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Research Article

Investigation of the Sound Absorption and Transmission Loss Performances of Green Homogenous and Hybrid Luffa and Jute Fiber Samples

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Abstract
In order to promote the use of natural fibers in noise and vibration applications, the properties of these structures should be fully identified. The sound absorption coefficients (SACs) and transmission losses (TLs) of green luffa fiber samples are thoroughly investigated and their acoustic performances are compared with the acoustic performances of green homogenous jute and hybrid jute/luffa fiber samples in this study. For this purpose, green homogenous luffa and jute fiber samples and their green hybrid fiber samples with different thicknesses (10, 20, 30, and 40 mm) are produced and their SACs and TLs are determined using the impedance tube method. First, the methods for the experimental identification of acoustic properties are presented and the variations in the measured acoustic properties are identified. After that, the effects of sample thickness on the acoustic performances of homogenous luffa as well as jute samples and their hybrid fiber samples as a function of frequency are explored. The thickness-dependent tendencies of the SACs and TLs of homogenous and hybrid luffa and jute fiber samples for low, medium and high frequency ranges are determined. Then, the acoustic performances of the homogenous and hybrid luffa and jute samples are compared and evaluated. The results and analyses for the acoustic properties of homogeneous luffa and jute fiber samples and their hybrid fiber samples for a variety of thicknesses and different frequencies presented here can be used to design homogenous as well as hybrid luffa and jute fiber structures in practical applications.

Keywords: Luffa, Jute, Hybrid fiber samples, Sound absorption, Transmission loss

1 Introduction

Natural fibers are biodegradable, non-hazardous and environmentally friendly [1]. Among many natural fibers, jute is the most produced worldwide [2]. Luffa, which grows in many regions around the world including Egypt and the Mediterranean part of Turkey, has received considerable attention from engineers and researchers in recent years [3]. In order to utilize these two materials effectively in practical applications, the acoustic properties of these two fibers and their hybrid samples of different thickness need to be thoroughly investigated. Although natural fiber composites with high mechanical strength can be obtained when a

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conventional resin (e.g., epoxy) is used [4], [5], there is currently an effort to obtain green natural fiber samples, i.e., natural fiber based structures with no resin or with natural resins [6]. Furthermore, there is currently an interest in producing hybrid structures that provide superior and combined properties compared to conventional monolithic samples [7].

Acoustic properties of many natural fiber based structures including jute and luffa have been studied in the literature. Investigations have been conducted to highlight the benefits of the use of natural fibers against synthetic substitutes in production areas [8], [9]. The sound absorption coefficients (SACs) and transmission losses (TLs), of either fiber or composite forms, of luffa and jute have been determined experimentally in some works [10]–[16]. The acoustic and mechanical properties of homogenous and hybrid jute and luffa fiber-reinforced epoxy composites with an epoxy/fiber ratio of 30–60% have been recently explored [5], [14]. It is seen that the SACs of these jute and luffa fiber-reinforced epoxy composites are quite low [5], [14]. Sengupta *et al.* determined that fiber thickness and density affect sound absorption as well as TL [17]. Suardana *et al.* investigated the effect of fiber volume fraction and panel thickness on the acoustic and mechanical properties of coconut fibers and it was shown that the optimum volume fraction needs to be determined for best sound absorption and mechanical strength [18]. Tahir *et al.* determined the effect of density and thickness on the acoustic properties of kapok natural fiber. They showed that sound absorption increases with sample density [19]. Lim *et al.* investigated the effect of thickness on the SACs of kenaf fibers. It was shown that the sound absorption of kenaf fiber samples increases with sample density and additional air gap further improves sound absorption at low frequencies [20]. Taban *et al.* investigated the sound absorption of coir fiber samples with different thicknesses. They showed that thicker coir fiber samples have better sound absorption performance and introducing air gap effectively enhance sound absorption [21]. While similar studies have been published for some other natural fibers, to the knowledge of the authors, the effect of thickness on the acoustic properties of green luffa fiber samples have not been investigated. Furthermore, the acoustic properties of green hybrid jute and luffa fiber samples have not been investigated in the literature before. Moreover, there is a need to determine the thickness-dependent tendencies of the SACs and TLs of jute and luffa fiber samples for different frequency ranges. The work presented here aims to fill these gaps in the literature.

The outline of the paper is as follows. The variations in the measured SACs and TLs of the nominally identical green homogenous and hybrid jute and luffa samples are presented. The effect of sample thickness on the acoustic performances of homogenous luffa as well as jute fiber samples and their hybrid fiber samples as a function of frequency is investigated. The thickness-dependent tendencies of the SACs and TLs of luffa and jute fiber samples for low, medium and high frequency ranges are determined. The acoustic performances of the homogenous and hybrid luffa and jute samples are compared and evaluated.

2 Materials and Methods

2.1 *Test samples*

The homogeneous jute and luffa fiber samples [Figure 1(a) and (b)] contain only one type of natural fiber material (i.e., jute or luffa) while there are three layers in each hybrid sample [Figure 1(c) and (d)]. As seen, the hybrid samples consist of layers of luffa and jute fibers in different orders. The first type of the hybrid samples has two thin layers of jute and a thick core layer of luffa and it is named as jute-luffa-jute, JLJ for short [Figure 1(c)]. The other type of hybrid sample has two layers of luffa and a core layer of jute and it is named as luffa-jute-luffa, LJL for short [Figure 1(d)]. It should be noted that the samples here contain no resin, i.e., they are 'green'. The layers are stacked to produce the samples. Since the dry fiber layers are stacked and no adhesive or matrix is used, the samples are porous and have air pockets. The diameter of the samples is chosen to be equal to the inner diameter of the impedance tube which is D = 29 mm. In order to investigate the effect of thickness on the acoustic properties, samples with different thicknesses were manufactured. Initially, samples were produced with a thickness of h = 10 mm. The thicknesses of the jute, luffa and jute layers in the hybrid JLJ samples are 1.6, 6.8, and 1.6 mm, respectively. The thicknesses of the luffa, jute and luffa layers in the hybrid LJL samples are 3.5, 3.0, and 3.5 mm,

Figure 1: Designs of the test samples: green homogeneous (a) jute and (b) luffa fiber samples, and their hybrid (c) jute-luffa-jute (JLJ) and (d) luffa-jute-luffa (LJL) fiber samples.

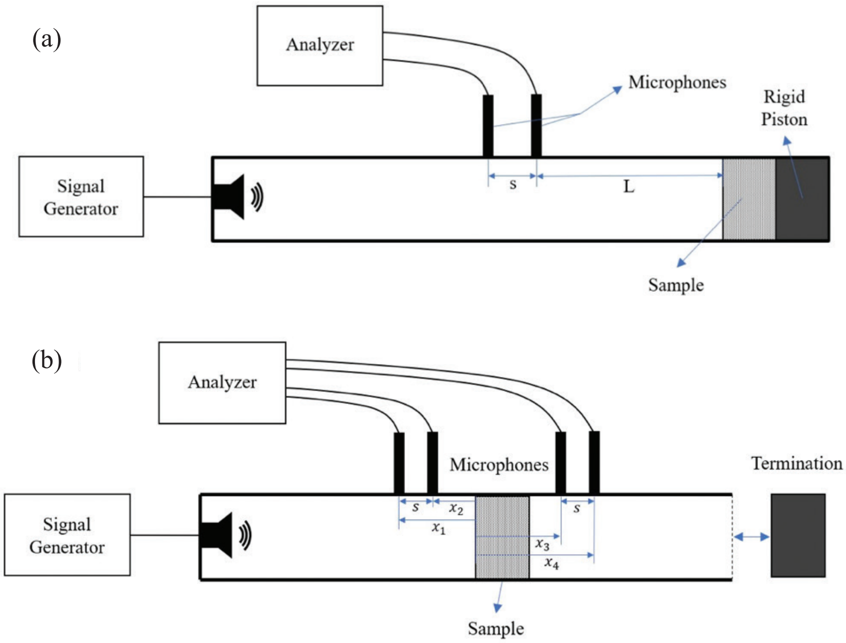

Figure 2: The schematic pictures of the experimental setups for the SAC (a) and TL (b) measurements.

respectively. The bulk densities of the samples, based on their measured masses and volumes, are ρ_b = 419.8, 73.6, 187.4, and 178.0 kg/m^3 for the jute, luffa, JLJ and LJL samples, respectively. The 10 mm fiber samples of the same kind were placed on top of each other and tied to obtain samples of h = 20, 30, and 40 mm thickness.

2.2 *Measurement of acoustic properties*

The schematic pictures of the experimental setups for the SAC and TL measurements based on the impedance tube method are shown in Figure 2. The Brüel&Kjaer 4206 (for SACs) and 4206T (for TLs) impedance tubes, Brüel&Kjaer 4187 microphones, Brüel&Kjaer 3560C analyzer and Brüel&Kjaer 276C power amplifier were used for the acoustic measurements in this study. For each case, the experiments were performed for a few nominally identical samples.

For the SAC measurements, a signal generator is used as a sound signal source and two microphones are used to measure the acoustic pressures at the depicted positions of the microphones. The SACs of the test sample are calculated using the tube dimensions and the measured acoustic transfer function. The input parameters for the calculation of SACs are the distance between two microphones s, the distance between the right microphone and the test sample L, the complex valued acoustic transfer function H_{12} (f) which is calculated from sound pressure signals p_1 to p_2 measured with two microphones, wave number $k = 2\pi f/c$ where c is the speed of the sound in the air and f is frequency. By using these parameters, the complex-valued normal incidence reflection coefficients $R(f)$ are calculated using [Equation (1)] [22]:

$$R = \frac{H_{12} - e^{-jks}}{e^{jks} - H_{12}} e^{2jk(s+L)} \tag{1}$$

(a)

(b)

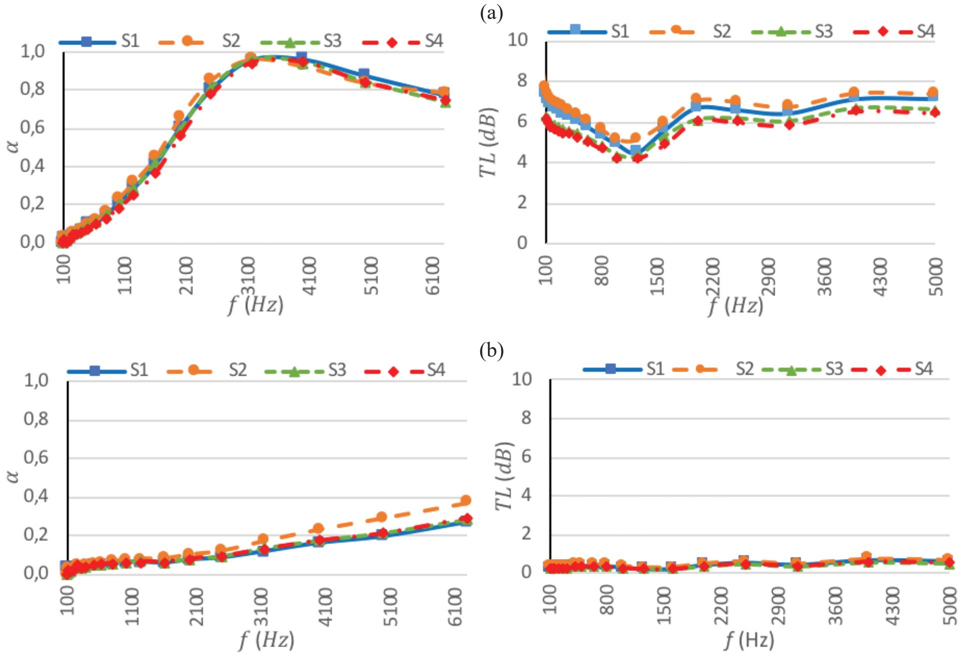

Figure 3: The SACs (left) and TLs (right) of four nominally identical homogenous (a) jute and (b) luffa fiber samples (thickness: 10 mm).

By using the normal-incidence reflection coefficients, the normal-incidence SACs are calculated via [Equation (2)] [22]:

$$\alpha = 1 - |R|^2 \tag{2}$$

For the TL measurements, a similar setup for the SAC measurements is used, however additional two microphones are positioned between the test sample and termination this time. The input parameters for the calculation of the normal-incidence sound TLs are the distance between each pair of microphones s, transfer functions $H_{12}(f)$ and $H_{34}(f)$ which are calculated from sound pressure levels p_1 to p_2 and p_3 to p_4, respectively, the ratio between upstream (S_u) and downstream (S_d) auto-spectrums $H_t = |S_d/S_u|^{0.5}$, wave number k and the positions of the individual microphones x_1, x_2, x_3 and x_4 with front face of the sample as one-dimensional reference point. The mathematical expression for the TLs of the test sample is calculated using [Equation (3)] [22]:

$$TL = 20\log\left|\frac{e^{jks} - H_{12}}{e^{jks} - H_{34}}\right| - 20\log|H_t| \tag{3}$$

3 Variations in the Measured Acoustic Properties

In contrast to synthetic fibers, each natural fiber in a batch/plant can have different individual mechanical and physical properties. Furthermore, current manufacturing methods for natural fiber-based structures are not very precise. In addition, the diameter of the test sample may not match precisely with the inner diameter of the impedance tube and the mounting condition of the test sample affect the measured acoustic properties. Therefore, first, variations in the acoustic properties of natural fiber-based structures are determined and presented in this section.

The experimentally identified SACs and TLs of four nominally identical homogenous jute and luffa fiber samples are determined and presented in Figure 3. It is seen that, although there are some small variations, both the SAC and TL experiments for homogenous jute and luffa fiber samples can be considered as repeatable. The average values and associated deviations of the SACs for the four jute samples studied are determined as 0.040 ± 0.005, 0.268 ± 0.024, and 0.822 ± 0.023 for 500, 2000, and 5000 Hz, respectively. On the other hand, the average values and standard deviations of

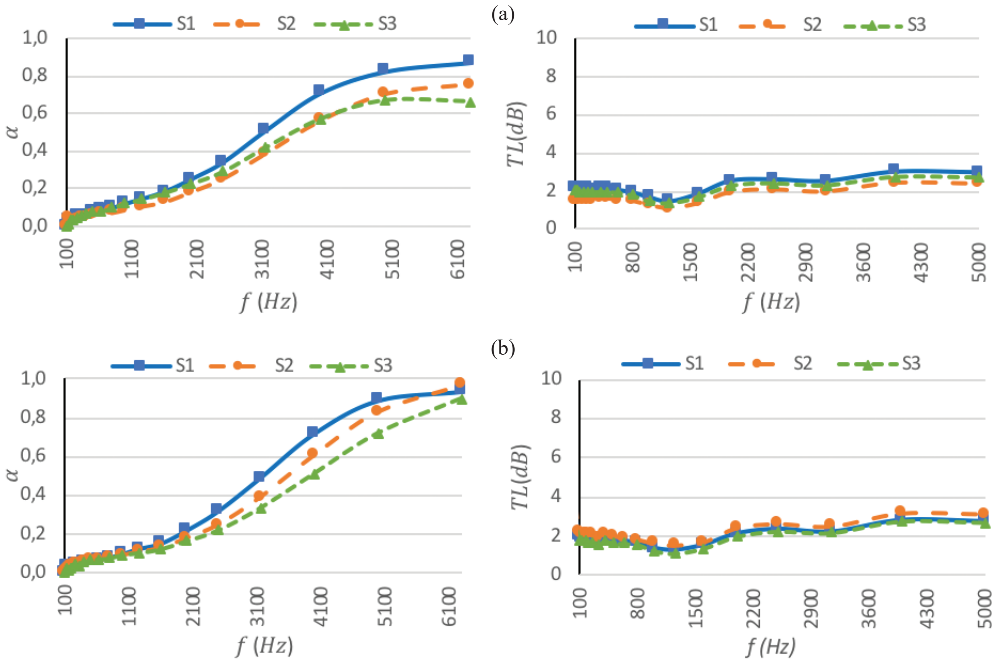

Figure 4: The SACs (left) and TLs (right) of three nominally identical hybrid (a) JLJ and (b) LJL samples (thickness: 10 mm).

the TLs for the same four jute samples are found to be 6.28 ± 0.65 dB, 5.38 ± 0.47 dB and 6.61 ± 0.43 dB for 500, 2000, and 5000 Hz, respectively. Similarly, the SACs for the four luffa samples are 0.029 ± 0.006, 0.062 ± 0.008, and 0.171 ± 0.03 for 500, 2000, and 5000 Hz, respectively, and the TLs for the four luffa samples are 0.252 ± 0.06 dB, 0.269 ± 0.06 dB and 0.43 ± 0.10 dB for 500, 2000, and 5000 Hz, respectively.

In addition to the results for the homogeneous jute and luffa fiber samples, the acoustic properties of hybrid jute and luffa fiber samples are presented here. The SACs and TLs of the hybrid JLJ and LJL samples are given in Figure 4. It is seen that, similar to the results of the homogeneous samples, the variations of the test results among hybrid samples can be considered small. The average values and deviations of the SACs and TLs for the three JLJ samples are 0.041 ± 0.007, 0.132 ± 0.023, and 0.538 ± 0.080; 1.73 ± 0.42, 1.6 ± 0.34, and 2.3 ± 0.42 dB at 500, 2000, and 5000 Hz, respectively. The corresponding values for the three LJL samples are 0.034 ± 0.004, 0.112 ± 0.018, and 0.573 ± 0.098; 2.25 ± 0.75, 1.94 ± 0.57, and 2.87 ± 0.71 dB for 500, 2000, and 5000 Hz, respectively.

Overall, the results show that the variations in the measured SACs for the samples in this study are determined to be about 15.7, 13.8, and 13.1% for 500, 2000, and 5000 Hz, respectively. Similarly, the variations in the TLs for the samples in this study are found to be 0.47, 0.36, and 0.42 dB for 500, 2000, and 5000 Hz, respectively. It is worth restating that these variations are considered to be due to the variability of the properties of fibers, the accuracy of the manufacturing process, and the mounting conditions of the test samples in the impedance tube.

4 Results and Discussion

4.1 *Homogenous samples*

The SACs and TLs of the homogenous jute and luffa fiber samples with different thicknesses are presented in Figure 5. It is seen that, at lower frequencies, SAC increases as sample thickness increases for the jute fiber samples and then exhibits some fluctuations at higher frequencies. For luffa samples, on the other hand, SAC tends to increases at almost all frequencies as sample thickness increases. It is seen that the frequency of the first peak in the SAC curves decreases as sample

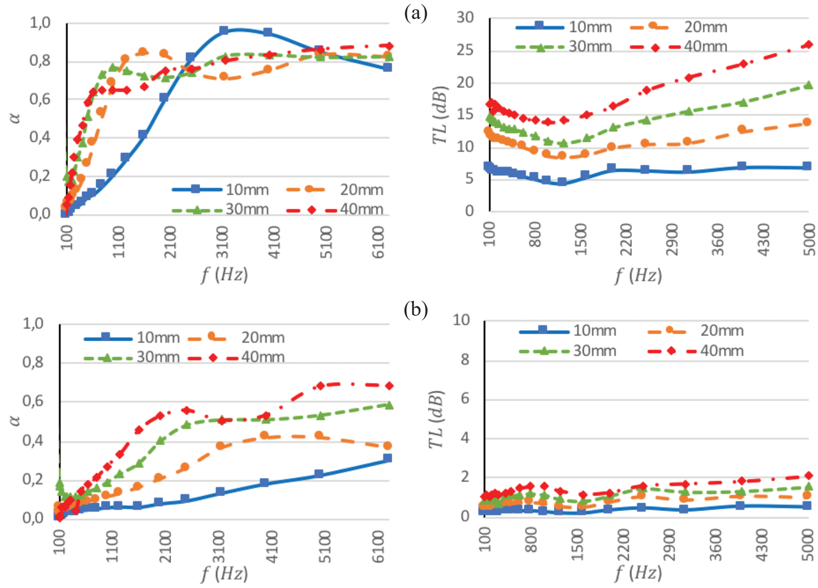

Figure 5: The SACs (left) and TLs (right) of the homogenous (a) jute and (b) luffa samples with different thicknesses.

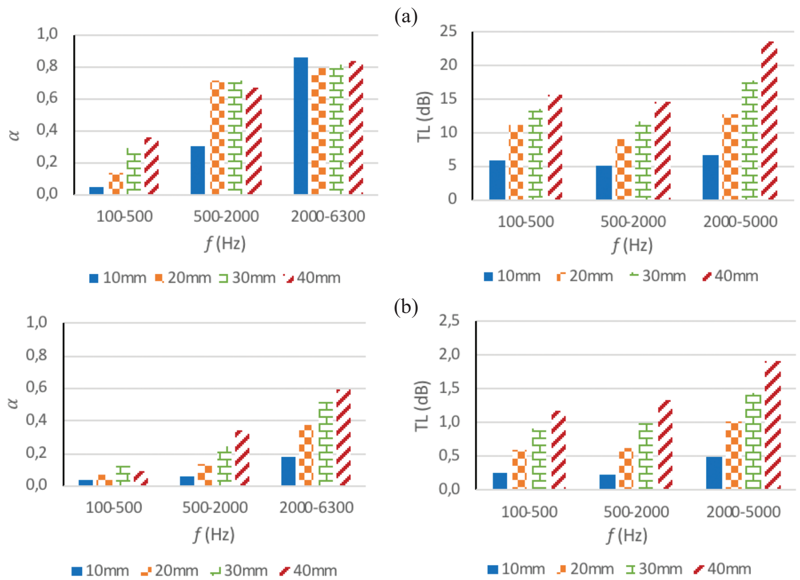

Figure 6: The SACs (left) and TLs (right) of the homogenous (a) jute and (b) luffa samples with different thicknesses for different frequency ranges.

thickness increases, a feature which is observed in the literature [23]. It is apparent that TLs consistently increase with thickness for both the jute and luffa samples.

The average SACs and TLs of the homogeneous jute and luffa fiber samples for low (100–500 Hz), medium (500–2000 Hz) and high (2000–6300 Hz for SAC and 2000–6300 Hz for TL) frequency ranges are plotted in Figure 6. It is seen that the SACs of the jute sample at low frequencies increases as sample thickness increases. Although the SACs of the jute sample at medium frequencies increase as sample thickness

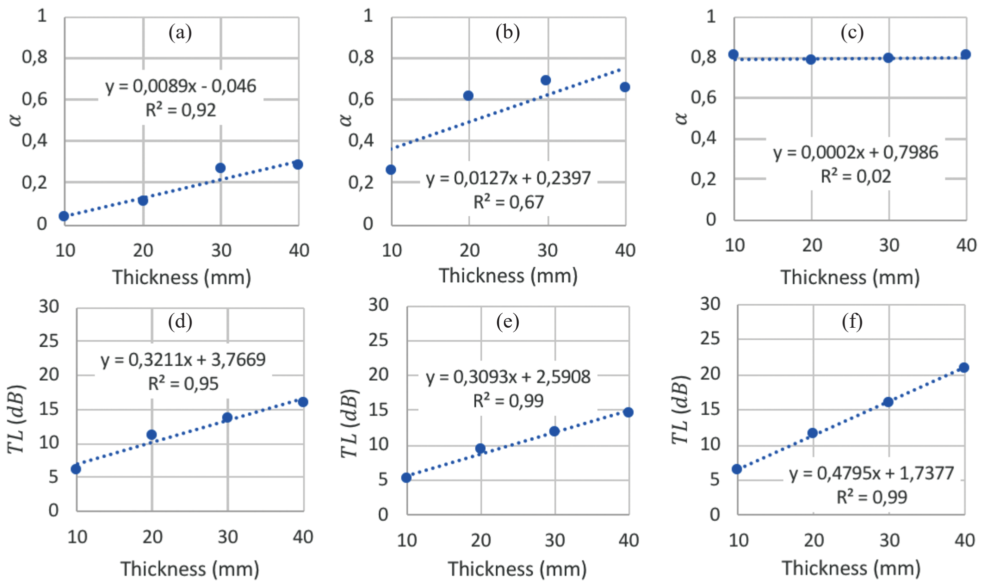

Figure 7: The average SACs and TLs of the homogenous jute fiber samples with different thicknesses for low (a and d), medium (b and e) and high (c and f) frequency ranges (bulk density: 419.8 kg/m^3).

increases from 10 to 20 mm, the SACs of the 20, 30, and 40 mm thick jute samples at medium frequency range are close to each other. It is also seen that the SACs of the 10, 20, 30, and 40 mm jute samples at high frequency range are close to each other, hence there is no need to use relatively thicker jute samples at high frequency range for higher SACs. On the other hand, the SACs of the luffa sample at all frequency ranges increase as sample thickness increases. As seen, the TLs of the homogeneous jute and luffa fiber samples consistently increase as sample thickness increases for all frequency ranges.

In order to determine the thickness-dependent tendencies of the SACs and TLs of the homogenous jute and luffa fiber samples for different frequency ranges, the averaged results corresponding to different thicknesses at low, medium and high frequency ranges and the first order curves fitted to the measured data together with the correlation coefficient *R* are shown in Figures 7 and 8. The results show that the SACs of the homogenous jute samples increase linearly with frequency for low frequency range, but there is an increase up to a certain thickness value for medium frequency range, and there is no effect of thickness increase at high frequency range. On the other hand, the SACs of the homogenous luffa samples and the TLs of all samples increase almost linearly with thickness for low, medium and high frequency ranges.

4.2 *Hybrid samples*

The SACs and TLs of the hybrid jute and luffa samples with different thicknesses are identified and results are presented in Figure 9. The TLs of the hybrid JLJ an LJL samples consistently increase with thickness just as observed before for the homogeneous jute and luffa fiber samples.

A similar investigation is carried out to establish the dependency of the SACs and TLs of the hybrid samples on thickness and frequency, and the results are summarized in Figure 10. It is seen that the acoustic properties of the hybrid JLJ and LJL samples are quite close to each other for all frequency ranges and thicknesses. The SACs and TLs of the hybrid JLJ and LJL samples tend to increase consistently with thickness for all frequency ranges.

The averaged results corresponding to different thicknesses at low, medium and high frequency ranges and the first order curves fitted to the measured data together with the correlation coefficient *R* are shown in Figures 11 and 12. It is seen that there is a good correlation between the acoustic properties and thickness for the

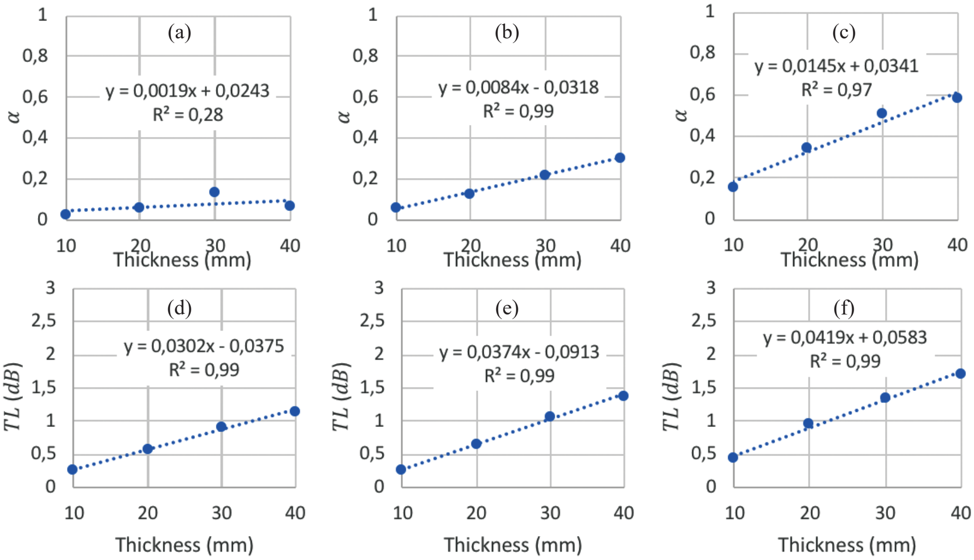

Figure 8: The average SACs and TLs of the homogenous luffa fiber samples with different thicknesses for low (a and d), medium (b and e) and high (c and f) frequency ranges (bulk density: 73.6 kg/m^3).

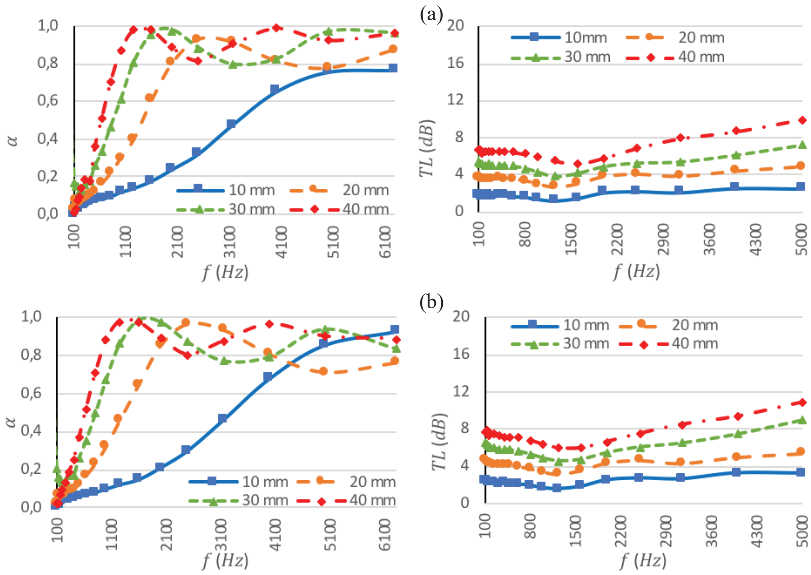

Figure 9: The SACs (left) and TLs (right) of the hybrid (a) JLJ and (b) LJL samples with different thicknesses.

hybrid samples for all frequency ranges ($R^2 > 0.8$). The curves presented here can be used to predict the acoustic properties of homogenous and hybrid jute and luffa structures at different frequencies and thicknesses. It should be stated that the trend curves should be used with caution as they are valid only when the thickness is close to the values used in the tests here.

4.3 *Comparison of homogenous and hybrid samples and evaluation*

The SACs and TLs of the homogenous as well as hybrid fiber samples with different thicknesses are compared in Figure 13. It is clear that, for the same thickness, the acoustic performance of the jute sample

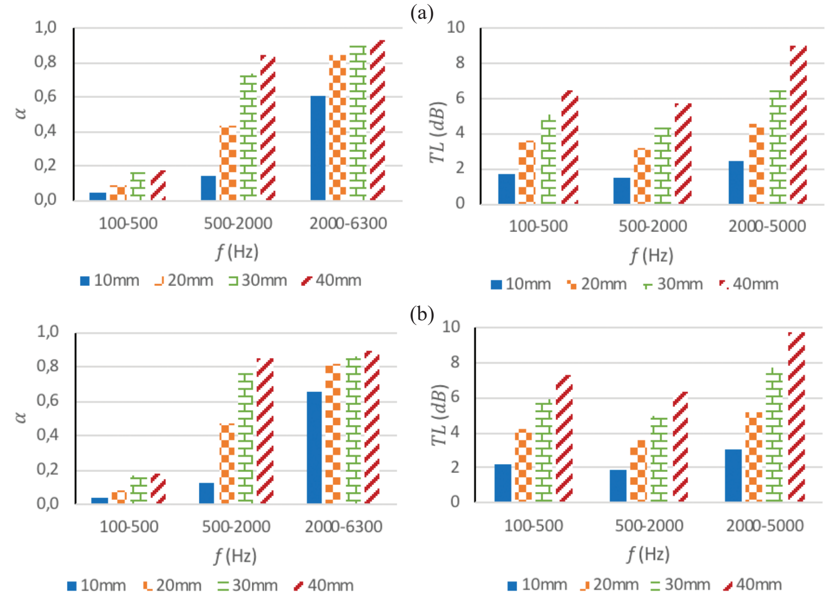

Figure 10: The SACs (left) and TLs (right) of the hybrid (a) JLJ and (b) LJL samples with different thicknesses for different frequency ranges.

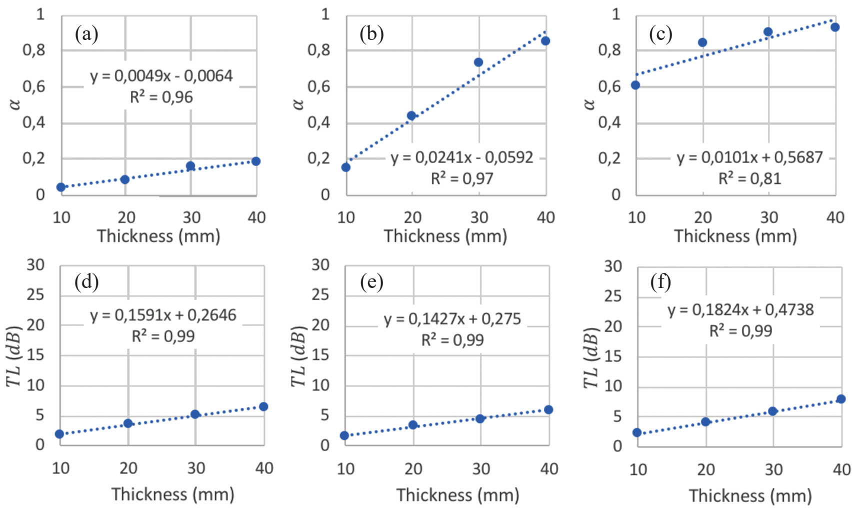

Figure 11: The average SACs and TLs of the hybrid JLJ samples with different thicknesses for low (a and d), medium (b and e) and high (c and f) frequency ranges (bulk density: 187.4 kg/m^3).

is better than that of the luffa sample. However, it is noted that the jute samples (ρ_b = 419.8 kg/m^3) are much heavier than the luffa samples (ρ_b = 73.6 kg/m^3). On the other hand, the SACs and TLs of the hybrid LJL and JLJ samples are quite close to each other. It should be remembered that the bulk densities of the porous JLJ (ρ_b = 187.4 kg/m^3) and LJL (ρ_b = 178.0 kg/m^3) are close to each other. It is seen that the arrangement of the layers does not affect the SACs and TLs of the JLJ and LJL samples significantly. In general, the hybrid samples show better absorption characteristics than the homogeneous luffa samples. The SACs of the homogenous jute fiber samples are higher at low frequencies for any thickness value, though the hybrid

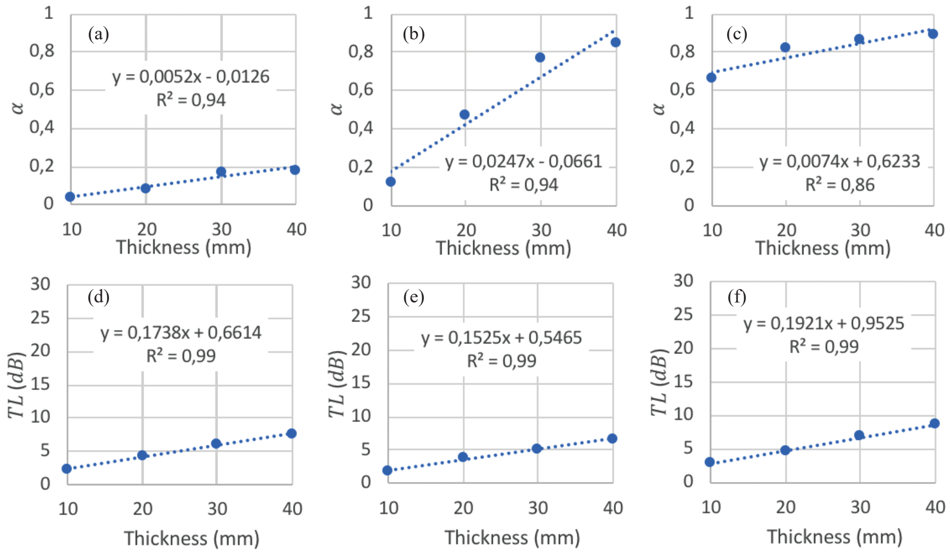

Figure 12: The average SACs and TLs of the hybrid LJL samples with different thicknesses for low (a and d), medium (b and e) and high (c and f) frequency ranges (bulk density: 178.0 kg/m^3).

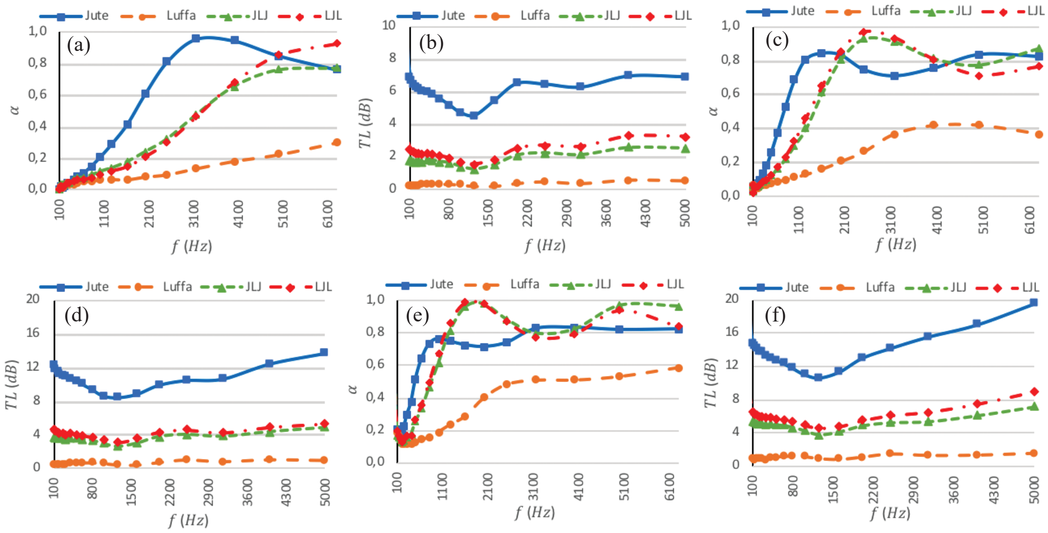

Figure 13: The SACs and TLs of the homogeneous and hybrid samples with (a and b) 10, (c and d) 20 mm and (e and f) 30 mm thicknesses.

fiber samples can have higher absorption values than those of the jute sample at medium and high frequency ranges when thickness is increased. The homogenous jute fiber samples have higher TLs than those of other samples. It should be noted that the frequency of the first peak in the SAC curves for all samples decreases as the density and thickness of the samples increase, a trend which is in agreement with the results in the literature [23].

The SACs of the sample can be divided by its thickness and bulk density to obtain a parameter that reflects the effect of the specimen mass [22]. For a thickness of 40 mm, although the SACs of the jute fiber sample (0.54 on average) are higher than those of the luffa fiber sample (0.26 on average), the absorption of the luffa sample per unit mass is 2.5 times higher than the absorption of the jute sample per unit mass. Furthermore, the SACs of the hybrid JLJ (0.55 on average) and LJL (0.55 on average) samples are close to those of the homogenous jute sample (0.54 on average), though the bulk density of the hybrid samples is almost half of the homogenous jute samples. Moreover, the absorption per unit mass of the hybrid samples is 2.3 times higher than that of the homogenous jute sample. Regarding insulation performance, the jute sample has quite high TLs (17 dB), the hybrid samples have moderate TLs (7 dB) and the luffa sample has low TLs (2 dB). The combination of jute and luffa fibers may be used when low weight structures are needed due to the relatively low density of luffa fiber.

5 Conclusions

The sound absorption coefficients (SACs) and transmission losses (TLs) of green luffa fiber samples are thoroughly investigated and their acoustic performances are compared with the acoustic performances of green homogenous jute and hybrid jute/luffa fiber samples in this study. Although there are some small variations among specimens, both the SAC and TL experiments for the homogenous and hybrid jute and luffa fiber samples can be considered repeatable. The average variations in the SACs and TLs of the samples investigated in this study are 10–15% and 0.5 dB, respectively. The SACs of the homogenous jute fiber samples appear to increase linearly with frequency for low frequency range, but there is an increase up to a certain thickness value for medium frequency range and there is no effect of thickness increase at high frequency range. On the other hand, the SACs of the homogenous luffa and hybrid jute and luffa samples and the TLs of all samples tend to increase linearly with thickness for low, medium and high frequency ranges. Although the SACs of the jute fiber samples are higher than those of the luffa fiber samples with the same thickness, the absorption of the luffa samples per unit mass are much higher than the absorption of the jute samples per unit mass. The SACs of the hybrid jute/luffa samples are close to those of the homogenous jute samples, though the bulk density of the hybrid samples is almost half of the homogenous jute samples. The homogenous jute samples have quite high TLs (15–20 dB for a sample thickness of 30–40 mm), the hybrid samples have moderate TLs (5–10 dB for a sample thickness of 30–40 mm) and the luffa samples have low TLs (a few dB for a sample thickness of 30–40 mm). The results and analyses for the acoustic properties of the green homogeneous jute and luffa fiber samples and their green hybrid fiber samples for a variety of thicknesses and different frequencies presented here can be used to design homogenous as well as hybrid luffa and jute fiber structures in various applications.

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