Journal of Cleaner Production 245 (2020) 118917

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A novel sound absorbing material comprising discarded luffa scraps and polyester fibers

Yuxia Chen [a, 1], Fangcheng Yuan [a, 1], Qin Su [a], Canming Yu [a], Kaiting Zhang [a], PanPan Luo [a], Dingfeng Hu [b], Yong Guo [a, *]

[a] College of Forestry & Landscape Architecture, Anhui Agricultural University, Hefei, 230036, China
[b] College of Material Science and Engineering, Nanjing Forestry University, Nanjing, 210037, China

ARTICLE INFO

Article history:
Received 20 December 2018
Received in revised form
30 August 2019
Accepted 16 October 2019
Available online 22 October 2019

Handling editor: Zheming Tong

Keywords:
Luffa scraps
Polyester fibers
Noise pollution
Porous structure
Sound absorption coefficient

ABSTRACT

For promoting the recycling of industrially discarded luffa resources and preventing environmental pollution caused by the incineration of luffa waste, abundant luffa scraps and environmentally friendly polyester fibers were used as raw materials to produce luffa fiber sound absorbing composites by the clean hot-pressing technology. Results revealed that the polyester fiber surface becomes rougher, with a large number of porous structures, affording a three-dimensional network after hot-pressing. Within the range of the test design, the sound absorption coefficient of the samples increased with increasing density, thickness, and distance of the back air gap. With the increase in the thickness from 2 cm to 6 cm, the average sound absorption coefficient of the material increased from 0.442 to 0.684, and the maximum sound absorption coefficient increased from 0.907 (4000 Hz) to 0.991 (1000 Hz). At back air gap distances of 0 cm, 1 cm, and 2 cm, their average sound absorption coefficients were 0.602, 0.606, and 0.645, respectively. At a density of 0.09 g/cm^3, a thickness of 4 cm, and a back air gap distance of 2 cm, the average sound absorption coefficient of the luffa fiber composite reached 0.645, revealing a high-efficiency sound absorbing material. In addition to exhibiting a good sound absorption performance, the luffa fiber composite exhibited a soft surface and good buffer performance. Moreover, compared to other plant fiber composites, the luffa fiber composite exhibited better performance for hygroscopic and moisture dissipation.

1. Introduction

Luffa, typically referred to as vegetable sponge or luffa cloth, is obtained from the matured dried fruit of Luffa cylindrica. As an emerging economic crop with abundant resources, the luffa sponge is cultivated in several countries for its fibers. Its plantation areas in China include Jiangxi, Henan, Sichuan, Guangdong, Jiangsu, Anhui, and other places (Chen et al., 2017). Traditionally, luffa sponges have been used for bathing and washing dishes. Meanwhile, the advance in science and technology has led to the wide application of luffa sponges in environmental engineering (Ahmadi et al., 2006), biotechnology (Roble et al., 2003), and industrial products (Shen et al., 2013). At the same time, consumers have been increasingly purchasing daily products processed from luffa. Currently, luffa bath products, including bath towels as well as sponge bath, have been widely applied in high-grade hotels. Among these products, the annual output and sales of luffa products in Cixi of Zhejiang Province amount to 800–1000 tons (Yan et al., 2010). However, due to the inhomogeneity of natural columnar luffa, a large amount of luffa scraps are directly discarded during processing. Most of the discarded luffa scraps are incinerated, leading to environmental pollution. In addition, a majority of the luffa products on the market are disposable, low added-value products. Luffa resources are severely wasted and underutilized. Hence, it is imperative to effectively recycle and utilize discarded luffa resources.

With the rapid development of the modern industrial process, noise pollution has severely affected daily life and caused considerable harm to the physical and mental health of humans (Black, 1986; Goines and Hagler, 2015). In recent years, the reduction of noise by using sound absorbing materials has been one of the most effective methods to prevent noise. Porous sound absorbing

* Corresponding author.
E-mail address: fly828828@163.com (Y. Guo).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.jclepro.2019.118917
0959-6526/

materials with a low density and a high porosity have become the most widely used sound absorbing materials (Huang and Liu, 2015; Huang et al., 2016). Currently, the matrix of porous sound absorbing material mainly includes metal (Arroyo et al., 2014; Hakamada et al., 2006; Zhang et al., 2009; Liu et al., 2017), inorganic materials (Duan et al., 2012; Hung et al., 2014), and organic polymers (Gama et al., 2017; Zhou et al., 2010). Apart from being high-energy-consumption and petrochemical products, these materials need to be added as chemical reagents, including adhesives and foaming agents, which are not conducive to the environment and human health. With increasing demands for health and sound environment quality, the single conventional sound absorbing material can no longer satisfy the requirements of environmental protection and high-efficiency sound absorption, while porous fibrous materials have been found to be one of the most effective methods for controlling noise (Liu et al., 2014; Sun et al., 2010). Natural fibers have been widely used in composite materials due to their high specific strength and specific modulus, cost-effectiveness, renewability, and biodegradability (Li et al., 2000). In addition, the hollow structure makes it a good sound insulation material (Netravali and Chabba, 2003). Hence, Luo and Li have proven that natural-fiber-reinforced composites exhibit better acoustic properties than their synthetic counterparts (Li et al., 2010). Hence, it is theoretically appropriate to use luffa with a natural three-dimensional reticular structure (Bal et al., 2004), high porosity (79%–93%), low density (0.02–0.04 g/cm^3), and high pore volume (21 g/cm^3) to prepare porous fiber sound absorbing materials (Chen et al., 2018a,b,c; Saeed and Iqbal, 2013). Currently, acoustic studies on natural fibers mainly focus on wood fibers (Dong et al., 2017; Wang et al., 2016), bamboo fibers (Koizumi et al., 2002; Pantjawati et al., 2015), and jute fibers (Bansod et al., 2016; Fatima and Mohanty, 2011; Zhou et al., 2016); however, these composites tend to exhibit a relatively high density as well as hardness and a small application range. In addition, the screening process of wood fibers is complex, and the utilization rate is low. Bamboo fiber is prone to mildew, affecting the product service life. Moreover, to obtain a porous structure, some additives, including foaming agents and adhesive, will be added to these plant-fiber sound absorbing composites by a complex production process, which is not conducive to the indoor environment and human health. To address the issues of the above plant-fiber sound absorbing composites, low-melting-point hollow polyester fiber was selected as the adhesive fiber herein. Polyester fiber is derived from polyethylene terephthalate (Gooch, 2011). It can not only bond luffa fibers but also increase the acoustical absorptivity and softness of the composites. Polyester fiber overcomes the disadvantages of inorganic fibers, environmental pollution, and damage to human health, which has been widely used in the field of sound absorbing materials because of its non-toxic nature, no pollution, high porosity, good air permeability, fatigue resistance, and elasticity and deformation resistance, corrosion resistance, insulation, and insect-proof and good sound absorption properties (Huang et al., 2012). The loss factor of this low-melting-point hollow polyester fiber, also exhibiting higher porosity, was greater than that of a typical polyester fiber; hence, the sound absorption coefficient of the former is greater than that of the latter (Na and Cho, 2010).

In this study, a novel environmentally friendly porous material was prepared by the clean hot-pressing technology using readily available luffa fibers and low-melting-point hollow polyester fibers as the matrix and adhesive, respectively. The fabrication of this composite was described, and its sound absorption property, compressive mechanical properties, hygroscopicity, and moisture dissipation were examined. In addition, the simple prediction of its application in future was described.

2. Materials and methods

2.1. Raw materials

Luffa scraps were recycled from Meier luffa Co., Ltd., (Jiangxi, China). Recycled luffa scraps were washed with water to remove the unwanted foreign particles from the fiber surface. Alkali treatment (85 °C; 1 h; 5% NaOH + 5%H_2O_2) was utilized for cleaning, affording a higher pore index for the treated fibers (Chen et al., 2018a,b,c). The low-melting-point hollow polyester fibers were purchased from Jilong Plastics Group Co., Ltd., (Guangzhou, China).

2.2. Composite fabrication

Fig. 1 shows the preparation process of the luffa fiber/polyester fiber composite. The fibrosis of luffa scraps was prepared using a grinder, affording 1-3-cm-long luffa fibers (Chen et al., 2018a,b,c). Polyester fibers were fed into the airlaid web-forming machine for opening, mechanical beating, and tearing to loosen the fiber bundle, followed by processing in a carding machine for combining. The luffa and polyester fibers were evenly mixed according to a mass ratio of 3:2 and combined using a carding machine. The mixture was weighed according to the three densities and needed to be paved according to certain specifications through a cross lapper, followed by hot-pressing by the hot press (6 min; 120 °C; 1 MPa). Finally, the sample was cooled and shaped by a cold press. No reagents were added in the process. Before the test, samples were placed in a constant temperature and humidity box for 24 h to adapt to the environment (see Fig. 2).

2.3. Methods

2.3.1. Sound absorption measurement

The sound absorption test was conducted according to the measurement of the sound absorption coefficient and acoustic impedance in the acoustic impedance tube part ii: transfer function method (GB/T 18696.2-2002, Fig. 3). The normal coefficient of the 1/3 octave was measured using a four-channel impedance tube system from the Beijing Prestige Company (SW 422, SW 477). The samples were cut into circles with diameters of 10 cm and 3 cm. The sample with a diameter of 10 cm was used to measure the sound absorption coefficient at a low-frequency stage (63–500 Hz, 250–1600 Hz). The sample with a diameter of 3 cm was used to measure the sound absorption coefficient at a high-frequency stage (1000 Hz–6300 Hz). Three samples were tested in each group; each sample was rotated twice. Six replicate measurements were carried out, and the average values were reported. For each variable, 1500 separate data points in the frequency range of 63–6300 Hz were obtained at every 4 Hz. The samples were placed in a constant temperature and humidity box (20 °C and 65% RH) for 24 h before the test under ambient conditions at room temperature at (25 ± 2) °C with an RH of (50 ± 5)% (see Fig. 4).

2.3.2. Quasi-static uniaxial compression test of samples

The quasi-static uniaxial compression test ($15 \times 15 \times 5$ cm^3) was performed using a universal testing machine (SHIMADZU AG-X Plus, Japan), and samples were placed in a constant temperature and humidity box (20 °C and 65% RH) for 24 h before test under ambient conditions at room temperature at (25 ± 2) °C with an RH of (50 ± 5)%. The crosshead speed was 3 mm min^{-1}. The maximum compression of the samples was 70%.

2.3.3. Hygroscopicity and moisture dissipation test

The hygroscopicity and moisture dissipation tests ($5 \times 5 \times 5$ cm^3) were carried out according to the ISO 22649: 2003,

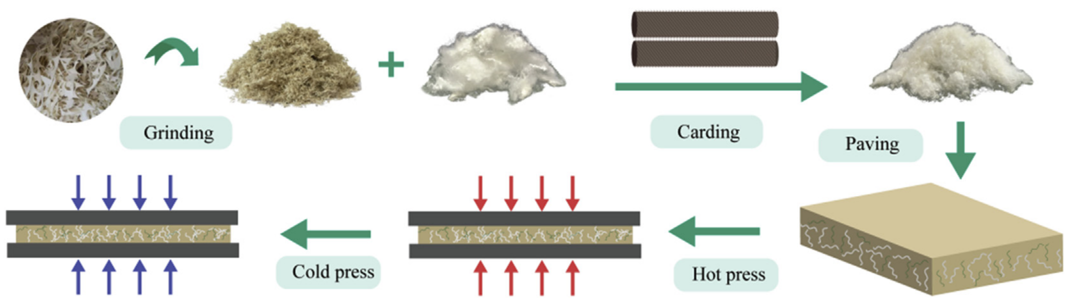

Fig. 1. Raw materials as well as the processing of the luffa fiber composite.

Fig. 2. Luffa fiber/Polyester fiber sound absorbing composites.

IDT. 50. The samples were placed in a constant temperature and humidity box at 20 °C and 65% RH for 24 h. Then, the sample weight was recorded as m_o. Furthermore, the samples were soaked in distilled water for 6 h and then taken out and drained until they had no dripping water. The sample weight was recorded as m_F at this time. After weighing, samples were placed in a constant temperature and humidity box, and the sample weight was tested every 1 or 2 h and recorded as m_R. The hygroscopicity and moisture dissipation were calculated using Equations (1) and (2), respectively, as follows:

$$C_A = \frac{m_F - m_0}{m_0} \tag{1}$$

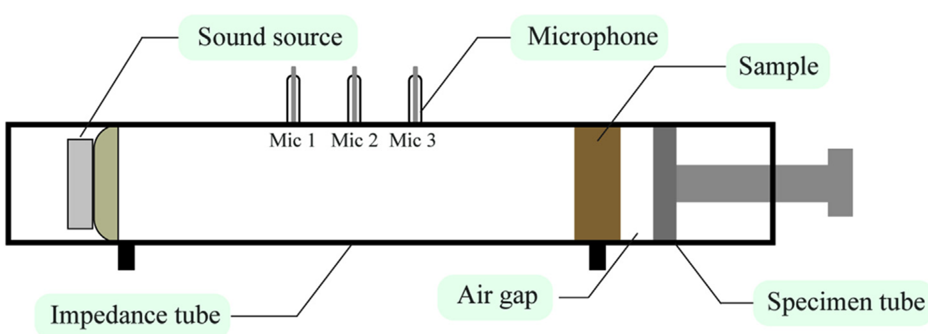

Fig. 3. Structure of an acoustic impedance tube.

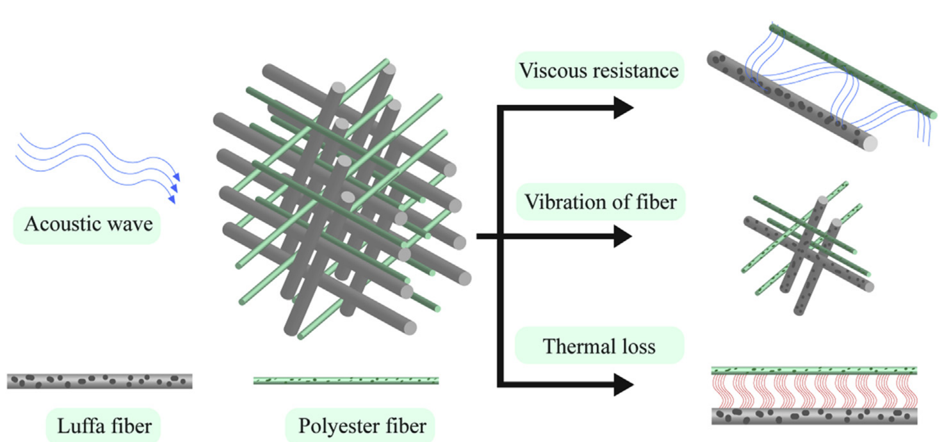

Fig. 4. Schematic of the sound absorbing mechanism.

$$C_A = \frac{m_F - m_0}{m_0} \tag{2}$$

where C_A represents the hygroscopicity of the sample (g/m^3); W_D represents the dissipation rate of the sample (%); m_o represents the original weight of the sample in the dry state (g); m_F represents the final weight of the sample in the wet state (g); and m_R represents the weight of the sample after environmental adjustment (g).

2.3.4. Scanning electron microscopy

To examine the morphology of the fiber surface and the adhesion morphology of the luffa and polyester fibers after hot-pressing technology, scanning electron microscopy (SEM) images were recorded on a Hitachi S-4800 microscope (Tokyo, Japan) at an accelerating voltage of 1.0 kV.

3. Results and discussion

3.1. Sound absorption properties

3.1.1. Fiber morphology

As can be observed from the SEM image, the luffa fiber surface was irregular, with a large number of pore structures (Fig. 5). With the propagation of acoustic waves into fibrous materials, the airflow in the fiber pores vibrated and rubbed against cell walls, generating viscous resistance that converted acoustic energy into thermal energy attenuation (Allard and Daigle, 1994; Yang and Li, 2012). A single luffa fiber comprises a bundle of hollow sub-fibers. The sub-fiber cell wall comprises millions of nano-fibrils (Li et al., 2010). These nano-sized fibrils would lead to additional vibrations, causing increased dissipation of sound energy. A large number of cell cavities in the luffa fiber are available, and the airflow in these cavities can be exchanged with the outside space via the pores on the cell wall or the damaged fiber ends. In addition, during fiber breakage, the fiber may be damaged, making it easier for gas in the cavity to exchange with the outside. Compared to traditional natural fibers, which are often used to make sound absorbing materials, the luffa fiber exhibits a better loss of sound energy because of the a rougher surface and higher porosity. Hence, a high-porosity luffa fiber is extremely suitable as the matrix for porous sound absorbing materials.

As polyester fibers are flexible and exhibit high viscoelasticity, the hysteresis effect and elastic deformation are generated under the action of acoustic waves. In addition, the acoustic wave energy will be dissipated on account of the different types of deformation of compression and tension, shear stress, and strain (Wang et al., 2013). Fig. 5 shows the low-melting-point polyester fiber microstructure: The low-melting-point polyester fiber surface exhibited a large number of pore structures after hot-pressing. When the acoustic wave is incident on the surface, the pore structure plays a major role in the absorption of sound energy. The acoustic wave can be increasingly converted into kinetic energy and internal energy, which are more conducive to sound absorption. Moreover, a large number of folds were generated on the polyester fiber surface after hot-pressing. The rougher surface increased the contact area between material and sound energy and extended the absorption range of sound energy, leading to improved sound absorption performance (Hur et al., 2005). After hot-pressing, the polyester fibers melted and combined with the luffa fibers, affording a three-dimensional network structure (Fig. 6). This structure was also conducive to the sound energy absorption.

3.1.2. Effect of density on the sound absorption property of the luffa fiber composite

Fig. 7 shows the sound absorption performance of the luffa/polyester fiber composite with different densities with a sample thickness of 4 cm and no back air gap. Density reflects the degree of compactness of materials. The higher the density of materials, the lower the probability of the acoustic waves to pass through the materials. A relevant study revealed that the effect of density on the sound absorption coefficient of porous materials exhibits a normal distribution; that is, an extremely low or extremely high density will adversely affect the sound absorption performance of porous materials (Wang, 2013) for two reasons: 1. At an extremely low density, the material gap increases, making the material extremely loose. Hence, when an acoustic wave passes through the porous

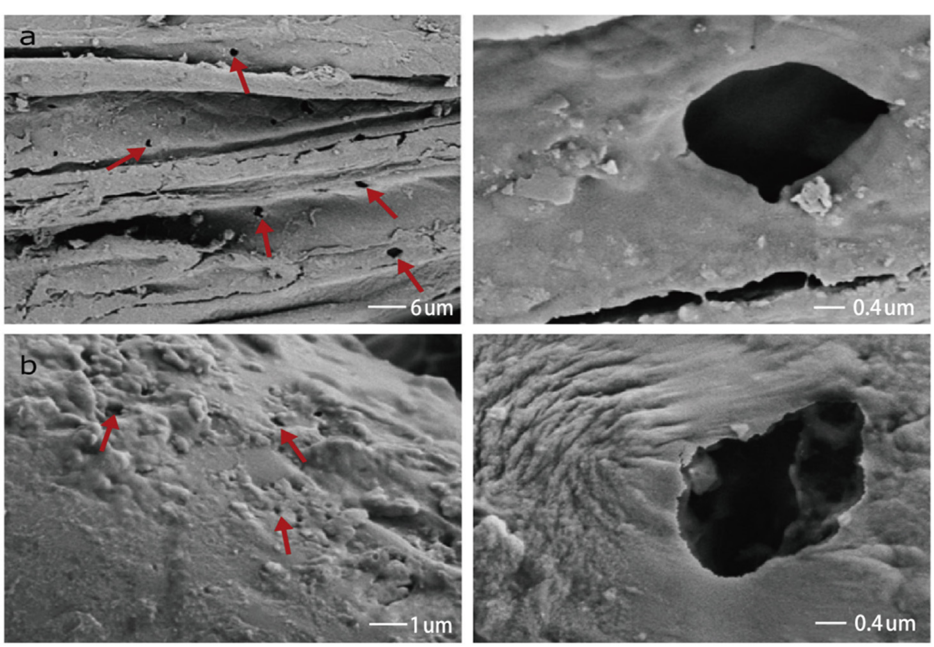

Fig. 5. a) SEM images of the luffa fiber surface; b) SEM images of the polyester fiber surface.

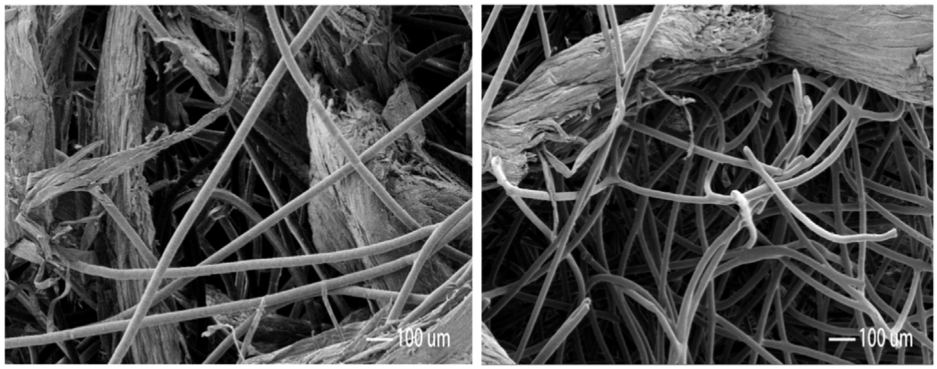

Fig. 6. SEM images of the luffa fibers and polyester fibers.

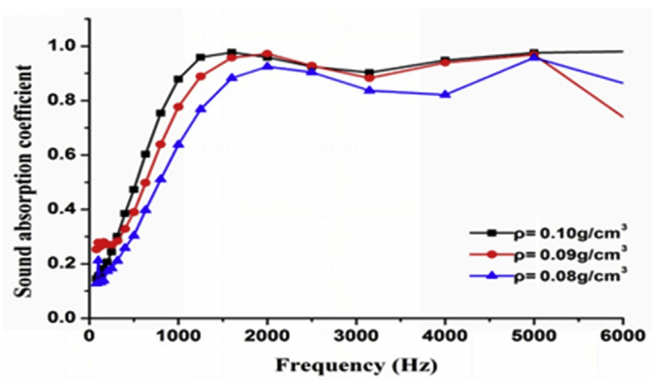

Fig. 7. Effect of density on the sound absorption coefficient of the luffa fiber composite.

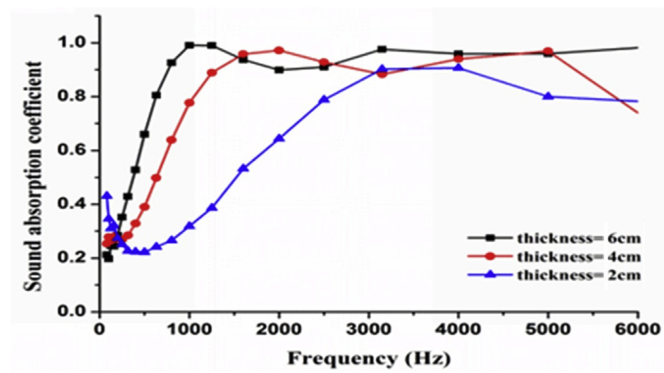

Fig. 8. Effect of the thickness on the sound absorption coefficient of the luffa fiber composite.

material, sufficient friction and vibration between the air and porous material are not available, leading to the decreased flow resistance and sound energy loss, even directly passing through the material. The friction and vibration between the fiber wall and airflow are not sufficient, resulting in the reduced loss of sound energy (Voronina, 1994); 2. If the density of the composite is extremely large, the acoustic wave cannot easily enter the material, and the advantages of porous sound absorbing materials will also cease to exist because of the low porosity.

The sound absorption coefficient of the luffa fiber composite increased with the density, especially in the medium-high frequency range (500 Hz–1500 Hz, Fig. 6). At a high density, the number of fibers per unit volume increased, and the porosity decreased; however, the pores formed between the fibers became smaller; the pore structure became more complex; the internal surface area increased; and the sound energy absorbed into the material exhibited increased damping, which was increasingly caused by the sound-wave-derived friction. Under the action of sound waves, the fiber molecular chains produce motion, consuming increased sound energy (Lafarge et al., 1997; Sagartzazu et al., 2008). 2. With increasing density, the maximum sound absorption coefficient of the composite increased and moved toward low frequency because with increasing material density, the flow resistance and resonance absorption coefficient also increased accordingly, and the low frequency exhibited selectivity to high flow resistance. The low-frequency sound absorption performance of the material significantly increased with density.

3.1.3. Effect of the thickness on the sound absorption coefficient of the luffa fiber composite

Fig. 8 shows the sound absorption performance of the luffa fiber composite with different thicknesses at a material density of 0.09 g/cm^3, with no back air gap. As can be clearly observed in Fig. 8, with increasing material thickness, the sound absorption coefficient increased. Results revealed that with increasing material thickness, the air permeability decreased, and the flow resistance improved, leading to enhanced sound absorption; increased loss of sound energy; and better material sound absorption performance (Küçük and Korkmaz, 2012). The lower the material thickness, the shorter the time and distance through the channel, and the lower is the energy the acoustic wave absorbed by the material; hence, the sound absorption coefficient of the material decreases (Kucuk and Korkmaz, 2015). Therefore, thickness is often considered to be an important factor that governs the sound absorption behavior of the material (Hassan and Rus, 2013). However, with the increase in the material thickness to a certain extent, the effect is not clear by the sole increase in the thickness to improve the material absorption performance (Su et al., 2009).

With material thicknesses of 2 cm, 4 cm, and 6 cm, the average sound absorption coefficients were 0.442, 0.602, and 0.684 respectively, with the maximum sound absorption coefficients of 0.907 (4000 Hz), 0.972 (2000 Hz), and 0.991 (1000 Hz), respectively. With the increase in the thickness by 2 times, the resonance absorption peak also shifted to the low-frequency by half a distance. For the same sound absorbing material, when the thickness is doubled, the first resonant frequency will move to low frequency by an octave (Xiang et al., 2011). The increased material thickness significantly improved the sound absorption performance at low frequency, and the sound absorption coefficient at high frequency slightly decreased. As the first resonant frequency of porous materials was proportional to the speed of sound wave propagation and inversely proportional to the material thickness, when the speed of sound wave propagation in the fiber material remained unchanged, the increased thickness led the shift of the first resonant frequency to low frequency (Wang et al., 2016). Therefore, when the thickness of material increased, the maximum sound absorption coefficient shifted toward low frequency. When it is greater than the first resonant frequency, with increasing thickness, acoustic peaks and acoustic valleys will be formed, leading to the fluctuation of the acoustic absorption performance, or even slight decline mainly because of the following reasons: 1. High-frequency acoustic waves are mainly absorbed on the material surface, while the low-frequency acoustic waves are absorbed inside the material; 2. The reflection of the material rear surface affected the secondary absorption of acoustic waves on the front surface of the material. With increasing thickness, the attenuation of acoustic waves in the material increased, and the secondary absorption on the front surface relatively decreased, leading to the decrease in the sound absorption performance for high-frequency sound waves (Wang et al., 2013).

3.1.4. Effect of the backed air gap on the sound absorption coefficient of the luffa fiber composite

Fig. 9 shows the sound absorption performance of the luffa fiber composite with different back air gaps with a material density of 0.09 g/cm^3 and a thickness of 4 cm. The average sound absorption coefficients were 0.602, 0.606, and 0.645 for back air gap distances of 0 cm, 1 cm, and 2 cm, respectively. The average sound absorption coefficient increased because the acoustic wave propagation distance increased with the back air gap distance, leading to the increasing conversion of sound energy into other forms of energy (Ismail et al., 2017). In addition, the peak of sound absorption coefficient wave shifted to the low-frequency direction. During absorption, sound energy was partly consumed by the resonance between the material and airflow. When producing resonance, only when the vibration frequency of the material particles was near the resonant frequency, an absorption peak was produced. The vibration frequency of airflow was clearly less than that of the composite with increasing air thickness, and the resonance frequencies of the material also decreased; hence, the peak of the sound absorption coefficient wave shifts to the low-frequency direction.

3.2. Compressive mechanical properties

Table 1 summarizes the compressive mechanical properties of luffa fiber composites with different densities, high-density columnar luffa, and low-density columnar luffa. As can be observed from the table, with increasing density of the composite, the compressive strength, peak stress, and energy absorption per unit volume increased. Among these properties, the compressive strength reflected the stress value of the weakest layer of the material being crushed. Due to the bonding of the low-melting-point polyester fiber, the compressive strength of the 0.10 g/cm^3 luffa fiber composite (0.04 MPa) material was far less than the maximum compressive strength of the high-density columnar luffa. The compressive strength of the low-density columnar luffa ranged from 0.005 to 0.034 MPa; this range is similar to that of the compressive strength of the luffa fiber composite (0.018−0.04 MPa), indicative of the relatively low hardness of the luffa fiber composite. Peak stress reflects the ratio of the energy absorption at the maximum energy absorption efficiency to the compact strain, which is an important index to characterize the energy absorption capacity of the material (Li et al., 2006). The peak stress of the columnar luffa and luffa fiber composites increased with density. The higher the peak stress, the better the energy absorption performance. The peak stress of high-density columnar luffa was 0.10−0.34 MPa; that of low-density columnar luffa was 0.009−0.034 MPa, while that of the 0.10 g/cm^3 luffa fiber composite was 0.017 MPa, only 5% of the maximum peak stress of high-density columnar luffa, indicative of the better flexibility and buffering performance of luffa fiber composite.

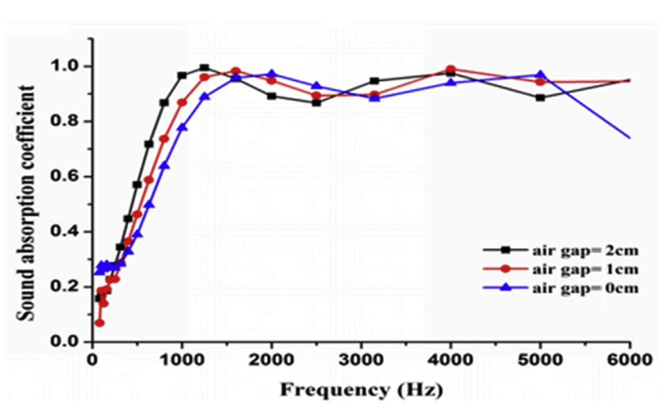

Fig. 9. Effect of the back air gap on the sound absorption coefficient of the luffa fiber composite.

3.3. Hygroscopicity and moisture dissipation property

Fig. 10 shows the comparison of the hygroscopicity and moisture dissipation of luffa fiber composites with other natural fiber composites (3D, jute and palm). With increasing density, the hygroscopicity of luffa fiber composites increased, while the moisture dissipation decreased (Fig. 10). The hygroscopicity of the 0.10 g/cm^3 luffa fiber composite was better than those of the other plant fiber composites, and its moisture dissipation was still significantly better than those of the other plant fiber composites. The 3D jute composite took nearly 70 h to attain a moisture dissipation ratio of 60%, while the highest-density luffa fiber composite exhibited a moisture dissipation ratio of greater than 95% in the same duration. Hence, the luffa fiber composite can effectively absorb moisture and release it into the air in time.

4. Conclusion

In this study, the discarded, underutilized, high-porosity luffa scraps and non-toxic low-melting-point hollow polyester fiber were used to prepare a porous material by the clean hot-pressing technology. Microstructure images were examined by scanning electron microscopy, and the sound absorption coefficient, compressive mechanical properties, the hygroscopicity, and moisture dissipation of the materials were subsequently investigated. Results revealed that (1) The polyester fiber surface becomes rough, with a large number of porous structures, affording a three-dimensional network after hot-pressing technology, which is conducive to sound energy absorption. (2) The sound absorption characteristics of the luffa fiber composite satisfy the general sound absorption law of the fibrous sound absorbing materials; That is, the sound absorption coefficient at low frequency is relatively low, and the sound absorption coefficient gradually increases with increasing frequency (within a certain frequency range). Within the density range of the test design, the overall sound absorption coefficient of the samples increases with density, and the sound absorption coefficient significantly increases, especially in the medium-high frequency region (500 Hz−1500 Hz). (3) With the increase in the thickness of the luffa fiber composite, the sound absorption coefficient of the material increases at all frequencies.

Table 1
Compressive mechanical properties of composites.

	Compressive strength ($\times 10^{-3}$) (MPa)	Peak stress ($\times 10^{-3}$) (MPa)	Energy absorption per unit volume ($\times 10^{-3}$) N/mm^2
A1	18.209 ± 0.649	4.397 ± 0.781	1.950 ± 0.441
A2	23.195 ± 1.702	9.347 ± 1.560	4.962 ± 0.599
A3	40.245 ± 4.983	16.881 ± 2.333	9.128 ± 1.271
B1	60.145−312.471	96.246−341.228	68.763−345.803
B2	5.467−33.894	8.500−33.929	10.203−37.275

Note: A1, A2, A3, B1, and B2 refer to 0.08 g/cm^3 luffa composite, 0.09 g/cm^3 luffa composite, 0.10 g/cm^3 luffa composite, high-density luffa sponge, and low-density luffa sponge, respectively.

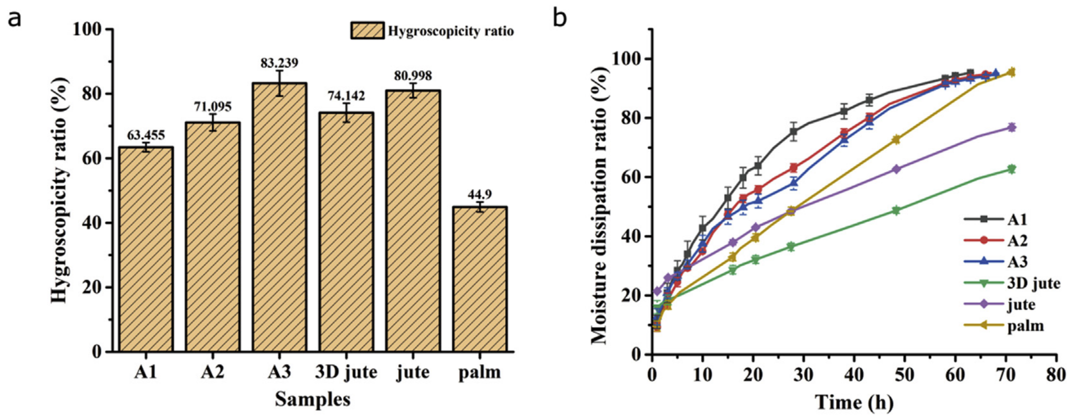

Fig. 10. a) Hygroscopicity of different plant fiber composites; b) Moisture dissipation of different plant fiber composites.

With the increase in the thickness from 2 cm to 6 cm, the average sound absorption coefficient of the material increases from 0.442 to 0.684, and the maximum sound absorption coefficient increases from 0.907 (4000 Hz) to 0.991 (1000 Hz). However, with the increase in the thickness of the material to a certain extent, the effect is not clear by the sole increase in the thickness of the material to improve the sound absorption performance. (4) The effect is similar to that of the increase in the material thickness via the increase in the back air gap distance. At back air gap distances of 0 cm, 1 cm, and 2 cm, the average sound absorption coefficients are 0.602, 0.606, and 0.645, respectively. The average sound absorption coefficients of the samples are improved. (5) The average absorption coefficient is the arithmetic mean of six sound absorption coefficient values at the central frequencies of 1 octave bandwidth ranging from 125 to 4000 Hz. Typically, sound absorbing materials are considered to have an average sound-absorbing coefficient of greater than 0.2. If the average sound absorbing coefficient was greater than 0.56, it is called a high-efficiency sound-absorbing material (Xue, 2002). At a density of 0.09 g/cm^3, a thickness of 4 cm, and a back air gap distance of 2 cm, the average sound absorption coefficient of the luffa fiber composite reached 0.645, corresponding to a high-efficiency sound absorbing material. Hence, this material is found to be suitable for applications in sound absorption materials. (6) In addition to exhibiting a good sound absorption performance, the luffa fiber composite exhibited a soft surface and good buffer performance. Moreover, compared to the other plant fiber composites, the luffa fiber composite exhibits better performance for hygroscopic and moisture dissipation, making it suitable for applications in sound absorbing cushion, buffer material, and filling materials of sleep products, with a wide application prospects.

In this study, the characteristics and application of this material were preliminarily examined, with the aim of using renewable luffa resources to manufacture an environmentally friendly sound absorbing material by a simple, clean manufacturing process, promote the recycling of industrially discarded luffa resources, and add value to luffa products. The novel production took an overall preventive environmental strategy in terms of the raw materials, production process, and products, eliminated potential harm to humans and the environment, and maximized social and economic benefits. However, further in-depth research on its sound absorption mechanism, comprehensive performance, and process parameters is required, and these studies are of significance for the further development of this novel material and expansion of its application fields.

Acknowledgment

This study was supported by Anhui Provincial Natural Science Foundation under Grant Numbers 1808085MC69 and 1708085MC56, National Natural Science Foundation of China under Grant Number 31800477 and Anhui Agricultural University Innovation Foundation for Postgraduate under Grant Numbers 2019ysj-15.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.118917.

References

Ahmadi, M., Bonakdarpour, F.V., Mehranian, M., 2006. Empirical modeling of olive oil mill wastewater treatment using loofa-immobilized Phanerochaete chrysosporium. Process Biochem. 41, 1148−1154.
Allard, J.F., Daigle, G., 1994. Propagation of sound in porous media: modeling sound Absorbing Materials. J. Acoust. Soc. Am. 95, 2785.
Arroyo, E., Rayess, N., Weaver, J., 2014. Enhanced sound absorption of aluminum foam by the diffuse addition of elastomeric rubbers. J. Acoust. Soc. Am. 135, 2375.
Bal, K.E., Bal, Y., Lallam, A., 2004. Gross morphology and absorption capacity of cell-fibers from the fibrous vascular system of loofah (Luffa cylindrica). Text. Res. J.

74, 241–247.
Bansod, P.V., Mittal, T., Mohanty, A.R., 2016. Study on the acoustical properties of natural jute material by theoretical and experimental methods for building acoustics applications. Acoust Aust. 44, 1–16.
Black, F., 1986. Noise. J. Financ. 41, 529–543.
Chen, Y., Su, N., Zhang, K., Zhu, S., Zhao, L., Fang, F., Ren, L., Guo, Y., 2017. In-depth analysis of the structure and properties of two varieties of natural Luffa sponge fibers. Materials 10, 479.
Chen, Y., Zhang, K., Yuan, F., Zhang, T., Weng, B., Wu, S., Huang, A., Su, N., Guo, Y., 2018a. Properties of two-variety natural Luffa sponge columns as potential mattress filling materials. Materials 11.
Chen, Y., Su, N., Zhang, K., Zhu, S., Zhu, Z., Qin, W., Yang, Y., Shi, Y., Fan, S., Wang, Z., Guo, Y., 2018b. Effect of fiber surface treatment on structure, moisture absorption and mechanical properties of luffa sponge fiber bundles. Ind. Crops Prod. 123, 341–352.
Chen, Y., Yuan, F., Guo, Y., Hu, D., Zhu, Z., Zhang, K., Zhu, S., 2018c. A novel mattress filling material comprising of luffa fibers and EVA resin. Ind. Crops Prod. 124, 213–215.
Dong, W., Limin, P., Feng, F., Meihong, L., Boqi, S., 2017. Analysis of polyester/wood composite fiber needling mat sound absorption performance. Polym. Compos. 39 (11), 3823–3830.
Duan, C., Cui, G., Xu, X., Liu, P., 2012. Sound absorption characteristics of a high-temperature sintering porous ceramic material. Appl. Acoust. 73, 865–871.
Fatima, S., Mohanty, A.R., 2011. Acoustical and fire-retardant properties of jute composite materials. Appl. Acoust. 72, 108–114.
Gama, N., Rui, S., Carvalho, A.P.O., Ferreira, A., Barros-Timmons, A., 2017. Sound absorption properties of polyurethane foams derived from crude glycerol and liquefied coffee grounds polyol. Polym. Test. 62, 13–22.
Goines, L., Hagler, L., 2015. Noise pollution: a modern plague. South. Med. J. 100, 287–294.
Gooch, J.W., 2011. Polyester Fiber. Springer, New York.
Hakamada, M., Kuromura, T., Chen, Y., Kusuda, H., Mabuchi, M., 2006. High sound absorption of porous aluminum fabricated by spacer method. Appl. Phys. Lett. 88, 1697.
Hassan, N.N.M., Rus, A.Z.M., 2013. Influences of thickness and fabric for sound absorption of biopolymer composite. Appl. Mech. Mater. 393, 102–107.
Huang, Z., Liu, Y., 2015. Analysis of porous sound-absorbing materials in sound absorption and noise reduction of houses. Hous. Sci. 35 (11), 38–40.
Huang, C.H., Li, T.T., Chuang, Y.C., Lou, C.W., Chen, J.M., Lin, J.H., 2012. The primary study on polyester/polypropylene sound-absorption nonwoven fabric. Adv. Mater. Res. 554–556, 136–139.
Huang, Z., Zhe, D.U., Duan, Y.J., Sun, Y.Q., 2016. Research status and development of porous sound-absorbing materials. Chin. J. Urban & Rural Enterp. Hyg. 31 (11), 43–45.
Hung, T.C., Huang, J.S., Wang, Y.W., Lin, K.Y., 2014. Inorganic polymeric foam as a sound absorbing and insulating material. Constr. Build. Mater. 50, 328–334.
Hur, B.Y., Park, B.K., Ha, D.I., Um, Y.S., 2005. Sound absorption properties of fiber and porous materials. Mater. Sci. Forum 475–479, 2687–2690.
Ismail, A.Y., Omar, M.R., Hashim, M.A.A., Radzi, M.R.M., 2017. Improved sound absorption performance of nonwoven fabric using fabric facing and air back cavity. In: MATEC Web of Conferences, vol. 97. EDP Sciences, 01086.
Koizumi, T., Tsuijuchi, N., Adachi, A., 2002. The development of sound absorbing materials using natural bamboo fibers and their acoustic properties. High Perform. Struct. Mater. 27, 210–216.
Kucuk, M., Korkmaz, Y., 2015. Sound absorption properties of bilayered nonwoven composites. Fibers Polym. 16, 941–948.
Küçük, M., Korkmaz, Y., 2012. The effect of physical parameters on sound absorption properties of natural fiber mixed nonwoven composites. Text. Res. J. 82 (20), 2043–2053.
Lafarge, D., Lemarinier, P., Allard, J.F., Tarnow, V., 1997. Dynamic compressibility of air in porous structures at audible frequencies. J. Acoust. Soc. Am. 102, 1995–2006.
Li, Y., Mai, Y.W., Ye, L., 2000. Sisal fibre and its composites: a review of recent developments. Compos. Sci. Technol. 60, 2037–2055.
Li, Q.M., Magkiriadis, I., Harrigan, J.J., 2006. Compressive strain at the onset of densification of cellular solids. J. Cell. Plast. 42 (5), 371–392.
Li, Y., Luo, Y., Han, S., 2010. Multi-scale structures of natural fibres and their applications in making automobile parts. J. Biobased Mater. Bioenergy 4, 164–171.
Liu, S., Chen, W., Zhang, Y., 2014. Design optimization of porous fibrous material for maximizing absorption of sounds under set frequency bands. Appl. Acoust. 76, 319–328.
Liu, S., Li, A., Zhang, C., Li, D., 2017. High-temperature acoustic properties of porous titanium fiber metal materials. J. Cent. South Univ. 24, 1762–1766.
Na, Y., Cho, G., 2010. Sound absorption and viscoelastic property of acoustical automotive nonwovens and their plasma treatment. Fibers Polym. 11, 782–789.
Netravali, A.N., Chabba, S., 2003. Composites get greener. Mater. Today 6, 22–29.
Pantjawati, A.B., Juanda, E.A., Mulyanti, B., Mujtahid, A., Wiryadi, A., 2015. Development of sound absorbent material based on waste and bamboo fiber. Adv. Mater. Res. 1112, 367–370.
Roble, N., Ogbonna, J., Tanaka, H., 2003. A novel circulating loop bioreactor with cells immobilized in loofa (Luffa cylindrica) sponge for the bioconversion of raw cassava starch to ethanol. Appl. Microbiol. Biotechnol. 60, 671–678.
Saeed, A., Iqbal, M., 2013. Loofa (Luffa cylindrica) sponge: review of development of the biomatrix as a tool for biotechnological applications. Biotechnol. Prog. 29, 573–600.
Sagartzazu, X., Hervella-Nieto, L., Pagalday, J.M., 2008. Review in sound absorbing materials. Arch. Comput. Methods Eng. 15, 311–342.
Shen, J., Xie, Y.M., Huang, X., Zhou, S., Dong, R., 2013. Behaviour of luffa sponge material under dynamic loading. Int. J. Impact Eng. 57, 17–26.
Su, W., Qian, X.M., Li, X.Y., Liu, S.S., 2009. Influence of thickness and density of nonwoven sound-absorbing material on the sound-absorption capability. Adv. Mater. Res. 197–198, 440–443.
Sun, F., Chen, H., Wu, J., Feng, K., 2010. Sound absorbing characteristics of fibrous metal materials at high temperatures. Appl. Acoust. 71, 221–235.
Voronina, N., 1994. Acoustic properties of fibrous materials. Appl. Acoust. 42, 165–174.
Wang, J., 2013. Studying on the Sound-Absorbing Materials with Wood Fiber and Polyester Fiber [J]. Nanjing Forestry University, pp. 35–39.
Wang, J.F., Peng, L.M., Feng, F.U., Wang, D., 2016. Study on the Mechanical Properties of Sound-Absorbing Materials with Wood Fiber and Polyester Fiber, 43. China Forest Products Industry, pp. 8–12.
Wang, J., Peng, L., Feng, F.U., Zhang, Y., Liang, S., 2013. Study on the conditions of composite process of sound-absorbing materials with wood fiber and polyester fiber. J. Nanjing For. Univ. (Nat. Sci. Ed.) 37 (6), 132–136.
Xiang, H.F., Zhao, N., Jian, X.U., 2011. Recent progress in sound absorption materials based on polymer fibers. Polym. Bull. 34, 1–9.
Xue, J., 2002. Environmental Engineering [M]. China Forestry Publishing House.
Yan, L.I., Wen-Jia, L.I., Wang, Y.K., Long, M.H., 2010. Progress on application of loofah sponges in medicine, daily household cleaning and health products fields. Guangxi Agric. Sci. 41 (1), 85–87.
Yang, W., Li, Y., 2012. Sound absorption performance of natural fibers and their composites. Sci. China Technol. Sci. 55, 2278–2283.
Zhang, B., Chen, T., Lt, 2009. Calculation of sound absorption characteristics of porous sintered fiber metal. Appl. Acoust. 70, 337–346.
Zhou, H., Li, B., Huang, G., 2010. Sound absorption characteristics of polymer microparticles. Polym. Mater. Sci. Eng. 101, 2675–2679.
Zhou, Y., Sun, X., Zhang, X., Zhou, Y., Guo, Y., Jia, Y., 2016. Study on manufacturing technology and acoustic property of nonwoven jute fibers composites. J. Funct. Mater. 47 (11), 11131–11140.