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ACOUSTIC AND MECHANICAL PROPERTIES OF LUFFA FIBER REINFORCED BIOCOMPOSITES

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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].

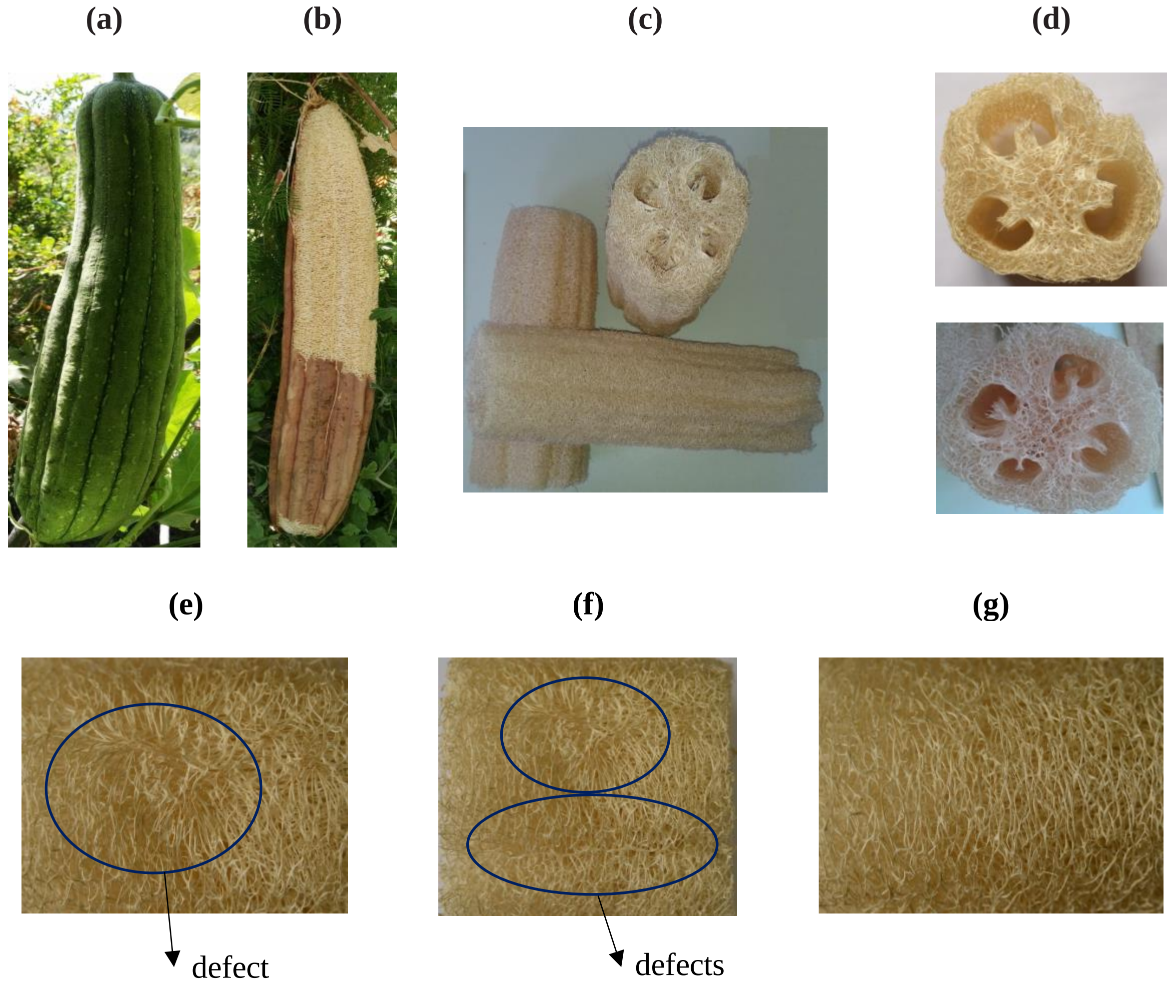

Fig. 1. Luffa fibers: (a) green plant, (b) dried plant, (c) fibrous structure, (d) the structure of luffa fiber with three and four holes, the luffa fibers (e-f) with and (g) without defects.

Table 1. Composition of luffa cylindirica 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 ^{0}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 though 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 $\widetilde{H}_{12}(\omega)$ 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:

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

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.

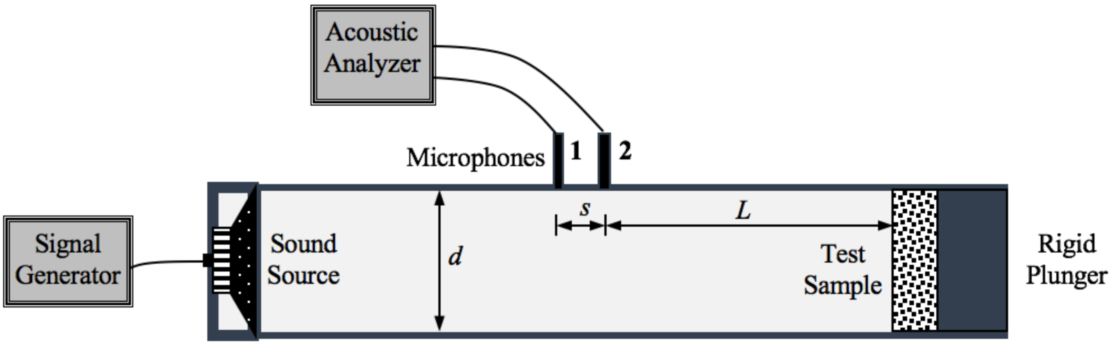

Fig. 2. The impedance tube with two microphones used to measure sound pressures inside the tube to determine sound absorption coefficients.

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].

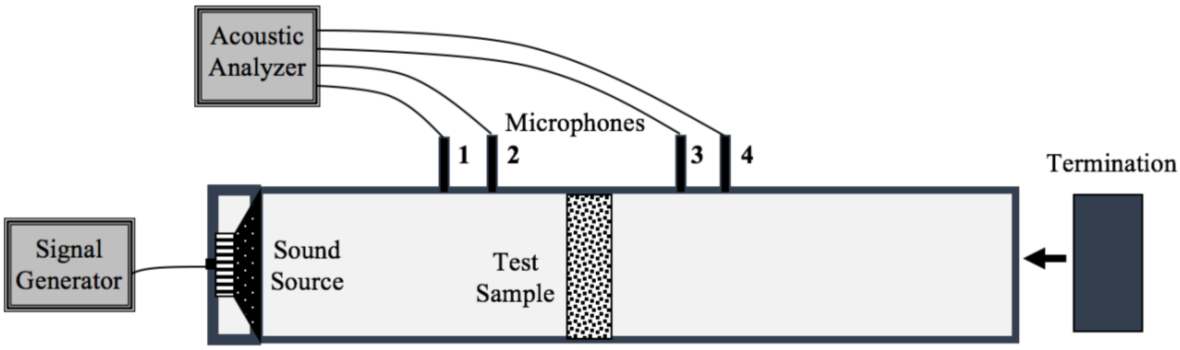

Fig. 3. The impedance tube with four microphones used to measure sound pressures inside the tube to determine transmission loss levels.

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].

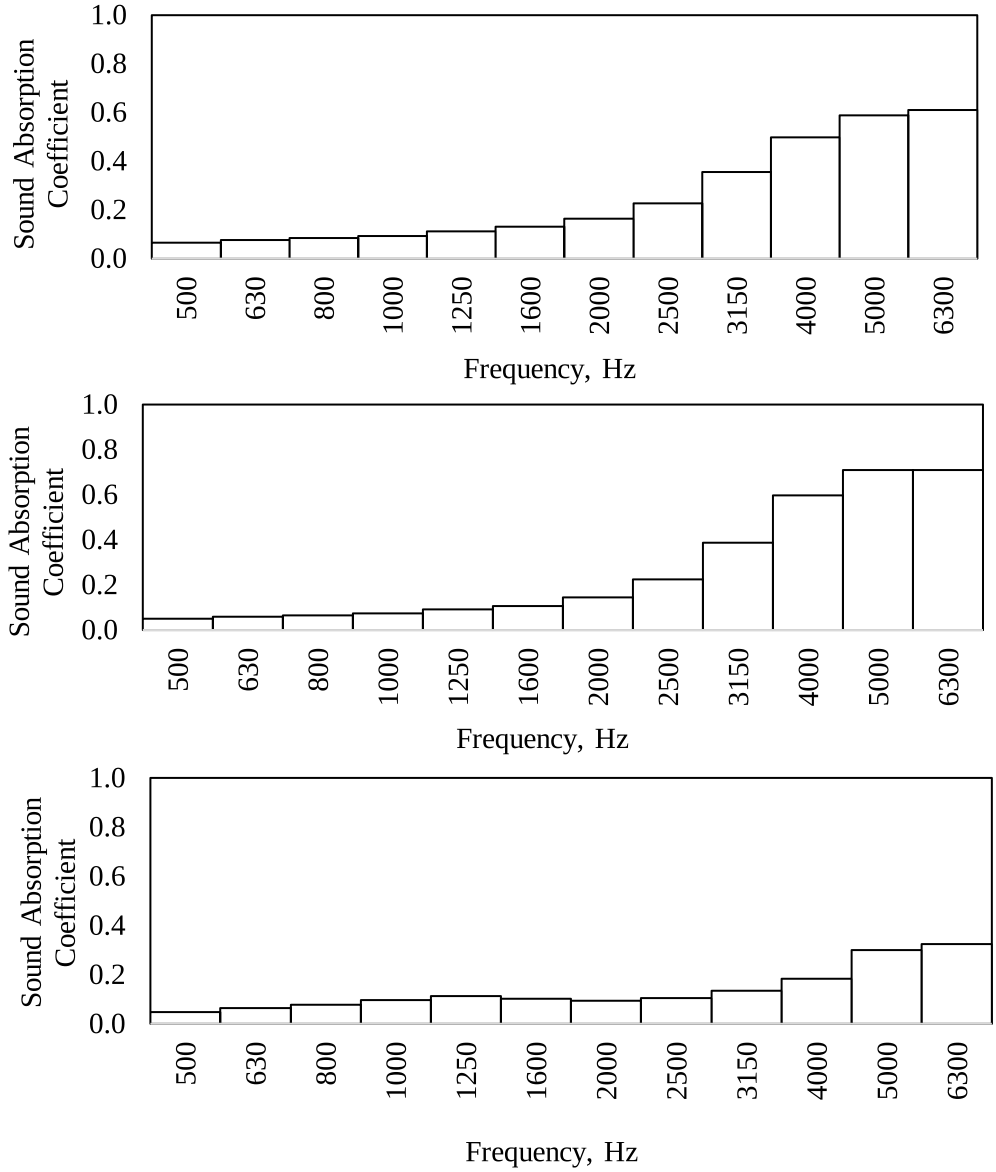

Fig. 4. Sound absorption coefficients of luffa samples with a thickness of about 10 mm: (a) luffa sample without matrix-epoxy, (b) luffa composite sample with high fiber/epoxy ratio (i.e., 4) and (c) luffa composite sample with low fiber/epoxy ratio (i.e., 1.5).

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].

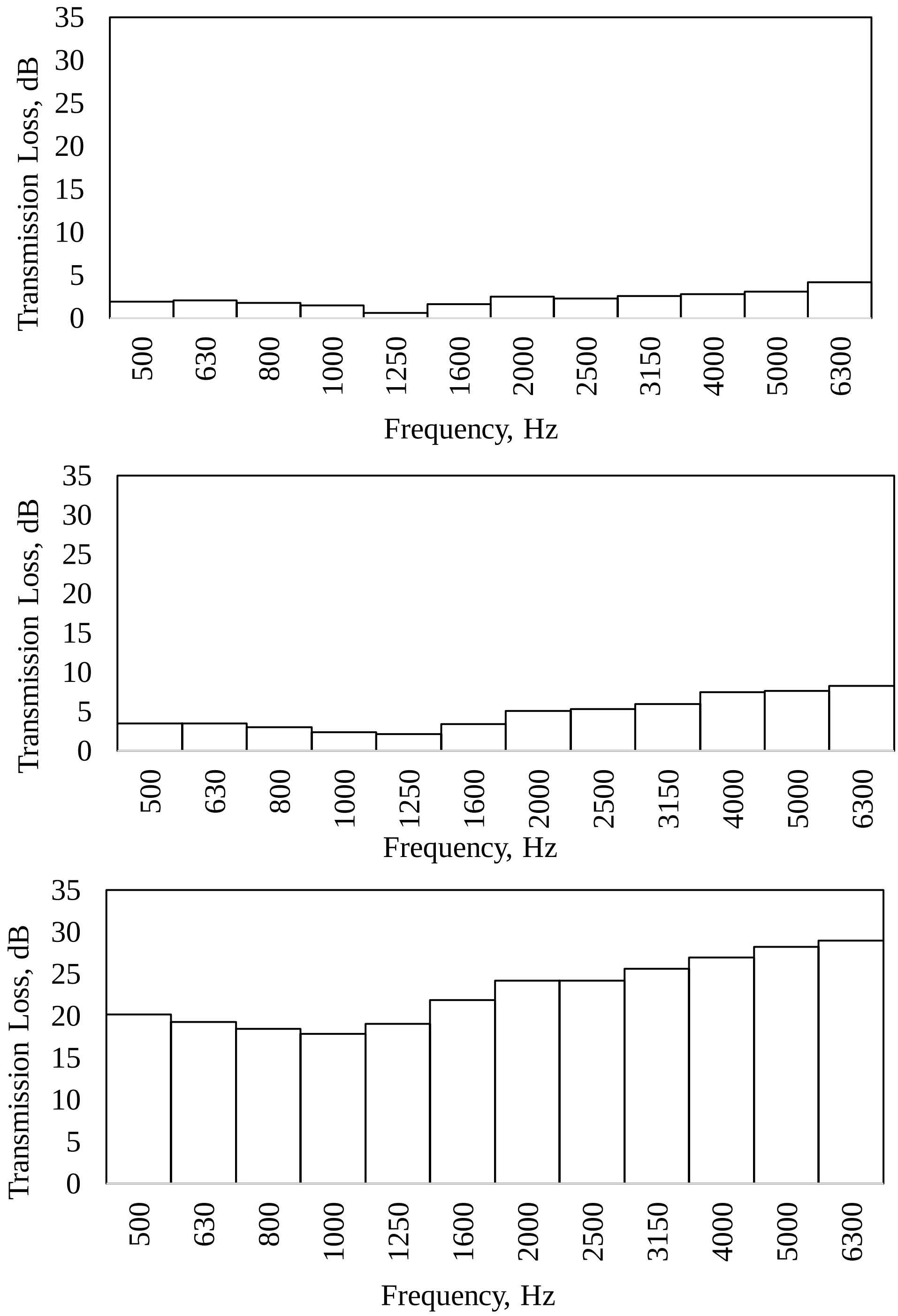

Fig. 5. Transmission loss levels of luffa samples with a thickness of about 10 mm: (a) luffa sample without epoxy, (b) luffa composite sample with high fiber/epoxy ratio (i.e., 4) and (c) luffa composite sample with low fiber/epoxy ratio (i.e., 1.5).

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/m^3, which is lower than some common natural fibers such as sisal (1260 to 1450 kg/m^3), hemp (1480 kg/m^3), coir (1250 kg/m^3), ramie (1500 kg/m^3), and cotton (1510 to 1600 kg/m^3) 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/m^3. 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:

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

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:

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

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.

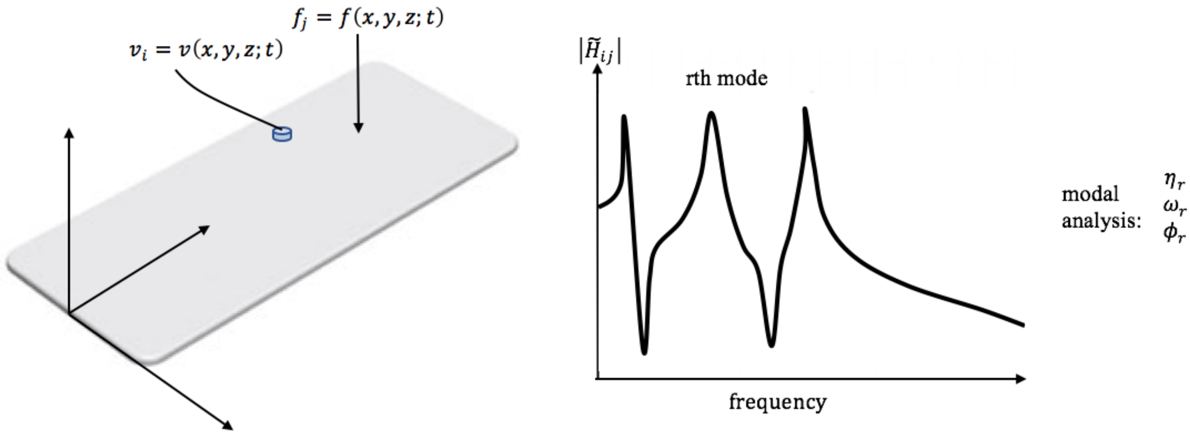

Fig. 6. Frequency response function ($\widetilde{H}_{ij}$) measurements for identification of modal parameters (η_r, ω_r, ϕ_r) of a test structure.

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:

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

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:

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

where R and h are the radius, and thickness of the plate, υ 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:

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

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 $\omega_r^2 = \mathrm{Real}(\lambda_r^2)$ and $\lambda_r = \mathrm{Imag}(\lambda_r^2)/\mathrm{Real}(\lambda_r^2)$. 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.

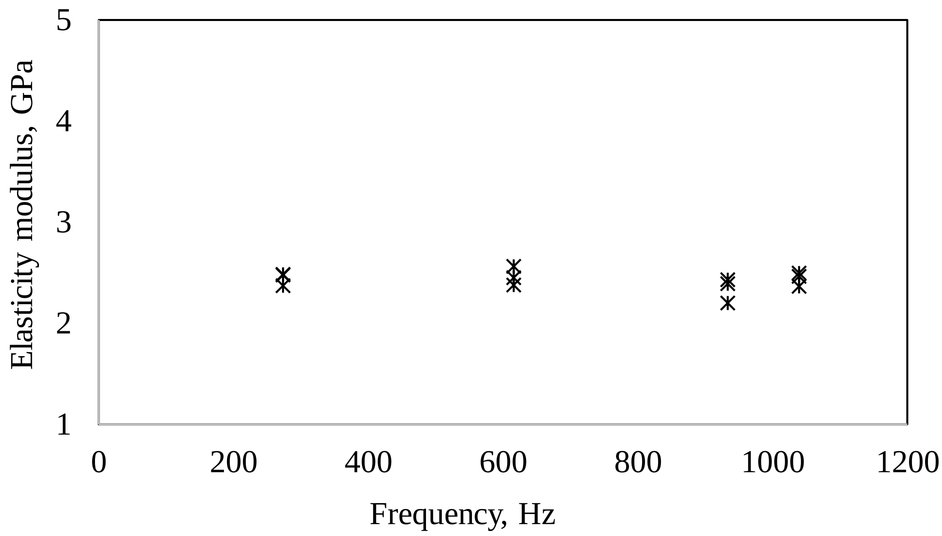

Fig. 7. Elasticity modulus of various luffa composites (volume fraction of fiber being 0.5 ± 0.1) as a function of frequency.

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 ± 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].

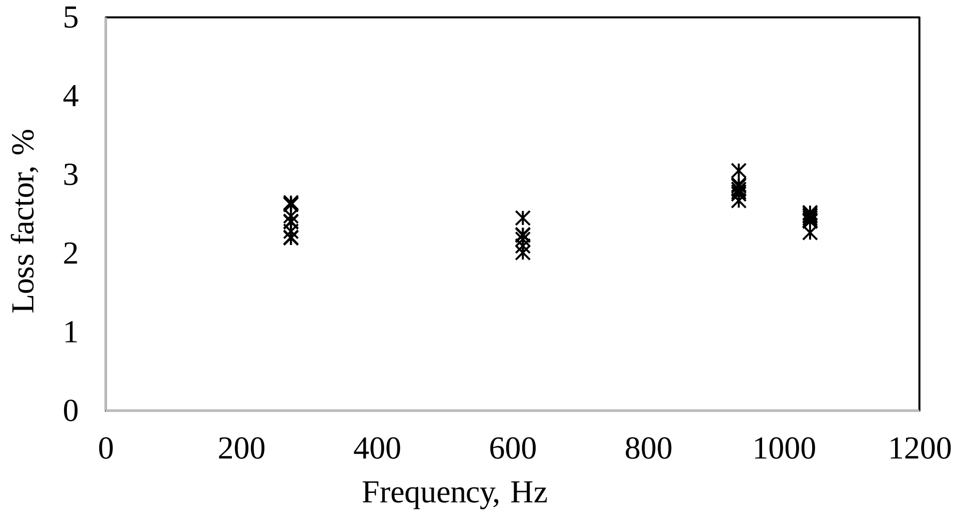

Fig. 8. Modal damping levels of various luffa composites (volume fraction of fiber being 0.5 ± 0.1).

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 expended 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 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 cylindrica 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 ± 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.

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