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Acoustic Properties of Hybrid Glass/Flax and Glass/Jute Composites Consisting of Different Stacking Sequences

Farklı Sıralama Dizilerinden Oluşan Hibrit Cam/Keten Ve Cam/Jüt Kompozitlerin Akustik Özellikleri

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Araştırma Makalesi / Research Article

ACOUSTIC PROPERTIES OF HYBRID GLASS/FLAX AND GLASS/JUTE COMPOSITES CONSISTING OF DIFFERENT STACKING SEQUENCES

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ABSTRACT: Natural fibres offer good acoustic properties due to their structures; hence natural fibre reinforced composites have been widely used as sound absorber materials for structural applications in recent years. This study aims to explore the relationship between sound absorption properties and stacking sequence of natural fibre and hybrid composites. Hybrid laminates consisted of glass/flax and glass/jute fabrics with various stacking sequences were produced using vacuum infusion method. Sound absorption coefficient and sound transmission loss (STL) of composites were measured through a medium type impedance tube with four microphones at frequencies from 100 to 3500 Hz. Results showed that composite laminates made from hybrid fabrics showed higher sound absorption coefficient than glass and natural (jute and flax) fibre composites. Stacking sequence played a critical role whilst using natural fibres at the face region offered higher sound absorption coefficient than using them at cores. It was observed that natural fibre and hybrid composites had higher transmission losses compared to glass composites, and less amount of sound were transmitted through when natural fibres were used at the outer region.

Keywords: Natural fibre reinforced composites, sound absorption coefficient, sound transmission loss, laminate stacking sequence.

FARKLI SIRALAMA DİZİLERİNDEN OLUŞAN HİBRİT CAM/KETEN VE CAM/JÜT KOMPOZİTLERIN AKUSTİK ÖZELLİKLERİ

ÖZET: Doğal lifler, yapıları nedeniyle iyi akustik özelliklere sahiptirler; bu nedenle son yıllarda doğal lif takviyeli kompozitler yapısal uygulamalar için ses emici malzemeler olarak yaygın bir şekilde kullanılmaktadır. Bu çalışmanın amacı, doğal lif ve hibrit kompozitlerin ses absorpsiyon özellikleri ile kumaşların yerleştirme dizileri arasındaki ilişkiyi araştırmaktır. Vakum infüzyon yöntemiyle çeşitli dizilim sekanslarına sahip cam/keten ve cam/jüt kumaşlardan oluşan hibrit kompozitler üretildi. Kompozitlerin ses yutum katsayısı ve ses iletim kaybı (STL), 100 ile 3500 Hz frekanslarında dört mikrofonlu orta tip empedans tüpü ile ölçüldü. Sonuçlar, hibrit kumaşlardan yapılan kompozit laminantların, cam ve doğal (jüt ve keten) lif içeren kompozitlerden daha yüksek ses absorbe katsayısı gösterdiğini ortaya koydu. Elde edilen sonuçlara gore dizilim sırasının kritik rol oynadığı, dış yüzeyi doğal liften oluşan kompozitlerin daha yüksek ses yutumuna sahip olduğu görülmüştür. Doğal lif ve hibrit kompozitlerin cam kompozitlere göre daha yüksek iletim kayıplarına sahip olduğu ve dış bölgede doğal lifler kullanıldığında daha az miktarda sesin yayıldığı gözlenmiştir.

Anahtar Kelimeler: Doğal lif takviyeli kompozitler, ses yutum katsayısı, ses iletim kaybı, laminant dizilim sıralaması

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1. INTRODUCTION

Natural fibre reinforced composite materials have had a rapid growth in the last two decades in different applications such as in automotive, civil engineering and aerospace applications [1-4]. The main advantages of natural fibre composites are their low cost, biodegradability [5] and specific strength compared to high performance fibre composites [6]. More recent attention has focused on the usage of natural fibres and their composites as sound absorber and insulator materials due to their distinctive structure [7-12]. Up to now, several studies investigated the effects of different types of natural fibres on sound absorption properties. Seddeq et al. [13] investigated the sound absorption characteristics of nonwoven materials produced from recycled natural fibres, synthetic fibres and agricultural lignocellulosic fibres. Prabhakaran et al. [14] found out that flax/epoxy composites had higher sound absorption than glass/epoxy and glass/flax/epoxy composites.

Sound absorption coefficient and sound transmission loss (STL) are some of the criteria to choose appropriate fibres for the production of sound absorber composite laminates [15-18]. Lee et al. [19] compared sound absorption performance of flax/epoxy and glass/epoxy composites, and observed that noise reduction coefficient of glass composites was lower than flax composites. Veerakumar and Selvakumar used different polypropylene and kapok fibre ratios for producing nonwoven composites to compare their sound absorption and noise reduction coefficients [20]. Fatima and Mohanty [21] analysed acoustical properties (sound absorption and transmission coefficient) of jute fabrics and jute/latex composites, and observed higher sound transmission values when jute fibres was used in composite structure. Yang et al. [22] analysed sound absorption properties of different types of fibres (kapok, goose, cashmere and acrylic) to understand the effect of fibre mass, type, and air gap thickness. They observed that sound absorption coefficient of natural fibres were higher than acrylic fibres. WeiDong and Li Yan [23] measured that sound absorption and noise reduction coefficient of natural fibres (jute, flax, and ramie) and their composites were higher than that of carbon and glass fibres composites. Chen et al. [24] proposed that addition of short ramie fibre, flame retardants and plasticizers enhanced sound absorption coefficient of composites.

Previous studies suggested that sound absorption properties of natural fibre composites were affected by the type of the fibres (jute, flax, sisal, etc.) and structure of fabrics (thickness, areal density, air permeability) [25, 26]. ALRahman et al. [27] compared acoustic performance of date palm and oil palm fibre composites with different material thicknesses. They observed that date palm fibre composites provided better sound absorbency in various frequencies. Hajj et al. [28] analysed sound absorption coefficient of flax tows with various thicknesses and observed that thicker samples showed higher coefficient values. Reddy and Yang [29] compared sound absorption behaviour of jute/zein and jute/polypropylene composites and observed that zein based composite showed higher sound absorption between the range of 3000-5000 Hz. Lim et al. [30] investigated the sound absorption behaviour of kenaf fibres under various thicknesses and bulk densities. They observed that sound absorption increased with increasing bulk density and specimen thicknesses and kenaf fibres had better sound absorption performance compared to synthetic rock wool materials. Peng et al. [31] investigated sound absorption behaviour of wood fibre/polyester composites and found that the absorption coefficient decreased as airflow resistivity increased and there was a strong correlation observed between airflow resistivity and composite densities.

There is a relatively small body of literature that is concerned about using hybrid natural fibre composites as sound absorbing materials. Zheng et al. [32] studied the sound absorption performances of natural fibre-reinforced sandwich composites using ramie, jute and glass yarns in terms of yarn sizes and fibre types. They pointed out that using natural fibre composite as the skin showed better sound absorption properties than those of glass fibre. This was due to natural fibres' lower flow resistance characteristic, hence more sound were absorbed by them compared to glass fibres. Abdullah et al. [33] compared sound absorption properties of sugarcane, banana, and their hybrid composites using various fibre volume fractions. Their results indicated sound absorption increases with increasing fibre volume fraction and hybrid composites had higher sound absorption compared to individual fibres. Krucinska et al. [34] compared sound absorption coefficients of thermoplastic composites containing cotton, flax and hybrid fibres. They obtained the best sound absorption when hybrid fibres were used.

Existing research recognises the critical role played by natural fibre on sound absorption properties of composite laminates. However, understanding of how hybrid fibre composites contribute to sound absorption performance with different stacking sequence is still lacking whilst stacking sequence may affect sound absorption coefficients significantly as mechanical and thermomechanical properties. In this work, the sound absorption coefficient and sound transmission loss (STL) of glass/epoxy, flax/epoxy, jute/epoxy and their hybrid structures with two different stacking (glass/flax/glass, flax/glass/flax, glass/jute/glass, and jute/glass/jute) sequences were analysed with the aid of a medium type impedance tube at the frequencies from 100 to 3500 Hz.

2. EXPERIMENTAL

2.1. Materials

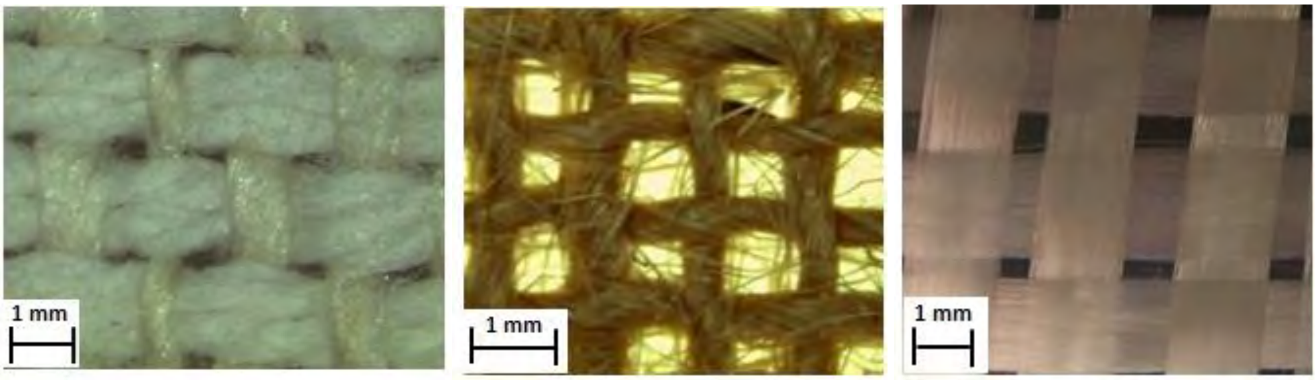
Table 1 shows properties of plain glass, canvas flax and plain jute woven fabrics that were used to manufacture composite laminates. Glass fabrics were supplied from Fibermak [35] while jute and flax fabric were purchased from Kumasci [36]. Fabrics with similar areal densities were chosen to make an accurate comparison between composite laminates. Figure 1 presents fabrics containing glass and natural fibres (jute and flax). The twist level of jute yarns is 280 turn/meter while flax yarns have the twist level of 200 turn/meter.

2.2. Methods

For this study, seven different types of composites were manufactured through different fabric types and sequences. Fabrics were placed in different sequences as shown in Figure 2 and, vacuum infusion method was used with an epoxy system comprised of FBRMAK 1564 epoxy resin (75% wt) and FBRMAK 3487 (25% wt) hardener at the required curing temperature and time (90°C degrees for one hours) as advised by the supplier. Composite samples were cut into circles (Fig.3) with the diameter of 50 mm using CNC equipment

Table1. Fabric properties

Fabric Type	Yarn Count (Tex)		Areal Density (g/m^2)	Warp yarn density (per cm)	Weft yarn density (per cm)
Glass	600 (warp)	600 (weft)	300	3	3
Jute	24 (warp)	24 (weft)	292	7	7
Flax	32 (warp)	10 (weft)	296	20	10



(a) (b) (c)

Figure 1. Photos of: **a)** flax fabric, **b)** jute fabric, and **c)** glass fabric

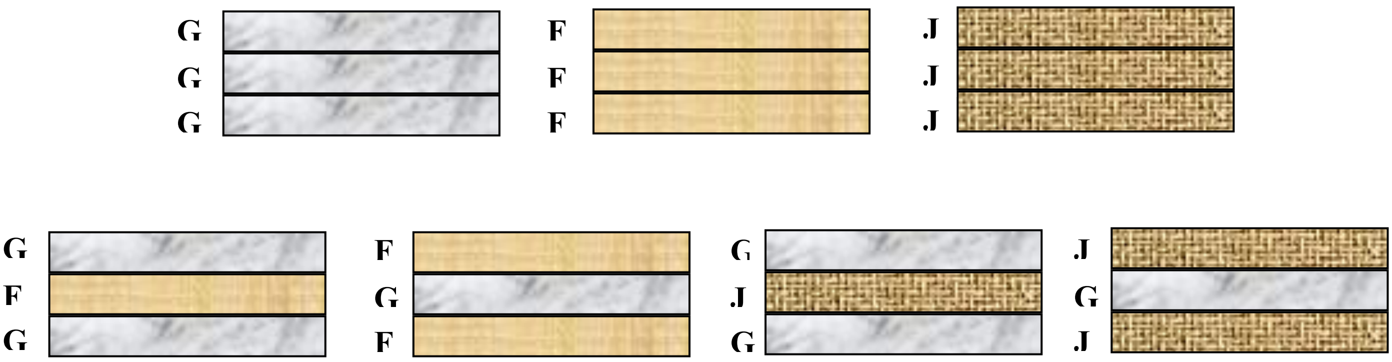


Figure 2. Fabric stacking sequence for composite laminates (G=glass, F=flax, and J=jute fabrics)

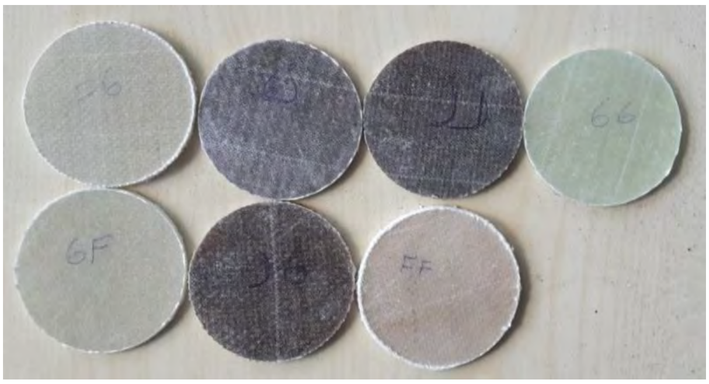


Figure 3. Test specimens for sound absorption coefficient and sound transmission loss measurement

The density and fibre volume fraction of the composite specimens were measured according to ASTM D792-08 and ISO 1172:1999 standards, respectively. The density measurement was made using a digital densimeter. Glass (GGG) and hybrid (GFG, FGF, GJG, and JGJ) were placed in a furnace to a temperature of 650 ºC for two hours to burn epoxy or natural fibre portion for fibre volume fraction calculations. However, JJJ and FFF samples do not have any glass portion, thus there were no remaining portion after the burning tests. Thus, volume fraction of the JJJ and FFF samples were calculated theoretically using equation (1):

$$Volume\ fraction\ (V_f)=\frac{Volume\ of\ fiber}{Volume\ of\ composite}=\frac{\frac{W_f}{d_f}}{L.w.h}=\frac{\frac{nlayer.gr.L.w}{d_f}}{L.w.h}=\frac{nlayer.gr}{h.d_f} \quad (1)$$

Where V_f, reinforcement fibre volume fraction (%); W_f, weight of reinforcement fibre; d_f, density of fibre; L, length of the specimen; w, width of the specimen; h, thickness of the specimen; gr, areal density of the fabric; nlayer , number of the layer in the laminate [37]. Experimental and theoretical (only for JJJ and FFF) fibre volume fractions are presented in Table 2 for all composites. It can be seen that laminates were produced with very similar thicknesses in order to compare sound absorption properties of samples more accurately. Each ply thickness can be calculated by dividing the total thickness of the laminate to number of the layers. For instance, ply thickness of GGG laminate is 0.25 mm since it has twelve layers of glass fibres as shown in Table 2. From the same table, number of other composites layers can be calculated. For example, JJJ has 4 layers of jute fabrics, FFF has five layers of flax, and GFG has 8 layers of glass and two layers of flax fabrics.

Void content (V_c) of composite laminates can be calculated using equation (2) [38].

$$V_c = \frac{\rho_t - \rho_e}{\rho_t} \quad (2)$$

Where ρ_t, theoretical density and ρ_e, experimental density of composite laminates. The void contents of the composites are presented in Table 2. The theoretical density was calculated using rule of mixture as in equation (3).

$$p_t = p_f V_F + p_m V_M \quad (3)$$

Where , p_t, p_f, and p_m are the densities of the composite, fibre and matrix; V_F and V_M are the volume fractions of the fibres and matrix. Densities of glass, jute, and flax fibres are 2.6 g/cm^3, 1.46 g/cm^3, 1.5 g/cm^3, respectively, whilst the density of the epoxy matrix is 1.15 g/cm^3

Sound absorption coefficient and sound transmission loss (STL) measurements of fabrics and composites were undertaken according to ASTM E1050-12 (transfer function method) and ASTM E2611-17 (4-pole transfer matrix method) standards, respectively.. Five specimens were tested for each fabric and composite sample. Sound test were conducted using a medium type impedance tube with four microphones at frequencies from 100 to 3500 Hz with TestSens analyzing systems developed by BIAS [39] in Mustafa Köseoğlu Composite Lab, Istanbul Technical University as shown in Figure 4. This device is capable of measuring sound absorption coefficient and STL at all frequencies in spite of specific frequencies.

The test device automatically measures the sound absorption coefficient and sound transmission loss (STL) values. Normally, sound absorption coefficient can be calculated using equations (4) and (5), respectively using the standards that were mentioned earlier.

Table 2. Properties of composite laminates

Sample code	Stacking sequence	Number of layers	Density (g/cm^3)	Void content (%)	Thickness (mm)	GF Vf (%)	Jute Vf (%)	Flax Vf (%)
GGG	$[(0/90)_3]_S$	12	1.81 (1.82)*	0.5	3.00 (±0.07)	46.5	-	-
JJJ	$[0/90]_S$	4	1.22 (1.23)*	0.8	2.95 (±0.04)	-	26.9	-
FFF	[0/90/0/90/0]	5	1.26 (1.28)*	1.5	2.79 (±0.04)	-	-	37.9
GJG	$[(0/90/0/)^G/(0)^J]_S$	8	1.47 (1.53)*	4.5	2.95 (±0.07)	23.9	13.5	-
JGJ	$[(0)^J/(0/90/0/)^G]_S$	8	1.47 (1.53)*	4.5	2.96 (±0.08)	23.5	13.5	-
GFG	$[(0/90)_2{}^G/(0)^F]_S$	10	1.61 (1.64)*	1.6	3.09 (±0.07)	30.5	-	13.7
FGF	$[(0)^F(0/90)_2{}^G]_S$	10	1.61 (1.64)*	1.6	3.09 (±0.09)	30.0	-	13.7

G=Glass, J=Jute, and F=Flax, *theoretical density

Figure 4. Impedance tube for sound absorption properties measurement

$$\text{Sound absorption coefficient } (\alpha) = \frac{\text{absorbed acoustic energy}}{\text{incident acoustic energy}} \quad (4)$$

$$\text{Transmission rate } (\tau) = \frac{\text{transmitted sound power}}{\text{incident sound power}} \quad (5.a)$$

$$\text{Sound transmission loss (STL) } = 10\log_{10}(1/\tau) \quad (5.b)$$

Air flow resistivity of fibrous materials also affect the sound absorption properties whilst thin fibres generally have higher airflow resistance compared to thick fibres [40]. Air flow resistivity of fibre based material can be calculated using several models. Table 3 presents air flow resistivity of natural fibres predicted by Mechel model using equations 6-7 [41]. Where σ, air flow resistivity (Pa.s/m^3); η, viscosity of air (1.84x10^{-5}); ε, porosity of yarns; a, radius of fibres (meter). Porosity of yarns can be calculated by the ratio of fibre density (ρ) to fibre bulk density (ρ_b).

$$\sigma = \frac{6.8\eta(1-\varepsilon)^{1.296}}{a^2\varepsilon^3} \quad (6)$$

$$\varepsilon = 1 - \frac{\rho_b}{\rho} \quad (7)$$

3. RESULTS AND DISCUSSIONS

3.1. Sound absorption coefficient test results

Figure 5 presents sound absorption coefficients of glass, jute and flax fabrics as a function of frequency. It can be seen that sound absorption coefficient shows variations until 750 Hz for all samples. However, all fabric samples show higher sound absorption as the frequency increased after passing 750 Hz. Figure clearly presents that jute and flax fibres have higher sound absorption coefficient than that of glass fabrics. This is due to rougher and fibrillose surface characteristics of natural fibres as shown in Figure 1 in which they enhance sound absorption properties of fabrics. Comparing natural fibres, flax fibres exhibited higher sound absorption coefficient than jute fabrics. This can be explained the fact that flax fabrics has higher porosity and air resistivity than jute fabrics as shown in Table 3.

Table 3. Air flow resistivity of natural fibres

Yarn Type	Fibre density (g/cm^3)	Fibre diameter[a] (µm)	Yarn diameter[a] (mm)	Fibre bulk density (g/cm^3)	Porosity (%)	Flow resistivity (Pa.s/m^2)
Jute	1.46	73	0.70	0.41 [32]	72	47378
Flax	1.50	20	0.54	0.34 [23]	77	395192

[a]Fibre and yarn diameters were measured experimentally using an optical microscope

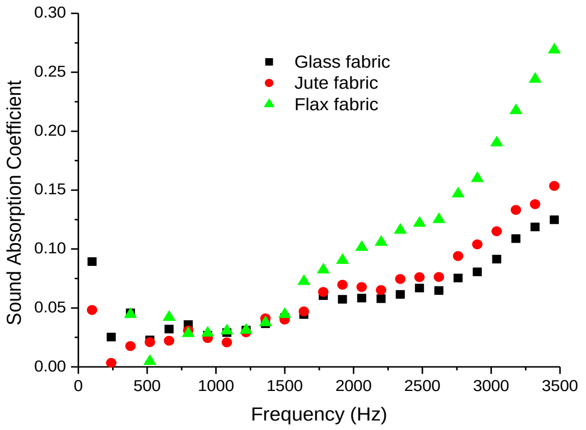


Figure 5. Sound absorption coefficient of glass, jute and flax fabrics at different frequencies

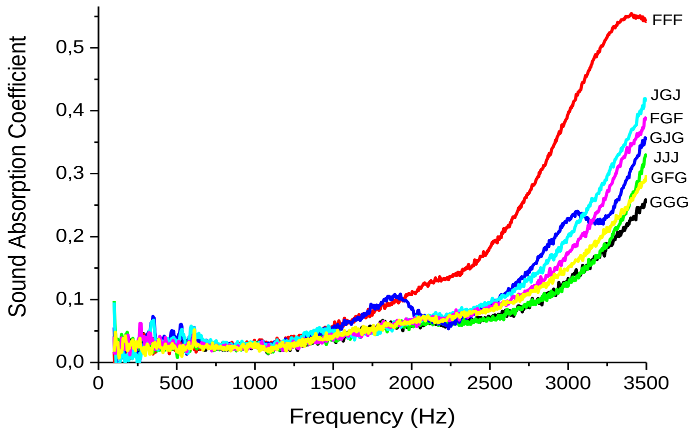


Figure 6. Sound absorption coefficient of composite samples at different frequencies

Table 4 and Figure 6 present sound absorption coefficients of natural, glass and hybrid composites. It can be seen that the coefficient of sound absorption depends on the frequency. Table 4 also shows average sound absorption coefficients of samples at specific frequencies to make an easier comparison. It can be seen from the table that all samples have very low and very similar coefficients at low frequencies. This is due to sound energy dissipates less at the lower frequencies. However, the increase in the sound absorption coefficient was dominant between 2000 and 3500 Hz compared to those at 100-2000 Hz. Comparing glass and natural fibre composites from Figure 6 and Table 4, they have similar sound absorptions at frequencies between 100-1500 Hz. After that ranges, coefficients increases rapidly especially for FFF sample. It can be seen that flax fibre composites had higher sound absorption than jute fibre composites at all frequencies. This is due to fibre volume fraction of FFF samples is higher than JJJ as shown in Table 2 since better absorption can be achieved when composites have higher fibre volume fractions. In addition, flax fabric has higher sound absorption than jute fabric (Fig.5); hence this directly affected the sound absorption properties of its composite form. It is also possible that composite structures become more compact with increasing fibre content as seen for flax fabric, and sound waves passed through longer distance along the composite thickness [42].

It can be seen from Figure 6 that GGG laminate had very similar absorption values with JJJ samples except at 3500 Hz. Similar results can be seen between glass and jute fabric as in Figure 5. However, it had lower sound absorption than FFF laminate at all frequencies although glass composites had higher fibre volume fraction as also observed in literature [19]. This result can be explained by the fact that flax or jute fibres have natural rough structure and fibrils along them as shown in Figure 7, which enhance sound insulation of composites. It can be seen from Table 3 that flax fibres had higher flow resistance than jute fibres which is one of the reason to have higher sound absorption coefficient for FFF laminate. It is also possible that jute fibres have more compact structure with less void content due to higher twist level which may lead to lower sound absorption compared to flax yarns [43].

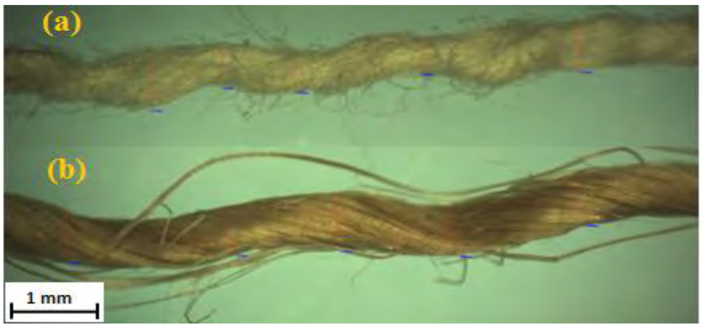


Figure 7. Microscopic images of: **a)** flax and **b)** jute yarns

Table 4. Sound absorption coefficient of composites at different frequencies

Frequency (Hz)	GGG	FFF	JJJ	FGF	GFG	GJG	JGJ
100	0.043	0.017	0.040	0.041	0.052	0.12	0.035
500	0.026	0.021	0.019	0.03	0.022	0.023	0.027
1000	0.027	0.034	0.026	0.031	0.029	0.033	0.029
1500	0.039	0.060	0.037	0.050	0.041	0.077	0.050
2000	0.06	0.115	0.061	0.051	0.069	0.083	0.065
3000	0.133	0.374	0.126	0.172	0.158	0.24	0.194
3500	0.247	0.498	0.330	0.385	0.316	0.354	0.490

The effect of stacking sequence on sound absorption of hybrid composites can be also seen from Figure 6 and Table 4. It can be seen that all samples have very low and similar coefficient values until 2000 Hz. Comparing hybrid samples, JGJ had similar sound absorption values with GJG laminate until 2500 Hz. Then, higher sound absorption is observed for JGJ sample. For example, sound absorption coefficients of JGJ and GJG samples are around 0.49 and 0.35, respectively at 3500 Hz. It can be also seen that the effect of stacking sequence is clearer when the frequency is higher. For JGJ sample; sound passes through around 0.75 mm jute layers first, then meets with 1.5 mm glass layers and finally leaves the laminates with 0.75 mm thick jute layers according to thickness measurements in Table 2. When the sound strikes the natural fibres first, sound waves encounters rougher surfaces compared to glass fibres because of the inherent surface characteristic of natural fibres. Then, a reasonable amount of sound dissipates due the higher friction between the fibre surfaces. After reaching the glass layers, the structure dissipate less amount of sound energy compared to natural fibres. Finally, sound exits the structure again with natural fibres with final dissipation. It seems that higher absorption was achieved when the sound stroke to natural fibres two times (JGJ) rather than only one (GJG). Comparing flax/glass (GFG and FGF) and glass (GGG) composites, they also had similar sound absorption properties until 2000 Hz. Nevertheless, both hybrid samples exhibit higher sound absorption than glass composites after passing 2000 Hz. To compare the effect of stacking sequence, GFG and FGF samples have very similar absorption coefficients until 3000 Hz. Then, coefficient values of FGF samples increases slightly compared to GFG samples. For instance, coefficient of FGF samples is around 0.38 whilst it is about 0.31 for GFG laminate at 3500 Hz. This shows that using flax fibres as outer layer are more effective at higher frequencies for hybrid laminates as also observed for jute/glass composites

Previous studies suggested that sound absorption coefficient of composites materials varies according to frequency, hence a single quantification value, which is noise reduction coefficient (NRC), can be used to make better comparison between samples as in equation (8) [44]. Most of the studies [20, 45] used four coefficient values while this study used six frequencies to evaluate the results with larger scale.

$$\frac{\alpha_{500}+\alpha_{1000}+\alpha_{1500}+\alpha_{2000}+\alpha_{3000}+\alpha_{3500}}{6} \tag{8}$$

Figure 8 presents calculated NRC values from measurement results of composite laminates. Figure shows that NRC of GGG laminate is comparatively lower than those of both JJJ and FFF laminates. Figure clearly indicates that FFF laminates had the highest NRC values compared to other laminates. It seems possible that these results are due to flax fibres had denser and more fibrillose structures compared to glass and jute fabrics as in Figure 1, and it has highest sound absorption coefficient (Fig.5). Lower weft and warp yarn density (yarn/cm) in jute fabric (Table 1) can also reduce the sound absorption for JJJ laminate due to creating easier path for sounds to pass through. It can be seen that hybrid laminates had slightly higher NRC compared to glass composites. It might be expected that GJG and JGJ samples should have lower coefficient values due to low absorption properties of JJJ and GGG sample as in Table 4 and Figure 6. However, their combination exhibited better sound properties compared to FGF and GFG. This is due to void content (porosity) of GJG and JGJ laminates were higher than other laminates as shown in Table 2, which results in higher sound absorption. It seems possible that hybrid jute/glass composites had slightly lower interfacial bonding compared to that of flax/glass composites. This weak bonding causes higher void content during manufacturing of hybrid composites [46]. It can be also seen that composite samples with the outer layers which are natural fibres had higher NRC values compared to glass fibre composites due to their higher sound absorption raw materials (Fig.5), indicating that the stacking sequence of fabrics highly affects sound absorption properties of composite laminates. The NRC of some of the commercial sound absorbing materials [47] are 0.15 and the hybrid composites that are used in this study are fairly compatible with those materials.

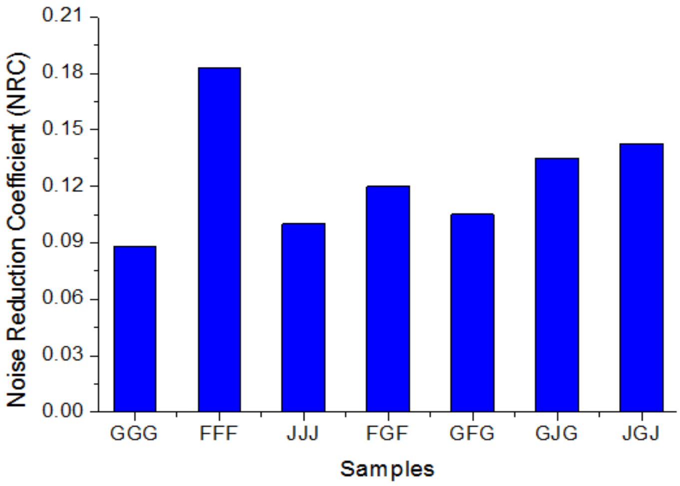


Figure 8. Noise reduction coefficient of different composite samples

3.2. Sound transmission loss test results

Coefficient of absorbency (α) defines the ability of absorbing acoustic energy while sound transmission loss (STL) is the ability of sound reflection or blocking. Figures 9-10 present STL of fabrics and composite laminates at different frequencies. STL indicates the sound decibels (dB) that are stopped by composite laminates at given frequencies. For instance, GGG laminate prevents around 14.5 dB of sounds whilst FFF and JJJ laminates prevents 14 dB and 12 dB, respectively at 100Hz as shown in Figure 10 and Table 5. However, STL values undulate for GGG, FFF and JJJ samples between 500-1250 Hz and rapidly increases again after 1250 Hz. As shown in Figure 10, the STL of natural fibre composites are slightly higher than glass composites although they have lower fibre volume fraction, indicating that they can prevent higher amount of sounds passing through other side. Table 5 presents that FFF and JJJ laminates had about 15% higher STL than GGG laminate at 1500 Hz. Similarly, FFF laminate showed approximately 12-15% higher STL compared to GGG between 2000-3500 Hz. This is due to flax fabric has higher transmission loss values compared to glass fabrics as shown in Figure 9. Jute and flax composites have lower density as in Table 2 and their inherent porous structure due to lumens can contribute more transmission loss compared to glass fibres at high frequencies. However, STL of JJJ exhibited very similar or slightly higher values compared to GGG laminate between 2000-3500 Hz. A possible explanation for this is that jute and glass fabrics have similar transmission loss values as presented in Figure 9.

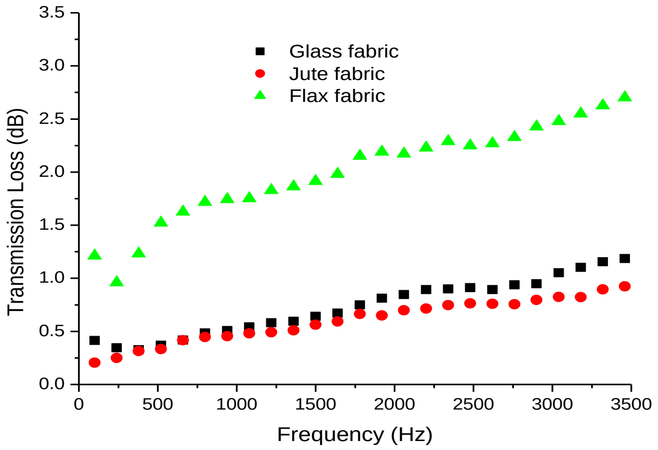


Figure 9. Transmission loss of glass, jute and flax fabrics at different frequencies

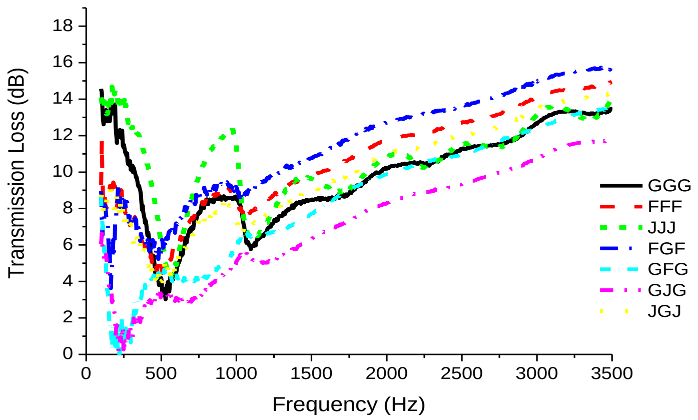


Figure 10. Transmission losses of composite samples at different frequencies

Figure 10 also depicts the STL of glass, flax and their hybrid (GFG and FGF) composites. It can be seen that FGF and GFG composites exhibited very similar STL values which is around 8.5dB at 100 Hz. After that frequency, FGF laminate performs better transmission loss at whole frequencies, and STL of samples exhibit an increasing tendency with the increase in frequency. It seems possible that using flax fibres at outer layers enhanced transmission behaviour of laminates compared to using glass fibres which is due to its better sound blocking performance (Fig.9). Table 5 also provides that FGF laminate had higher STL compared to GGG samples after passing 500 Hz although it has lower fibre volume fraction (Table 2). This is due to surface reflection of GGG is higher than FGF laminate at higher frequency regions, hence less lower amount of sound absorbed through the GGG laminate [45]. However, GFG laminate exhibited very identical STL with GGG laminate, especially at the frequencies between 1500-3500 Hz which is due to they have the same contact surface fabrics (glass). It is also possible that flax fibres may have higher resistivity to the long sound waves than short sound waves, hence less amount of sound transmitted through at higher frequencies. Table 5 also indicates that STL of JGJ laminate is higher than that of GJG laminate at all frequencies. This shows that changing stacking sequence by using jute fibres at outer layers provided higher transmission loss values compared to using glass fibres as also observed for flax/glass hybrid laminates.

Comparing hybrid composites, GFG had higher STL than that of GJG composites at all frequencies although they have very similar thicknesses as shown in Table 2. Similar results can be seen for FGF and JGJ laminates. This is due to total fibre volume fraction of glass/flax composites are higher than glass/jute composites whilst they are around 44 % and 37 %, respectively as in Table 2. It can be seen from Table 5 that hybrid composites can prevent up to 15.6 dB at the highest frequency. This value is compatible with some of the commercial material while a soundproof phone station can drop between 12-18 dB [48]. They are also compatible with noise barrier which can prevent 13dB at the frequency of 250 Hz [49].

Table 5. STL (dB) of composite laminates at different frequencies

Frequency (Hz)	GGG	FFF	JJJ	FGF	GFG	GJG	JGJ
100	14.5 (±1.6)	14 (±1.1)	12 (±1.3)	8.6 (±0.9)	8.8 (±1.1)	6.4 (±0.8)	8.9 (±1.3)
500	3.3 (±0.7)	4.6 (±1.1)	4.0 (±0.6)	5.7 (±1.2)	4.5 (±1.3)	3.1 (±0.5)	3.8 (±0.2)
1000	8.5 (±1.2)	8.8 (±1.3)	12.1 (±1.1)	9.0 (±0.8)	5.8 (±0.4)	5.1 (±0.5)	7.0 (±1.2)
1500	8.5 (±1.1)	9.8 (±0.7)	9.7 (±1.0)	10.8 (±0.9)	7.7 (±0.7)	6.4 (±0.8)	8.9 (±1.0)
2000	10.1 (±0.5)	11.6 (±1.0)	10.9 (±0.2)	12.8 (±0.9)	9.9 (±0.5)	8.4 (±0.4)	10.9 (±0.8)
2500	11.2 (±0.4)	12.9 (±0.7)	11.7 (±0.8)	13.6 (±0.5)	10.9 (±1.0)	9.4 (±0.7)	12.1(±0.8)
3000	12.5 (±0.6)	14.2 (±0.2)	13.2 (±0.3)	15.1 (±0.5)	12.4 (±0.8)	10.6 (±0.9)	13.4 (±0.4)
3500	13.2 (±0.8)	14.8 (±0.3)	13.8 (±0.7)	15.6 (±0.7)	13.5 (±0.2)	11.7 (±0.1)	14.3 (±0.7)

4. CONCLUSIONS

In this paper, the aim was to assess the effect of stacking sequence on sound absorption coefficient and transmission loss of composite laminates produced from natural (jute and flax) and glass fibres, which has not been investigated with details in the literature. The findings of this study suggest that natural fibre and hybrid composites are effective materials for sound absorbing structures with their low cost, lightweight and biodegradability. The following conclusions can be drawn from this work:

Flax and jute fabrics exhibited higher sound absorption coefficient than glass fabrics at all frequencies. However, flax fabrics showed the highest transmission loss while jute and glass fabrics had slightly similar values.

Flax/epoxy and jute/epoxy composites showed better sound absorption than glass/epoxy composite. Jute/epoxy composite displayed lower sound absorption behaviour than flax/epoxy composites,Hybrid composites displayed higher sound absorption than glass composites and using natural fibres at faces (flax/glass/flax or jute/glass/jute) exhibited higher sound absorption compared to using them at the core (glass/flax/glass or glass/jute/glass) parts of the composites.

Noise reduction results indicated that flax/epoxy composite (FFF) had the highest sound absorption coefficient than other samples while hybrid samples had higher coefficient values than the pure glass/epoxy composite.

Sound transmission loss (STL) of natural and hybrid composites were slightly higher than that of glass composites at most of the frequency levels. Higher transmission losses in terms of decibels were observed when natural fibres were used as outer layers compared to using them at the core regions.

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