

Acoustic and mechanical properties of luffa fiber-reinforced biocomposites

This is a post-refereeing final draft. When citing, please refer to the published version:

Hasan Koruk, Garip Genc, 17 - Acoustic and mechanical properties of luffa fiber-reinforced biocomposites, Editor(s): Mohammad Jawaid, Mohamed Thariq, Naheed Saba, In Woodhead Publishing Series in Composites Science and Engineering, Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites, Woodhead Publishing, **2019**, Pages 325-341, ISBN 9780081022924.

<https://doi.org/10.1016/B978-0-08-102292-4.00017-5>

ACOUSTIC AND MECHANICAL PROPERTIES OF LUFFA FIBER REINFORCED BIOCOMPOSITES

Hasan Koruk¹ & Garip Genc^{2,*}

¹MEF University, Mechanical Engineering Department, 34396, Istanbul, Turkey

²Marmara University, Mechanical Department, 34372, Istanbul, Turkey

*Corresponding author

E-mail: ¹*korukh@mef.edu.tr*, ²*ggenc@marmara.edu.tr*

Abstract

This chapter presents an overview of acoustic and mechanical behaviors of luffa fiber reinforced biocomposites. A growing number of studies are examining the composites of biodegradable fibers such as flax, hemp, kenaf and luffa due to the adverse effects of chemical materials on nature. The low cost and superior acoustic and acceptable mechanical properties of biocomposites make them very attractive for practical applications such as sound and vibration isolation. However, the acoustic and mechanical characteristics of biocomposites and their dynamic behaviors should be fully determined before considering them for practical applications. In this chapter, acoustic properties, such as sound absorption and transmission loss, and mechanical properties, such as damping and elasticity of luffa fiber reinforced composites, are presented. The variations in acoustic and mechanical properties due to different samples and manufacturing process are explored.

Keywords: luffa composites; defects; impedance tube method; sound absorption; transmission loss; modal analysis; elastic properties; Young's modulus; damping properties; finite element modelling.

1 Introduction

Composites reinforced by synthetic fibers, such as glass, carbon and aramid, are widely used in practice including aerospace, automotive, sports and biomedical sectors [1-11]. Although synthetic fibers have superior mechanical properties, such as low density and high strength, the recycling process for these materials takes a long time and hence causes pollution in nature. Furthermore, burning of substances derived from petroleum products releases enormous amounts of carbon dioxide into the atmosphere. This phenomenon is believed to be the root cause of the greenhouse effect and the world's climatic changes. Therefore, finding and developing new materials as alternatives to petroleum-based materials has become a necessity. Because of the biodegradability of natural fibers, the use of bio fibers as reinforcement for composite structures has recently received increased attention [12-14]. However, the acoustic and mechanical characteristics of biocomposites and their dynamic behaviors should be fully explored before considering them for practical applications.

The major bio-materials, such as flax, jute, hemp, kenaf, sisal, ramie and luffa cylindrica, have been investigated in many studies [12-36]. Despite the challenges, such as cultivation and continuity of these plant-based materials, their enhanced features are gaining immense importance [25]. In recent years, the luffa cylindrica plant has been recognized as a new biodegradable material, and luffa-reinforced composites are being investigated for practical applications. Like other natural fibers, luffa fibers do not create a health risk when individuals are exposed to them; in addition, they have quite a low cost. In this study, the identification methods for the characterization of the acoustic and mechanical properties of biocomposite structures are briefly described. Acoustic properties, including sound absorption and transmission loss, and mechanical properties, including damping and elasticity of luffa composites, are presented. Variations in acoustic and mechanical properties due to different

samples and manufacturing process are also explored in order to understand their limitations in practice.

2 Manufacturing, Defects and Structural Differences

The luffa cylindrica plant is commonly found in South America, Brazil, China, Japan, Turkey and some other countries in Asia. This plant has a form of a fruit which is covered with green peel on the outside (Fig. 1a). The outer green layer starts to dry when the ripening period of the fibers inside the fruit is completed (Fig. 1b) and the fibrous structure develops under the dried outer layer (Fig. 1c and d). Luffa plant size varies in relation to location, ranging from 0.15 m to 1 m (even more than 1 m in certain areas). In general, a luffa fiber contains cellulose, hemicellulose and lignin (Table 1), though the chemical composition of luffa fibers depends on several factors, such as plant origin, weather conditions (changeable every year) and soil. For instance, the cellulose content varies from 55 to 90%, the lignin content is within the range of 10 to 23%, the hemicelluloses content is around 8 to 22%, extractives amount to nearly 3.2%, and ash makes up around 0.4% [26, 28, 31, 37].

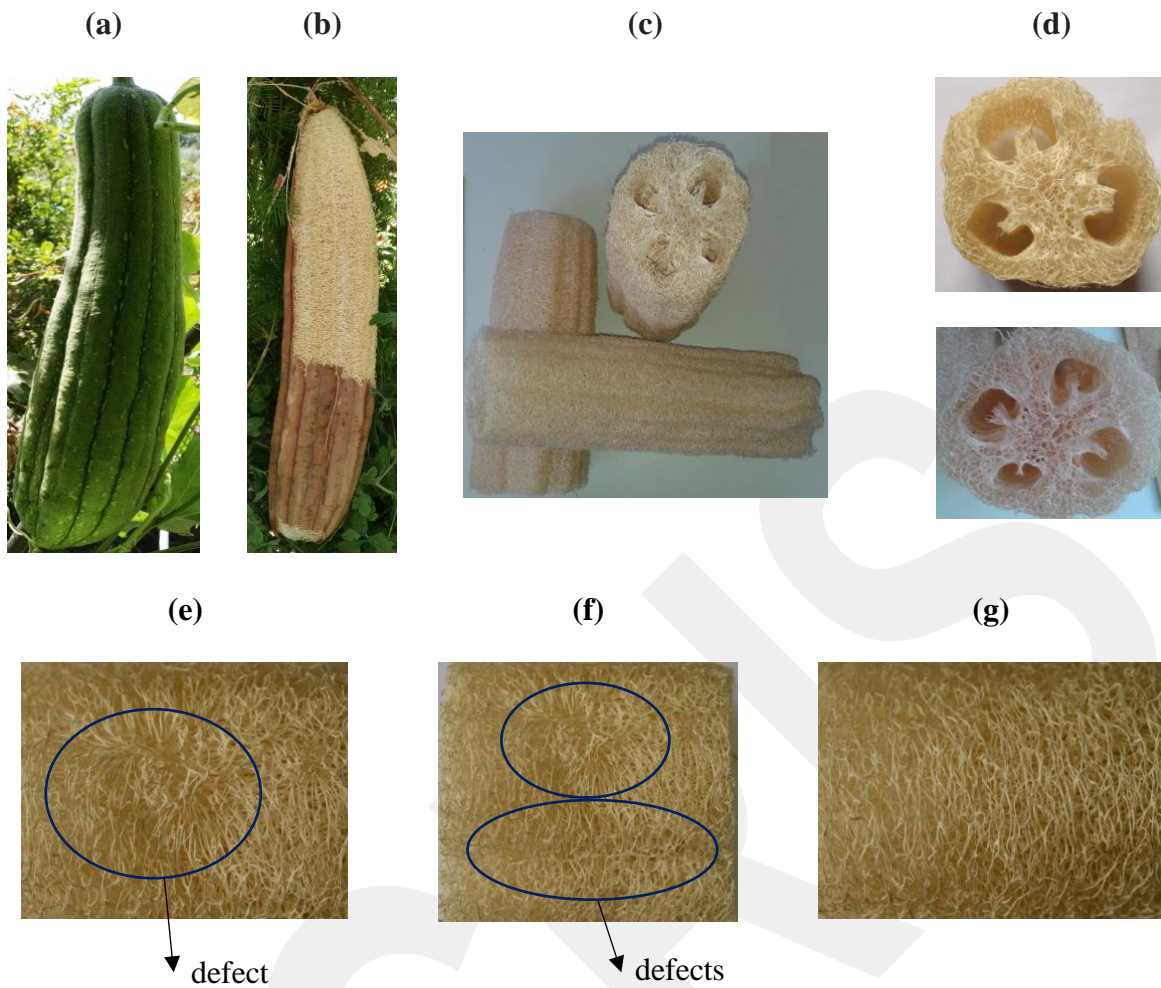


Fig. 1. Luffa fibers: (a) green plant, (b) dried plant, (c) fibrous structure, (d) the structure of luffa fiber with three and four holes, the luffa fibers (e-f) with and (g) without defects.

Table 1. Composition of luffa cylindrica fibers [26, 28, 31, 37].

Component	Content (%)
Cellulose	55 - 90
Hemicellulose	8 - 22
Lignin	10 - 23
Ash	0.4
Extractives	3.2

Luffa composites are produced through similar methods used for manufacturing chemical-fiber-based composites. It is noted that lignin, the outermost layer of a luffa fiber,

reduces the adhesion with the matrix. Therefore, the lignin layer could be weakened by various surface modifications to increase the matrix adhesion [26-30]. The increasing adhesion on the interface will lead to better mechanical properties. Nevertheless, the scanning electron microscopy (SEM) photomicrograph for sample luffa composite structures show that the interfacial compatibility between luffa fibers and matrix is acceptable even when any surface treatment is not applied to the luffa fibers. Therefore, luffa fibers are used with or without a surface treatment in practice and a resin such as epoxy is used as matrix to manufacture luffa composite structures. In general, luffa fibers are placed in between two plates and resin is passed through it. Luffa composite samples are cured at considerably high temperatures (50 - 100 °C) under pressure (5 - 10 Bars) for a period of time (5 - 10 hours). It should be noted that there are some attempts to use sodium hydroxide [22, 26, 29, 32], alkalization, furfurylation [36], formic acid, acetic acid [28, 33] and dithiothreitol [30] during manufacturing to improve the thermal and mechanical properties of composite structures.

Inherent to their nature, green plants including luffa cannot be identical and structural differences are always expected. For example, the measured masses of fifteen dry luffa fiber specimens with approximately the same dimensions show that the average mass of a luffa plant is 75 g with a standard deviation of 20 g. Whether the number of holes of a luffa plant is three, four or more (Fig. 1d), even for the same harvest, has an effect on the structure of fibers. In addition to these structural differences, there are some defects in the fibrous structure, as is the norm for many bio-fiber plants (Fig. 1e and 1f). Defects are formed during the growth of the plant. Regions with defects have different mechanical properties. It should be noted that luffa fibers in the matrix are randomly distributed (Fig. 1g). In addition, the press direction during manufacturing process may affect the properties of luffa composites.

The structural differences inherited from the nature of green plants, defects, and the manufacturing process affect the acoustic and mechanical properties of luffa composites.

Despite this, the structure of luffa fiber consists of a lot of short fibers and makes an interlocked mesh. This feature means luffa composites have small variations in acoustic and mechanical properties, as presented in Section 3 and 4. It should be emphasized that, despite the difficulties in homogenizing the batch of luffa cylindrica samples for mass production and manufacturing the luffa composite structures, increasing the use of these green materials to minimize the use of chemical based composites is vital for the environment. In future, new biocomposite materials, based on natural fibers and bio-resins, are expected to be produced through a chemical matrix, as is currently used in the manufacturing of biocomposites.

3 Acoustic Properties

Sound absorption and transmission loss are two important acoustic characteristics of materials. Therefore, these characteristics of biocomposites should be explored before they can be considered for practical applications. In what follows, first, identification methods for sound absorption and transmission loss are briefly described. Then, the acoustic properties of luffa fibers and their composites are presented.

3.1 Identification Methods

The impedance tube method with two microphones (Fig. 2) is widely used to identify the frequency dependent absorption properties of materials [38-41]. In this technique, material samples are inserted into the tube and a sound source in the tube emits a precisely quantified sound. Using the two microphones, the complex valued acoustic transfer function $\tilde{H}_{12}(\omega)$ from p_1 to p_2 is first measured. The complex valued normal incidence reflection coefficient $\tilde{R}(\omega)$ based on the measured transfer function is then determined by:

$$\tilde{R}(\omega) = \frac{\tilde{H}_{12}(\omega) - e^{-jks}}{e^{jks} - \tilde{H}_{12}(\omega)} e^{2jk(s+L)} \quad (1)$$

where $k = 2\pi\omega/c$ is the wave number, c is the speed of sound in the air, ω is the frequency, and $j = \sqrt{-1}$. Using the reflection coefficient, the sound absorption coefficient at normal incidence is calculated by:

$$\alpha(\omega) = 1 - |\tilde{R}(\omega)|^2 \quad (2)$$

Determination of sound absorption coefficients of materials using an impedance tube is described in ASTM E 1050-12 [38] and ISO 10534-2 [39] standards.

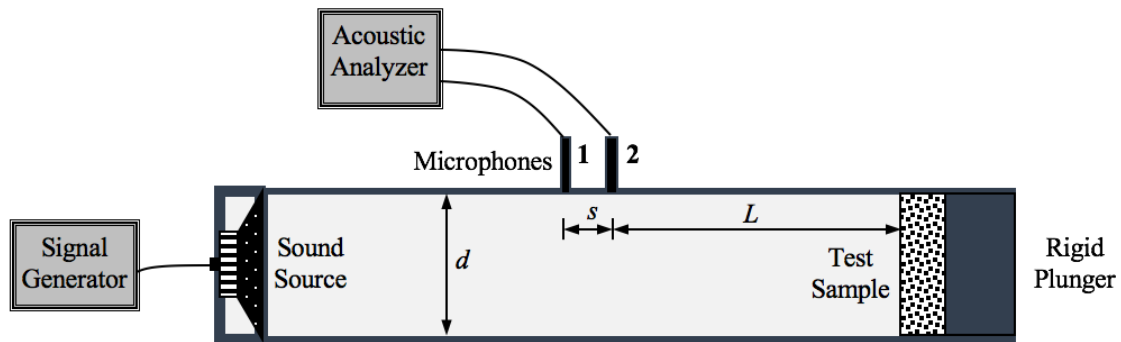


Fig. 2. The impedance tube with two microphones used to measure sound pressures inside the tube to determine sound absorption coefficients.

The transmission loss levels of material samples are determined using a tube with four microphones (Fig. 3). By measuring the sound pressure at four stations and calculating the complex transfer function using a four-channel acoustic analyzer, the transmission loss of the material is determined. It should be noted that the measurement of normal incidence sound transmission of materials based on the transfer matrix method is described in ASTM E2611-17 standard [42].

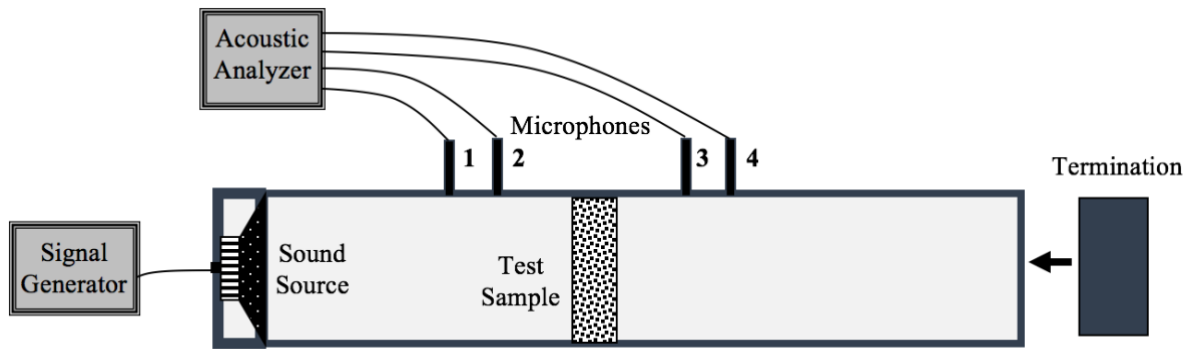


Fig. 3. The impedance tube with four microphones used to measure sound pressures inside the tube to determine transmission loss levels.

3.2 Sound Absorption

Experimental investigations [32, 41, 43] show that luffa fiber samples have considerably high sound absorption coefficients (Fig. 4). The average sound absorption coefficient of a luffa fiber sample with a thickness of 10 mm is around 0.3 for 0.5 - 6.3 kHz. It is seen that the acoustic absorption properties of luffa fibers compare favorably with the corresponding properties of acoustic foams used in practice [40]. Luffa fiber samples can be used as sound absorption materials in many applications that do not require very high load bearing capabilities. It is also seen that the sound absorption coefficients for all luffa fiber and composite samples increase with frequency. Luffa composites with higher sound absorption coefficients (compared to luffa fiber samples) can be obtained when the correct volume fraction of fiber is determined. The average sound absorption coefficient of a luffa composite sample with a thickness of 10 mm and fiber/epoxy ratio of 4 is around 0.35 for 0.5 - 6.3 kHz. It should be noted that the sound absorption coefficient of a 10-mm glass plate or thicker is around 0.04 for 0.5 - 4 kHz [44]. The hollow lumen structure of fibers and their random distribution is believed to be reason for the superior sound absorption properties of luffa structures [32, 41, 43].

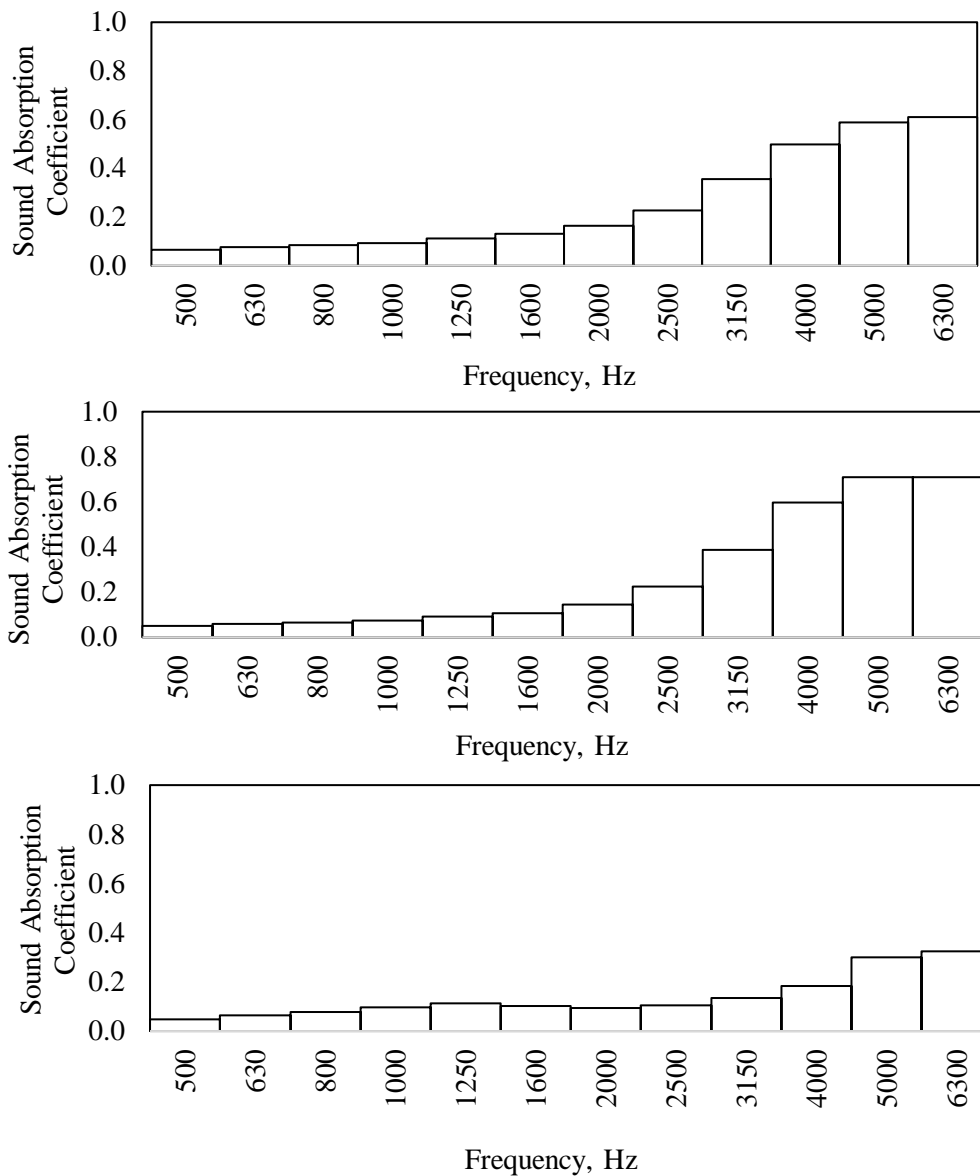


Fig. 4. Sound absorption coefficients of luffa samples with a thickness of about 10 mm: (a) luffa sample without matrix-epoxy, (b) luffa composite sample with high fiber/epoxy ratio (i.e., 4) and (c) luffa composite sample with low fiber/epoxy ratio (i.e., 1.5).

As a luffa composite sample has more elasticity strength compared to a luffa fiber sample, such samples can be used in practical applications where structural stiffness is required. However, identified sound absorption coefficients of a luffa composite decrease with an increasing volume fraction of matrix after a specific ratio. It was also reported that sound absorption coefficient increases when a perforated linen is used [41]. On the other hand, the

treatment (e.g., sodium hydroxide) of luffa fibers in the composites causes small decreases in the sound absorption coefficients of the luffa composites [32].

3.3 Transmission Loss

Experimental investigations [41, 43, 45] show that luffa composite samples can have considerably high transmission loss levels (Fig. 5). For a sample thickness of 10 mm, the average transmission loss levels of a luffa sample without epoxy, luffa composite sample with a fiber/epoxy ratio of 4, and luffa composite sample with a fiber/epoxy ratio of 1.5 are around 3, 6 and 25 dB, respectively. The transmission loss level increases with an increasing volume fraction of matrix (epoxy) in the composite structure. It is seen that the transmission loss levels of a luffa composite with a fiber/epoxy ratio of 1.5 and a thickness of 10 mm compare favorably with the transmission loss level of a cement or glass panel with a thickness of 10 mm [45, 46].

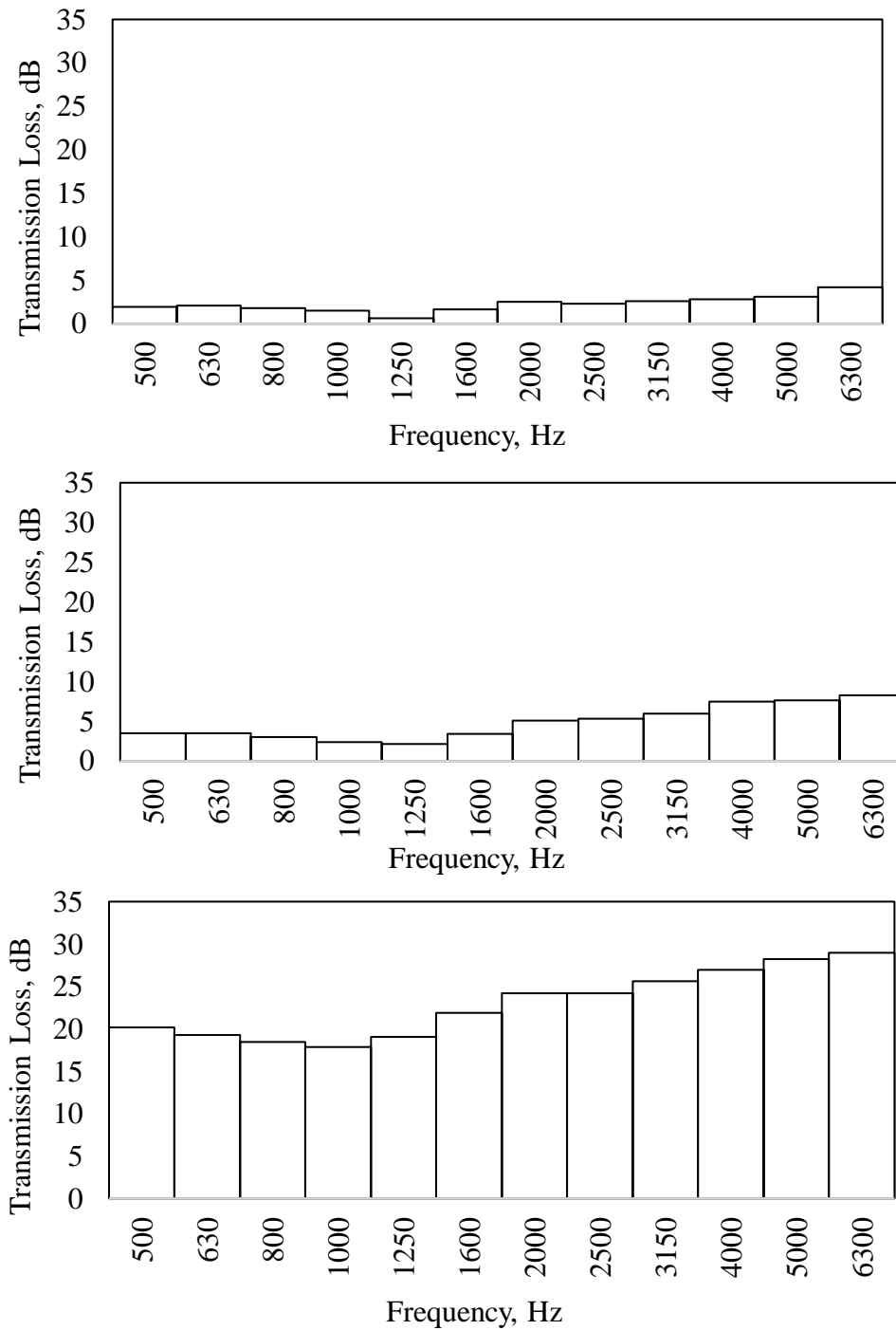


Fig. 5. Transmission loss levels of luffa samples with a thickness of about 10 mm: (a) luffa sample without epoxy, (b) luffa composite sample with high fiber/epoxy ratio (i.e., 4) and (c) luffa composite sample with low fiber/epoxy ratio (i.e., 1.5).

Luffa composites have the potential to be used in architectural applications, such as concert saloons, to absorb reverberant noise and provide sound transmission, as their sound

absorption and isolation capabilities are better than many plant materials [43]. It should be noted that some linens can be used to prepare acoustic samples using only the luffa material in practice, and those samples can be used in the acoustic design of halls. However, if a high sound isolation property is also required (in addition to a sound absorption property), then a luffa composite material with an appropriate matrix composition can be used.

4 Mechanical Properties

The main characteristics of a material affecting dynamic behavior are density, damping and elasticity. Therefore, these mechanical properties of biocomposites should be explored before considering them for practical applications. It should be noted that the density of luffa fiber is around 800-900 kg/m³, which is lower than some common natural fibers such as sisal (1260 to 1450 kg/m³), hemp (1480 kg/m³), coir (1250 kg/m³), ramie (1500 kg/m³), and cotton (1510 to 1600 kg/m³) as seen in Table 2 [18, 37, 47]. It should be noted that the density of the glass fiber widely used in practice is around 2550 kg/m³. In what follows, first, identification methods for elastic and damping properties are briefly described. Then, the elastic and damping properties of luffa composites are presented.

Table 2. Density of different natural fibers and glass fiber [14, 18, 37, 47].

Fiber	Density (kg/m ³)
Sisal	1260 - 1450
Hemp	1480
Coir	1250
Flax	1400
Jute	1460
Ramie	1500
Cotton	1510 - 1600
Luffa	800 - 900
Glass	2550

4.1 Identification Methods

Static elasticity modulus, ultimate elongation and tensile strength of materials are easily determined via tensile testing in practice [48-54]. Dynamic mechanical properties, such as modal damping levels and dynamic Young's moduli of materials, are frequently identified by first determining the modal parameters, such as modal frequencies and loss factors of special test structures (Fig. 6). For this purpose, the frequency response functions using contact or non-contact excitation and response sensors are first measured [55-57]. The frequency response function for the measured response and excitation can be calculated by:

$$\tilde{H}_{ij}(\omega) = \frac{\tilde{F}_j^*(\omega)\tilde{V}_i(\omega)}{\tilde{F}_j^*(\omega)\tilde{F}_j(\omega)} \quad (3)$$

where $\tilde{F}_j(\omega)$ and $\tilde{V}_i(\omega)$ are the Fourier Transforms of the time domain excitation force $f_j(t)$ applied at the point j and the vibration velocity (response) $v_i(t)$ measured at point i , respectively, t is time and superscript * indicates the complex conjugate. A modal analysis method such as half-power, circle-fit and line-fit can be used to identify modal damping and frequencies once the measured frequency response functions are measured. In the simplest method, the half-power method, the loss factor (η_r) for mode r (or mode shape ϕ_r) is determined by:

$$\eta_r = \frac{\omega_{r,2}^2 - \omega_{r,1}^2}{2\omega_r^2} \quad (4)$$

where $\omega_{r,1}$ and $\omega_{r,2}$ are the frequencies corresponding to half power points around the natural frequency ω_r being the peak for that mode.

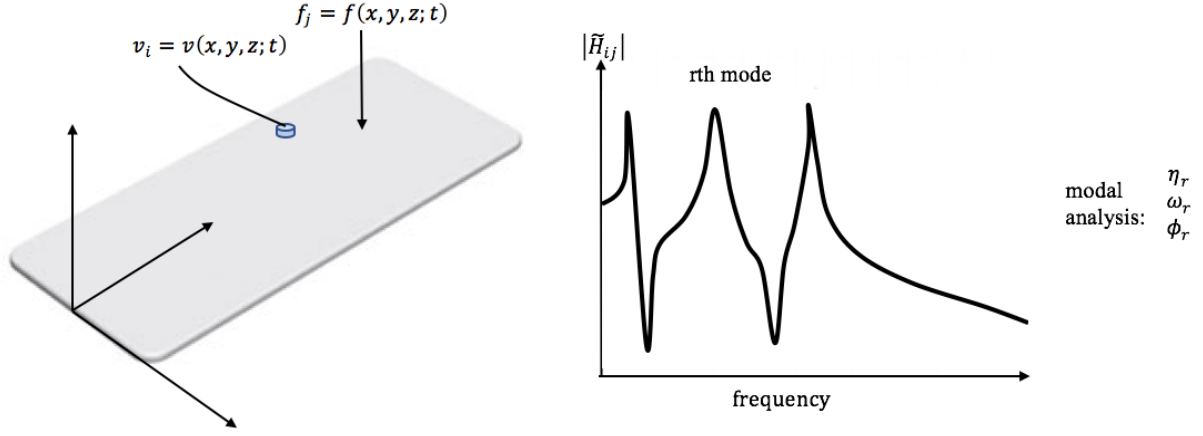


Fig. 6. Frequency response function (\tilde{H}_{ij}) measurements for identification of modal parameters (η_r , ω_r , ϕ_r) of a test structure.

Once the modal frequencies and loss factors are determined experimentally, modal elasticity moduli can be determined using the theoretical expressions relating modal parameters to elastic properties. Simple samples, such as beams and plates for identification of mechanical properties, are mostly used in experiments. For example, if the test sample is a clamped-free beam, the Young's modulus for the mode r is determined by:

$$E_r = \frac{12\rho L^4 \omega_r^2}{H^2 C_r^2} \quad (5)$$

where ρ , L and H are the density, length and the thickness of the beam, respectively, C_r is the coefficient for mode r of the clamped-free beam being $C_1 = 0.55959$, $C_2 = 3.5069$, $C_3 = 9.8194$ and $C_n = (\pi/2)(r - 0.5)^2$ for $r > 3$. If the test sample is a circular plate with rigid boundary conditions, then the Young's modulus for the mode r can be determined by:

$$\lambda_r^2 = 2\pi\omega_r R^2 \sqrt{12(1 - \nu^2) \frac{\rho h}{E_r h^3}} \quad (6)$$

where R and h are the radius, and thickness of the plate, ν is Poisson's ratio, and λ_r^2 is a frequency parameter given in the literature for different h/r values [58].

Numerical methods, such as finite elements, can be used to model test structure and extract mechanical properties when the test structure is complicated. Furthermore, more parameters, such as frequency dependent damping levels can be included in the finite element model for more accurate material properties. Overall, once the system matrices of the test structure are determined, the eigenvalue problem given by:

$$(\mathbf{K}^* - \lambda^2 \mathbf{M})\boldsymbol{\phi} = 0 \quad (7)$$

is solved to determine the eigenvalues and mode shapes $\boldsymbol{\phi}_r$ of the structure. Here, \mathbf{K}^* and \mathbf{M} are the system stiffness and mass matrices, respectively [59, 60]. In general, \mathbf{K}^* is complex and natural frequencies and loss factors are determined by $\omega_r^2 = \text{Real}(\lambda_r^2)$ and $\lambda_r = \text{Imag}(\lambda_r^2) / \text{Real}(\lambda_r^2)$. At the beginning, some elastic properties for the materials to be identified can be assumed and modal analyses are performed. The predicted modal parameters are compared with experimentally determined values, and analyses are repeated until the experimental and theoretical modal parameters are matched.

4.2 Damping and Elastic Properties

In many studies, static elasticity modulus, ultimate elongation, and tensile strength of different natural fibers are determined via tensile testing [13, 15, 17, 22, 23, 48, 61-70]. Results show that the elasticity modulus of luffa fiber (0.9 - 1.8 GPa) is low compared to other typical natural fibers such as sisal (9.4 - 22 GPa) and jute (26.5 - 32 GPa), as seen in Table 3. Similarly, the tensile strength of luffa fiber (1.7 - 20.5 MPa) is low compared to other typical natural fibers such as sisal (500 - 635 MPa) and jute (393 - 773 MPa). It should be noted the elasticity modulus and tensile strength of the widely used glass fiber in practice is around 73 GPa and 2400 MPa, respectively. One reason for the low strength of luffa is the random distribution of short fibers in the plant. Coir also has low strength compared to other natural fibers. The low strength of coir was reported to be due to its low cellulose content and reasonably high microfibrillar angle (i.e., angle between the fiber axis and the fibril of the fiber) [14, 71]. Fiber mechanical properties

such as elasticity modulus and ultimate tensile stress are related not only to the chemical composition of the fiber but also to its internal structure. It is reported in the literature that the treatment (e.g., sodium hydroxide) of luffa fibers in the composites increase tensile and yield strength [32].

Table 3. Static elasticity modulus, ultimate elongation, and tensile strength of different natural fibers and glass fiber determined via tensile testing.

Fiber	Elasticity Modulus (GPa)	Ultimate Elongation (%)	Tensile Strength (MPa)
Flax [13, 17, 48, 63, 64]	12 - 85	1 - 4	600 - 2000
Jute [15, 61, 65, 66]	26.5 - 32	1.5 - 1.8	393 - 773
Kenaf [15, 22, 67]	21 - 53	1.6 - 3.5	350 - 930
Coir [14, 72]	2.5-6	15-25	180-220
Sisal [15, 23, 61, 62]	9.4 - 22	1.6 - 2.5	500 - 635
Hemp [15, 22, 64]	44.5 - 70	1.6 - 1.8	690 - 788
Luffa [68-70]	0.9 - 1.8	1.1 - 2.2	1.7 - 20.5
Glass	73	3	2400

The dynamic (modal) elastic moduli of luffa composite structures (determined by analyzing frequency response functions), even for a volume fraction of matrix of 0.5 ± 0.1 , are acceptable (i.e., 2.5 ± 0.1 GPa) [35, 45]. It is seen that the elastic properties of luffa composites do not have large variation with respect to frequency for 100 - 1000 Hz (Fig. 7). The elasticity modulus of luffa composite structures for a low volume fraction of matrix are comparable to elastomers and plastics [73]. It should be noted that improving the mechanical properties of luffa composites is possible via surface treatment.

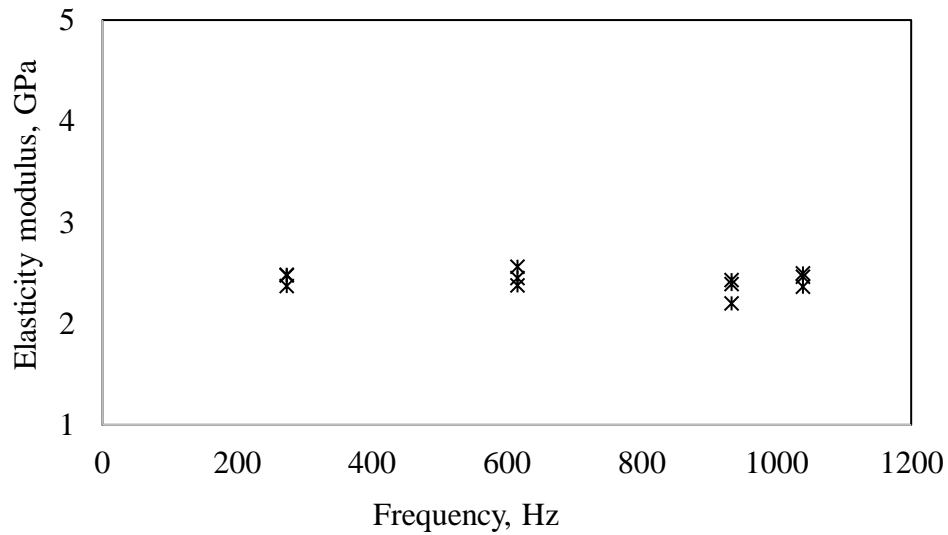


Fig. 7. Elasticity modulus of various luffa composites (volume fraction of fiber being 0.5 ± 0.1) as a function of frequency.

The modal damping levels of luffa composite structures for a volume fraction of resin of 0.5 ± 0.1 can be quite high (i.e., $2.6 \pm 0.05\%$), as seen in Fig. 8 [35, 45]. It is seen that the modal loss factors of luffa composite samples are higher than those of conventional materials, such as glass composites commonly used in practice, aluminum and steel [55, 74, 75], though the modal loss factors of the luffa composite samples are less than those of conventional viscoelastic damping materials [76].

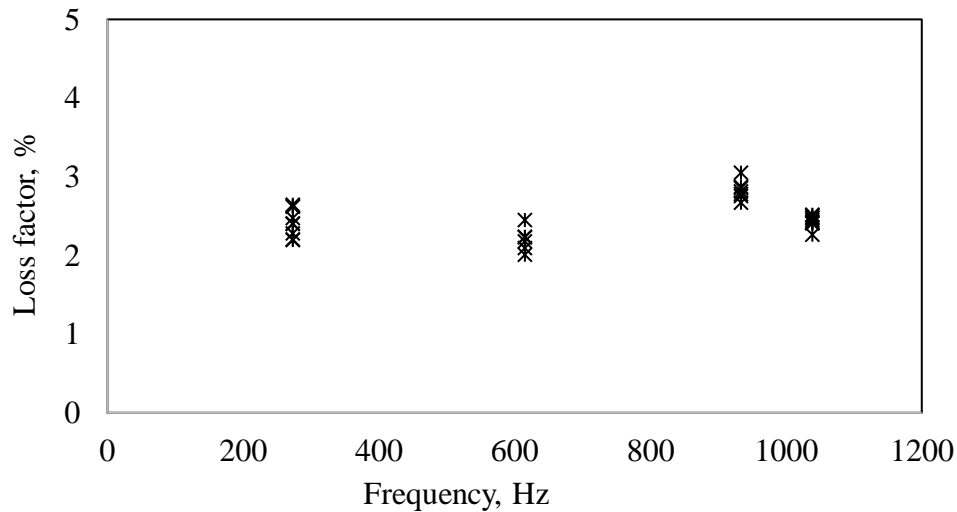


Fig. 8. Modal damping levels of various luffa composites (volume fraction of fiber being 0.5 ± 0.1).

Results show that luffa sponge material exhibits remarkable strength and superior energy absorption capabilities being comparable to some metallic cellular materials such as aluminum foams and Ni–P microlattices. The strength of luffa sponge is better than most other available cellular materials with a similar density range, such as expanded Polystyrene foams and Ni–P microlattices [69]. For example, due to the high strength-to-weight ratio of its cellular materials, luffa sponge can be used as a packaging material or an energy dissipation material [69]. It has been reported that it is possible to produce medium density fiberboards by using luffa fiber at various percentages as a mixture with the wood [37].

5 Conclusion

This chapter presents an overview of the acoustic and mechanical behaviors of luffa-fiber, reinforced biocomposites. Problems inherent to the nature of green fibers, such as structural differences and defects in luffa cylindrica samples, are introduced. Acoustic properties, such as sound absorption and transmission loss of luffa fibers and composites, as well as the acoustic identification methods, are presented. Mechanical properties, such as

damping and elasticity of luffa composites, as well as identification methods, are revealed. Finally, the potential of the use of luffa material in practical applications is evaluated.

There are some variations inherent in the nature of green fibers with regard to the structural properties of luffa plants, such as mass and density. For example, the standard deviation between the mass of fifteen different luffa plants with the same dimensions is around 25%. However, the results show that the deviations in the acoustic and elastic properties of the luffa composites are much lower. Thus, it can be stated that luffa composites with similar acoustic and elastic properties can be produced without any special selection of luffa cylindrical samples in order to homogenize the batch of fibers. However, a preliminary selection of raw samples is required if it is desired that the acoustic and mechanical properties of the luffa composites will only have small variations (e.g., less than five percent).

Accurate sound absorption and transmission loss levels of luffa fibers and composites can be determined using impedance tube experiments.

- Luffa fibers have superior sound absorption properties. For example, a thin luffa fiber (i.e., thickness being 10 mm) has an average sound absorption coefficient of 0.3 for 0.5 - 6 kHz. Sound absorption coefficient increases when a perforated linen is used.
- Luffa composites with higher sound absorption coefficients compared to luffa fiber samples can be obtained when the correct volume fraction of fiber is determined. However, sound absorption coefficients of a luffa composite decrease with an increasing volume fraction of resin after a specific ratio.
- Transmission loss levels of luffa fibers are acceptable and the level in general increases with an increasing volume fraction of matrix. For example, the transmission loss level is 6 and 25 dB for a luffa composite, thickness being 10 mm with a fiber/epoxy ratio of 4 and 1.5, respectively, for 0.5 - 6 kHz. The transmission

loss level of luffa composite with a volume fraction of matrix at 1.5 is comparable to cement and glass plate commonly used in practice.

Mechanical properties such as elasticity and damping levels of luffa composites can be identified by first determining the modal parameters of test samples. For this purpose, the frequency response functions using contact or non-contact excitation and response sensors are measured. Then, modal frequencies and loss factors of luffa composites can be identified by analyzing the measured frequency response functions and a modal analysis method. Using the measured modal parameters and a theoretical formulation of the test structure, elastic properties can be identified.

- The measured damping levels of luffa composite structures for a considerably low volume fraction of resin can be quite high. For example, the average loss factor is $2.6 \pm 0.05\%$ for a volume fraction of fiber at 0.5 ± 0.1 and frequency range 0.1 - 1 kHz.
- The elasticity moduli of luffa composite structures for a low volume fraction of matrix are comparable to elastomers and plastics, and the elastic properties of luffa composites do not have a large variation with respect to frequency. For example, the average elasticity modulus is 2.5 ± 0.1 GPa for a volume fraction of fiber at 0.5 ± 0.1 and frequency range 0.1 - 1 kHz.

That the vibro-acoustic properties of luffa fibers and composites will be able to be used in practical applications looks promising. The high damping and acceptable elastic properties of luffa composites may allow them to be used in many sound and vibration isolation applications, including airplanes, automobiles and yachts, to enhance the use of environmentally-friendly materials. Luffa composites also have the potential to be used in architectural applications, such as concert saloons, to absorb reverberant noise and provide sound transmission, as their sound absorption and isolation capabilities are better than many

green composites. For example, but not limited to, produced composite plates could prove a suitable material for decoration purposes. Overall, the superior acoustic and mechanical features of luffa composites, as well as their low density, low cost, and biodegradability, make luffa composites very attractive for various noise and vibration-control engineering applications.

Acknowledgment

We thank Dr. Caroline Fell Kurban, director of the Center for Excellence in Learning and Teaching at MEF University.

References

- [1] Baier H. Design of Fiber Composite Aerospace Structures Under Vibration Loads. *Comprehensive Composite Materials II*. Oxford: Elsevier; 2018. p. 351-66.
- [2] Baltopoulos A, Kostopoulos V. Multifunctional carbon nanotube-based nanocomposites for aerospace applications. *Multifunctionality of Polymer Composites*. Oxford: William Andrew Publishing; 2015. p. 448-90.
- [3] Brooks R, Shanmuga Ramanan SM, Arun S. Composites in Automotive Applications: Design. *Reference Module in Materials Science and Materials Engineering*: Elsevier; 2017.
- [4] Grande DH, Greist S, Jessie T, Daniel J. Composites in Sports Applications. *Comprehensive Composite Materials II*. Oxford: Elsevier; 2018. p. 469-526.
- [5] Ilcewicz L, Ashforth C. Scaling Crucial to Integrated Product Development of Composite Airframe Structures. *Comprehensive Composite Materials II*. Oxford: Elsevier; 2018. p. 26-90.
- [6] Komus A, Beley N. Composite Applications for Ground Transportation. *Comprehensive Composite Materials II*. Oxford: Elsevier; 2018. p. 420-38.
- [7] Kretsis G, Johnson AF. Conceptual Design of Composite Structures. *Comprehensive Composite Materials II*. Oxford: Elsevier; 2018. p. 26-46.
- [8] Megson THG. Laminated composite structures. *Introduction to Aircraft Structural Analysis (Third Edition)*: Butterworth-Heinemann; 2018. p. 685-735.
- [9] Ramanujam BTS, Annamalai PK. Conducting polymer-graphite binary and hybrid composites: Structure, properties, and applications. *Hybrid Polymer Composite Materials*: Woodhead Publishing; 2017. p. 1-34.
- [10] Karmakar B. Glasses and glass-ceramics for biomedical applications. *Functional Glasses and Glass-Ceramics*: Butterworth-Heinemann; 2017. p. 253-80.
- [11] Akkus N, Genc G. Influence of pretension on mechanical properties of carbon fiber in the filament winding process. *The International Journal of Advanced Manufacturing Technology*. 2017;91(9-12):1-7.
- [12] Bodros E, Pillin I, Montrelay N, Baley C. Could biopolymers reinforced by randomly scattered flax fibre be used in structural applications? *Composites Science and Technology*. 2007;67(3-4):462-70.

- [13] Bos HL, Müssig J, Oever VD, Martien JA. Mechanical properties of short-flax-fibre reinforced compounds. *Composites Part A: Applied Science and Manufacturing*. 2006;37(10):1591-604.
- [14] Wambua P, Ivens J, Verpoest I. Natural fibres: can they replace glass in fibre reinforced plastics? *Composites Science and Technology*. 2003;63(9):1259-64.
- [15] Faruk O, Bledzki AK, Fink H-P, Sain M. Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*. 2012;37(11):1552-96.
- [16] Koronis G, Silva A, Furtado S. Applications of Green Composite Materials. In: Kalia S, editor.: John Wiley & Sons; 2016.
- [17] Baley C. Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase. *Composites Part A: Applied Science and Manufacturing*. 2002;33(7):939-48.
- [18] Boynard CA, D'Almeida JRM. Morphological characterization and mechanical behavior of sponge gourd (*Luffa cylindrica*) - Polyester composite materials. *Polym-Plast Technol*. 2000;39(3):489-99.
- [19] Georgios K, Silva A, Furtado S. Applications of Green Composite Materials, in Biodegradable Green Composites. In: Kalia S, editor.: John Wiley & Sons, Inc, Hoboken, NJ.; 2016.
- [20] Satyanarayana KG, Arizaga GGC, Wypych F. Biodegradable composites based on lignocellulosic fibers—An overview. *Progress in Polymer Science*. 2009;34(9):982-1021.
- [21] Le Duigou A, Bourmaud A, Gourier C, Baley C. Multi-scale shear properties of flax fibre reinforced polyamide 11 biocomposites. *Composites Part A: Applied Science and Manufacturing*. 2016;85:123-9.
- [22] Aziz SH, Ansell MP. The effect of alkalization and fibre alignment on the mechanical and thermal properties of kenaf and hemp bast fibre composites: Part 1 – polyester resin matrix. *Composites Science and Technology*. 2004;64(9):1219-30.
- [23] Murali Mohan Rao K, Mohana Rao K, Ratna Prasad AV. Fabrication and testing of natural fibre composites: Vakka, sisal, bamboo and banana. *Materials & Design*. 2010;31(1):508-13.
- [24] Liu ZT, Yang YN, Zhang LL, Liu ZW, Xiong HP. Study on the cationic modification and dyeing of ramie fiber. *Cellulose*. 2007;14(4):337-45.
- [25] Genc G, El Hafidi A, Gning PB. Comparison of the mechanical properties of flax and glass fiber composite materials. *J Vibroeng*. 2012;14(2):572-81.
- [26] Tanobe VOA, Sydenstricker THD, Munaro M, Amico SC. A comprehensive characterization of chemically treated Brazilian sponge-gourds (*Luffa cylindrica*). *Polymer Testing*. 2005;24(4):474-82.
- [27] Gassan J, Bledzki AK. Modification methods on nature fibers and their influence on the properties of the composites. *Plastics*. 1996;42:2552-7.
- [28] Kocak D. The Study of the Effects of Different Chemical Compounds Applied on *Luffa Cylindrica* Fibres with the Help of Ultrasonic Energy. *J Polym Eng*. 2008;28(8):501-15.
- [29] Kocak D, Merdan N, Yuksek M, Sancak E. Effects of Chemical Modifications on Mechanical Properties of *Luffa cylindrica*. *Asian J Chem*. 2013;25(2):637-41.
- [30] Singh RC, Alam A, Singh V. Purification, characterization and chemical modification studies on a translation inhibitor protein from *Luffa cylindrica*. *Indian J Biochem Bio*. 2003;40(1):31-9.
- [31] Seki Y, Sever K, Erden S, Sarikanat M, Naser G, Ozes C. Characterization of *Luffa cylindrica* Fibers and the Effect of Water Aging on the Mechanical Properties of Its Composite with Polyester. *J Appl Polym Sci*. 2012;123(4):2330-7.
- [32] Jayamani E, Hamdan S, Rahman MR, Heng SK, Bin Bakri MK. Processing and Characterization of Epoxy/*Luffa* Composites: Investigation on Chemical Treatment of Fibers on Mechanical and Acoustical Properties. *Bioresources*. 2014;9(3):5542-56.

- [33] Kocak ED. The influence of ultrasonic energy on chemical treatment of surface properties and the properties of composites made of luffa cylindrical fiber-polyester resin. *Journal of Engineering Materials and Technology*. 2008;130(4):1-7.
- [34] Wang XJ, Shen JH, Zuo ZH, Huang XD, Zhou SW, Xie YM. Numerical investigation of compressive behaviour of luffa-filled tubes. *Compos Part B-Eng*. 2015;73:149-57.
- [35] Genc G, Koruk H. On the difficulties in manufacturing of luffa fibers reinforced bio-composites and variations in their dynamic properties. 45th International Congress and Exposition on Noise Control Engineering; 2016 August 21-24; Hamburg, Germany. 2016 p. 1566-70.
- [36] Saw SK, Ghose J, Sarkhel G. Potentiality of Luffa Fiber Used as Reinforcement in Polymer Composites. In: Jawaid M, Sapuan SM, Alothman OY, editors. *Green Biocomposites: Manufacturing and Properties*. Cham: Springer International Publishing; 2017. p. 293-310.
- [37] Akgul M, Korkut S, Camlibel O, Ayata U. Some Chemical Properties of Luffa and Its Suitability for Medium Density Fiberboard (MDF) Production. *Bioresources*. 2013;8(2):1709-17.
- [38] ASTM E 1050-12, Standard Test Method for Impedance and Absorption of Acoustical Materials Using A Tube, Two Microphones and A Digital Frequency Analysis System, (2012) New York.
- [39] ISO 10534-2, Acoustics - Determination of sound absorption coefficient and impedance in impedance tubes, Part 2: Transfer-function method, (2001).
- [40] Koruk H. An assessment of the performance of impedance tube method. *Noise Control Engineering Journal*. 2014;62(4):264-74.
- [41] Koruk H, Genc G. Investigation of the acoustic properties of bio luffa fiber and composite materials. *Materials Letters*. 2015;157(0):166-8.
- [42] ASTM E2611, Standard test method for measurement of normal incidence sound transmission of acoustical materials based on the transfer matrix method, (2017) West Conshohocken, PA.
- [43] Genc G, Koruk H. Investigation of the Vibro-Acoustic Behaviors of Luffa Bio Composites and Assessment of Their Use for Practical Applications. 23rd International Congress on Sound and Vibration: From Ancient to Modern Acoustics; 2016 July 10-14; Athens, Greece. 2016. p. 1-8.
- [44] Smith BJ, Peters RJ, Owen S. *Acoustics and Noise Control*. 2nd Edition ed: Addison Wesley Longman; 1996.
- [45] Genc G, Koruk H. Identification of the Dynamic Characteristics of Luffa Fiber Reinforced Bio-Composite Plates. *Bioresources*. 2017;12(3):5358-68.
- [46] Ng CF, Hui CK. Low frequency sound insulation using stiffness control with honeycomb panels. *Applied Acoustics*. 2008;69(4):293-301.
- [47] Siqueira G, Bras J, Dufresne A. Luffa Cylindrica as a Lignocellulosic Source of Fiber, Microfibrillated Cellulose, and Cellulose Nanocrystals. *Bioresources*. 2010;5(2):727-40.
- [48] Charlet K, Eve S, Jernot JP, Gomina M, Breard J. Tensile deformation of a flax fiber. *Procedia Engineering*. 2009;1(1):233-6.
- [49] Bodros E, Baley C. Study of the tensile properties of stinging nettle fibres (*Urtica dioica*). *Materials Letters*. 2008;62(14):2143-5.
- [50] Jumaidin R, Sapuan SM, Jawaid M, Ishak MR, Sahari J. Characteristics of thermoplastic sugar palm Starch/Agar blend: Thermal, tensile, and physical properties. *International Journal of Biological Macromolecules*. 2016;89:575-81.
- [51] Paiva MC, Bernardo CA, Edie DD. A comparative analysis of alternative models to predict the tensile strength of untreated and surface oxidised carbon fibers. *Carbon*. 2001;39(7):1091-101.

- [52] Bos HL, Van den Oever MJA, Peters OCJJ. Tensile and compressive properties of flax fibres for natural fibre reinforced composites. *J Mater Sci.* 2002;37(8):1683-92.
- [53] Hu W, Ton-That MT, Denault J. Tensile property characterization of natural fibers applying single fiber tensile test. *Abstr Pap Am Chem S.* 2009;238.
- [54] Do TT, Lee DJ. Analysis of tensile properties for composites with wrinkled fabric. *J Mech Sci Technol.* 2010;24(2):471-9.
- [55] Koruk H, Sanliturk KY. Identification and removal of adverse effects of non-contact electromagnetic excitation in Oberst Beam Test Method. *Mech Syst Signal Pr.* 2012;30:274-95.
- [56] Koruk H. Quantification and minimization of sensor effects on modal parameters of lightweight structures. *J Vibroeng.* 2014;16(4):1952-63.
- [57] Koruk H, Sanliturk KY. Damping uncertainty due to noise and exponential windowing. *Journal of Sound and Vibration.* 2011;330(23):5690-706.
- [58] Liew KM, Han JB, Xiao ZM. Vibration analysis of circular mindlin plates using the differential quadrature method. *Journal of Sound and Vibration.* 1997;205(5):617-30.
- [59] Sanliturk KY, Koruk H. Development and validation of a composite finite element with damping capability. *Composite Structures.* 2013;97:136-46.
- [60] Sanliturk KY, Koruk H. A new triangular composite shell element with damping capability. *Composite Structures.* 2014;118:322-7.
- [61] Alves C, Ferrão PMC, Silva AJ, Reis LG, Freitas M, Rodrigues LB, et al. Ecodesign of automotive components making use of natural jute fiber composites. *Journal of Cleaner Production.* 2010;18(4):313-27.
- [62] Jacob M, Thomas S, Varughese KT. Mechanical properties of sisal/oil palm hybrid fiber reinforced natural rubber composites. *Composites Science and Technology.* 2004;64(7-8):955-65.
- [63] Davies GC, Bruce DM. Effect of environmental relative humidity and damage on the tensile properties of flax and nettle fibers. *Text Res J.* 1998;68(9):623-9.
- [64] Duval A, Bourmaud A, Augier L, Baley C. Influence of the sampling area of the stem on the mechanical properties of hemp fibers. *Materials Letters.* 2011;65(4):797-800.
- [65] Liu L, Yu J, Cheng L, Qu W. Mechanical properties of poly(butylene succinate) (PBS) biocomposites reinforced with surface modified jute fibre. *Composites Part A: Applied Science and Manufacturing.* 2009;40(5):669-74.
- [66] Vilaseca F, Mendez JA, Pèlach A, Llop M, Cañigueral N, Gironès J, et al. Composite materials derived from biodegradable starch polymer and jute strands. *Process Biochemistry.* 2007;42(3):329-34.
- [67] Hao A, Zhao H, Chen JY. Kenaf/polypropylene nonwoven composites: The influence of manufacturing conditions on mechanical, thermal, and acoustical performance. *Composites Part B: Engineering.* 2013;54(0):44-51.
- [68] Papanicolaou GC, Psarra E, Anastasiou D. Manufacturing and mechanical response optimization of epoxy resin/*Luffa Cylindrica* composite. *J Appl Polym Sci.* 2015;132(22).
- [69] Shen J, Min Xie Y, Huang X, Zhou S, Ruan D. Mechanical properties of luffa sponge. *Journal of the Mechanical Behavior of Biomedical Materials.* 2012;15(0):141-52.
- [70] Paglicawan MA, Cabillon MS, Cerbito RP, Santos EO. Loofah Fiber as Reinforcement Material for Composite. *Philippine Journal of Science.* 2005;134(2):113-20.
- [71] Mohanty AK, Misra M, Hinrichsen G. Biofibres, biodegradable polymers and biocomposites: An overview. *Macromol Mater Eng.* 2000;276(3-4):1-24.
- [72] Yashwanth MK, Easwara Prasad GL, K. AN. Comparative Study on Properties of Coir and Sisal Fibre Reinforced Composites. *International Journal of Innovative Research in Science, Engineering and Technology.* 2016;5(9):922-6.

- [73] A. D. Nashif, D. I. G. Jones, Henderson JP. *Vibration Damping*. 1th ed. New York: Wiley-Interscience; 1985.
- [74] Prabhakaran S, Krishnaraj V, kumar MS, Zitoune R. Sound and Vibration Damping Properties of Flax Fiber Reinforced Composites. *Procedia Engineering*. 2014;97:573-81.
- [75] Koruk H, Dreyer JT, Singh R. Modal analysis of thin cylindrical shells with cardboard liners and estimation of loss factors. *Mech Syst Signal Pr*. 2014;45(2):346-59.
- [76] Koruk H, Sanliturk KY. Assesment of the complex eigenvalue and the modal strain energy methods for damping predictions. 18th International Congress on Sound and Vibration (ICSV 2011); 10-14 July; Rio de Janeiro, Brazil. 2011. p. 2182-9.

GCPRIS