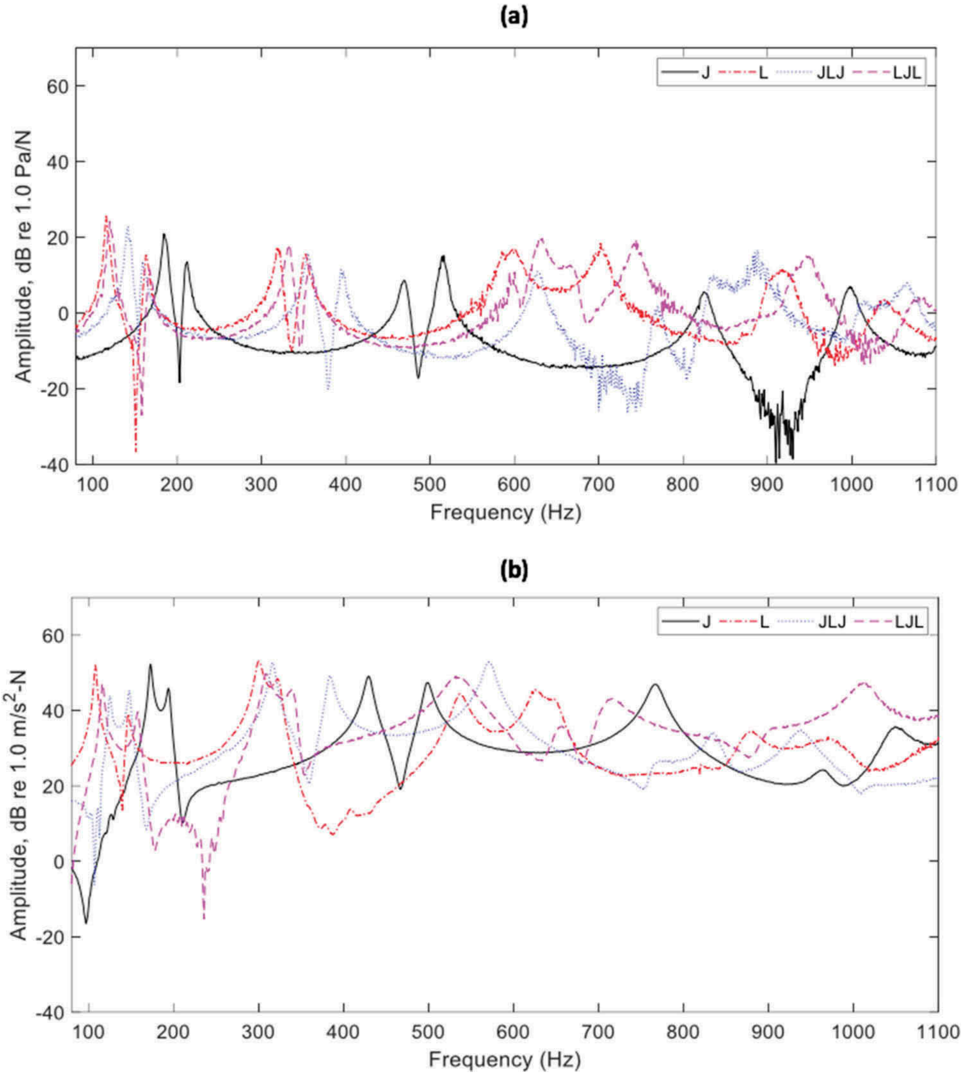

Figure 2. Sample (a) acoustic and (b) structural FRFs measured using the four composite plates.

factors are estimated using structural FRFs. Overall, the first five flexible modes of the plates are successfully identified. The identified modal loss factors (η_i) and elasticity moduli (E_i) of the composite plates for the first five modes are presented in Figure 3. The sound absorption coefficients and sound transmission loss levels of composite plates as a function of frequency are presented in Figure 4. The average values of the acoustic and mechanical properties of the composite plates in the frequency range of interest are listed in Table 1.

The damping level of the homogenous luffa composite plate (2.7%) is higher than that of the homogenous jute composite plate (2.0%). It is worth stating that these results are consistent with the results of the similar jute and luffa composite structures reported in the literature. For example, the loss factor of the jute composite with a fiber/epoxy volume fraction of 50% is reported to be around 1.5% (Ashworth et al. 2016) and the loss factor for the luffa composite with a fiber/epoxy volume fraction of 50 ± 10% is between 2.0–3.2% (Genc and Koruk 2017). It seems that the material and the inter-connected structure of the luffa sponge result in higher damping levels. On the other hand, the stiffness of the homogeneous jute composite (6.0 GPa) is higher than that of the homogenous luffa composite

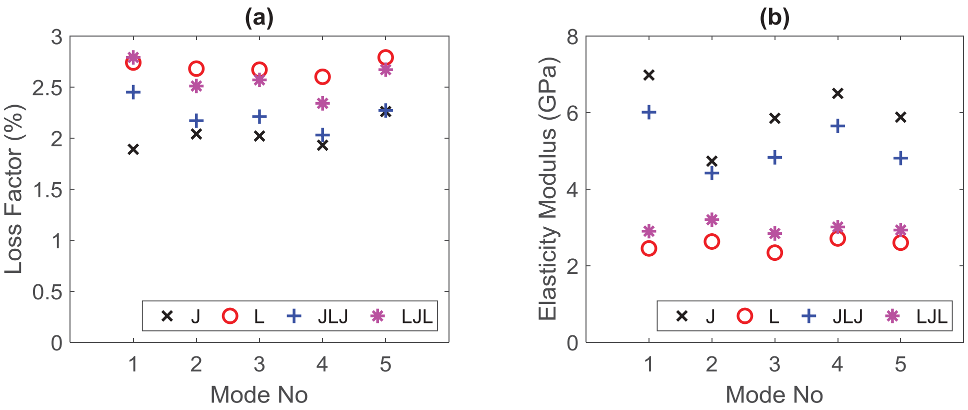

Figure 3. The mechanical properties of the jute, luffa, jute-luffa-jute and luffa-jute-luffa composites: (a) modal damping levels and (b) elasticity moduli.

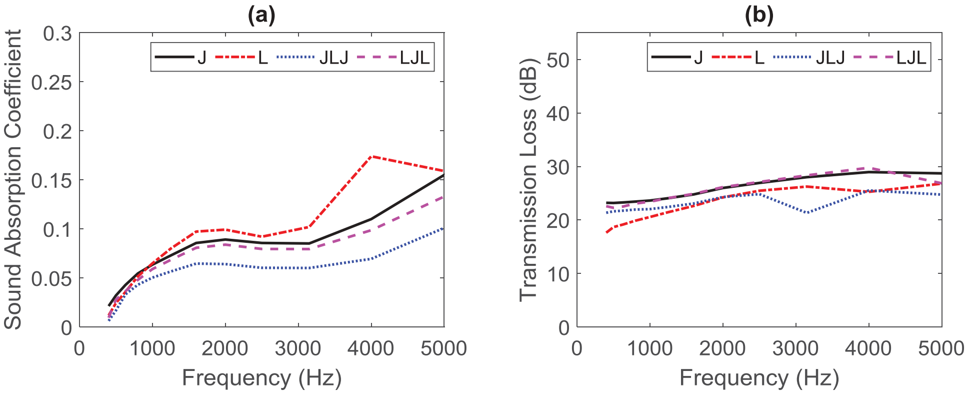

Figure 4. The acoustic properties of the jute, luffa, jute-luffa-jute and luffa-jute-luffa composites: (a) sound absorption coefficients and (b) sound transmission loss levels.

Table 1. The average values of the acoustic and mechanical properties for the composite jute, luffa, jute-luffa-jute and luffa-jute-luffa plates.

Property	J	L	JLJ	LJL
Density (kg/m^3)	1111	768	925	894
Elasticity Modulus (GPa)	6.0	2.6	5.1	3.0
Loss Factor (%)	2.03	2.70	2.23	2.58
Sound Absorption Coefficient	0.11	0.13	0.07	0.10
Sound Transmission Loss (dB)	27	25	24	27

(2.6 GPa). The results show that the damping levels of the hybrid JLJ (2.2%) and LJL (2.6%) configurations are higher than that of the homogenous jute composite plate. The stiffnesses of the hybrid JLJ (5.1 GPa) and LJL (3.0 GPa) configurations are higher than that of the homogenous luffa composite plate. It is seen that the use of hybrid configurations improved the damping and strength performances by 9.9 and 96.2% for JLJ and 27.1 and 15.4% for LJL composite plates, respectively.

It should be noted that the jute fiber is made of cellulose 61.2%, hemicellulos 23.2%, lignin 13.7% and wax and pectin 0.5% (Chandekar, Chaudhari, and Waigaonkar in press). On the other hand, the luffa fiber is made of cellulose 63.0%, hemicellulose 14.4%, lignin 1.6%, ash 0.9% and some other components 20.1% (Seki et al. 2012). Although the main component for both fibers is cellulose, jute and luffa fibers are substantially different materials. It is already reported in the literature that the Young's moduli of the jute and luffa fibers are within 10–30 GPa (Alves et al. 2010; Prabu, Rajamurugan, and Thirumurugan 2019) and 0.9–1.8 GPa (Koruk and Genc 2019; Papanicolaou, Psarra, and Anastasiou 2015), respectively. Therefore, the jute composites are stiffer than the luffa composites. Furthermore, the diameters of the jute and luffa fibers are different (the diameters of the single jute and luffa fibers in this study are around 0.05 and 0.3 mm, respectively) and it is known that the fiber diameter affects the acoustic and mechanical performances (Mamtaz et al. 2016). In addition, the random distribution of short fibers in the luffa plant affects its strength and high microfibrillar angle (i.e., angle between the fiber axis and the fibril of the fiber) decreases the mechanical strength (Koruk and Genc 2019). It should be noted, however, that the physical properties of the luffa plant result in higher damping levels.

The sound absorption coefficients of the four samples are close to each other, the average being 0.07–0.13 for such thin (4 mm) samples. These results are consistent with the results reported in the literature for similar composites. For example, the average sound absorption coefficient of the jute composite with a fiber/polypropylene volume fraction of 50% and thickness of 4 mm is around 0.09 (Thilagavathi et al. 2010). The sound transmission loss levels of the jute samples (27 dB) are higher than those of luffa samples (25 dB). The sound transmission loss levels of the hybrid JLJ and LJL samples are 24 and 27 dB, respectively. It should be noted that the jute composite is denser than the luffa composite, and, as stated before, the damping level of the luffa composite is higher than that of the jute composite. Therefore, the sound isolation performance of the jute composite sample is not much different than that of the luffa composite sample, and the sound isolation performances of the homogenous and hybrid composite samples in general are similar.

Conclusion

The acoustic and mechanical properties of homogeneous and hybrid jute and luffa composites are investigated in this study. It should be noted that this is the first study in the literature that evaluates and compares the acoustic and mechanical properties of hybrid as well as homogenous jute and luffa composites. The results show that the damping level of the luffa composite plate (2.7%) is higher than that of the jute composite plate (2.0%) while the elasticity modulus of the jute composite plate (6.0 GPa) is higher than that of the luffa composite (2.6 GPa). The jute and luffa composites can have moderate sound absorption coefficients (around 0.1) and transmission loss levels (27 dB for jute and 25 dB for luffa) even for a thin sample of 4 mm and their hybrid composites show similar acoustic performances. The superior damping performance of luffa and the superior stiffness property of jute can be used together to produce hybrid composite samples with high damping (2.2–2.6%) and elasticity modulus (3–5 GPa).

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