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Long-term Immersion in Water of Flax-glass Fibre Hybrid Composites: Effect of Stacking Sequence on the Mechanical and Damping Properties

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Abstract: The hybrid solution of natural-synthetic fibres can be an effective option to enhance the moisture resistance of natural fibre reinforced polymer composites. This work aims at studying the effect of long-term water immersion of hybrid composites on their mechanical and damping properties. These properties were investigated using free vibrations from samples composed of quasi-unidirectional flax and glass layers and epoxy resin. The results showed that the saturation mass uptake and the diffusion coefficient of the composites were strongly dependent on the stacking sequence between the flax and glass layers. For instance, less than 25 days were necessary to reach the water saturation when flax fibre reinforcements were in the outer layers, whereas it took over 10 months when these reinforcements were in the inner layers. Compared to the flax fibre reinforced composite, the flax-glass hybrid laminate with two inner flax layers and two outer glass layers was the most efficient for a specification where damping and bending modulus are the main criteria. This one enabled a significant increase in bending and specific bending moduli (+38 % and +79 % respectively compared to the unaged flax laminate), a considerable slowing down of the diffusion phenomenon, while limiting the decrease in damping property with ageing (-20 %).

Keywords: Hybrid composites, Flax fibre, Water ageing, Mechanical properties, Damping

Introduction

In recent years, the use of natural fibre reinforced polymer composites has been undergoing significant growth in several industrial sectors such as marine, sports and automotive applications. Indeed, many works have highlighted their strong potential in terms of specific mechanical properties and low environmental impact [1-3]. On the other hand, numerous works have also underlined their interesting damping properties compared to conventional fibre reinforced polymer composites [4-8]. In a review article, Saba *et al*. [8] investigated the viscoelastic properties of natural reinforced polymer composites using Dynamic Mechanical Analysis. They highlighted the strong potential of natural fibres as reinforcements for thermoplastic and thermosetting matrices particularly in terms of their ability to reduce the vibrations, thanks to their interesting damping properties. These results have also been supported by several works by considering the free vibration experimental analysis [6,9-12]. For example, Duc *et al*. [6] showed that flax fibre reinforced epoxy composites exhibit a damping coefficient two times higher than those of glass-epoxy ones. In another study, Le Guen *et al*. [11] indicated that the damping coefficient of composites reinforced with flax fibre was found to be 4 times higher than composites reinforced with carbon fibre, but to the detriment of the elastic modulus and strength. Recently, Furtado *et al*. [12] found that jute fibre composites presented higher damping behaviour than their glass-fibre equivalents, while being lighter in weight. Furthermore, the inverse characterisation method predicted the continuous decreasing trend in the damping properties of the composites as environmental exposure levels increased. Based on the literature results, the interesting damping properties of natural fibre reinforced polymer composites have been mainly attributed to the morphology of natural fibre [12]. Indeed, its hollow cellular and multi-layered structure promoted the friction mechanisms at the different scales of the fibre in particular through its cell wells and between them [12-17]. More recently, Mahmoudi *et al*. [18] characterized the damping performance of unidirectional flax-epoxy structure using experimental and numerical investigations. Considering the first four modes and without taking into account the frequency dependence of damping in the numerical approach, the authors showed the predicted modal loss factors were over-estimated for non-bending modes compared to experimental ones. Their experimental results also showed that the modal damping was greater when the flax fibres were oriented at 90 °, while being higher than those of glass and carbon fibre composites.

Despite all these advantages, the water sensibility of natural fibre reinforced composite materials remains one of the main drawbacks for their development in the structures exposed to wet environment. Indeed, several research works have already shown that the exhibition of natural fibre reinforced polymer composites to wet environment leads to high variations of their mechanical and dynamic properties [19-25]. Consequently, several studies have suggested the hybridisation "natural fibre-synthetic fibre" to limit these variations by improving the moisture resistance of natural fibre reinforced polymer composites [26-30]. For example,

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Panthapulakkal *et al.* [27] studied the effect of the hybridisation on the mechanical properties and moisture resistance of short hemp-glass fibre-reinforced hybrid composites. These authors found that the glass fibre incorporation improved the tensile, flexural and impact characteristics of the short hemp fibre reinforced polypropylene composite. In addition to that, they showed that the glass-hemp fibre hybridisation reduced the water absorption tendency of the studied composites, which limits the loss of their mechanical properties. Recently, Saidane *et al.* [28] studied the water ageing and its effect on the tensile properties of different stacking sequences of twill flax-glass fibre reinforced hybrid composites. Their results showed that the adding of glass layers outside the flax laminate significantly reduced its water uptake and diffusion parameters. Besides, the authors indicated that the flax-glass hybridisation presented a positive effect in a wet environment, at room temperature, on the Young's modulus and the tensile strength of the flax-glass hybrid composites. However, they concluded that the used hybridisation had a negative effect, in wet environment at 55 °C, on the tensile strength of the studied hybrid composites. This result has been attributed to the swelling of flax fibre that induced shear stresses concentration between flax and glass layers, resulting in their delamination. In similar works, Dhakal *et al.* [29] studied the effect the water immersion on mechanical and thermal properties of flax-carbon hybrid composites. Their results firstly showed that the adding of carbon layers on both sides of flax laminates decreased by about 85 % its water uptake and secondly reduced the loss of their mechanical and thermal properties.

So this research clearly showed that the hybrid solution between natural and synthetic fibres could constitute a promising solution to enhance several characteristics of natural fibre reinforced polymer composites such as their moisture resistance, their thermal and mechanical properties. In the continuation of the above-cited promising works, it is also interesting to analyse the effect of other parameters such as the stacking sequence on diffusion parameters and dynamic properties of the natural fibre reinforced polymer composites. Consequently, it is proposed hereafter to analyse the effect of the hybridisation between flax and glass layers on the diffusion parameters and damping properties of the constituted hybrid laminates. For this purpose, different flax-glass hybrid laminates, with outer or inner flax layers, were elaborated by a platen press process and then immersed in water during several months to obtain water saturation. Next, the diffusion parameters of these materials were assessed using an optimisation procedure, which consists in minimising the quadratic error between the analytical Fick's solution and the experimental results. On the other hand, the dynamic properties of these materials were determined from the free vibration tests. Finally, the present study aims at finding from all tested hybrid composites the one that will present the best compromise between mechanical properties, density and damping properties, taking into account ageing in water.

Experimental

Materials and Manufacturing Process

The composite materials studied in this work were manufactured by impregnating flax and/or glass fibres with SR 1500 epoxy resin and SD 2503 hardener. Flax and glass fibres are quasi-unidirectional fabrics with areal density of 200 g/m^2 and 300 g/m^2, respectively. The non-hybrid and hybrid plates were elaborated using press platen process. The fabrics were first impregnated one by one with the resin-hardener mixture and then the eight impregnated plies were placed between two steel trays to be cured at 40 °C for 3 hours with a pressure of 6 bars. Table 1 summarises the studied staking sequences and their main characteristics, where F refers to a flax layer and G to a glass layer. It should be noted that the fibre volume fractions and the porosity content of non-hybrid and hybrid laminates were estimated by the same procedure detailed in [31,32]. The porosity content was lower than 1.5 % for all studied composites.

Experimental Equipment

The dynamic properties of the aged and unaged hybrid

Table 1. Designation, thickness and fibre volume fraction of the non-hybrid and hybrid laminate composites

Laminate	Ply number Flax/Glass	Stacking sequence F: Flax, G: Glass	Thickness Flax/Glass (mm)	Fibre volume fraction V_f (%) Flax/Glass
$[F_4]_s$	8/0	FFFFFFFF	2.90/0.00	35/0
$[F/G_3]_s$	2/6	FGGGGGGF	0.70/0.90	15/40
$[F_2/G_2]_s$	4/4	FFGGGGFF	1.40/0.60	25/21
$[F_3/G]_s$	6/2	FFFGGFFF	2.10/0.30	32/9
$[G/F_3]_s$	6/2	GFFFFFFG	2.10/0.30	34/9
$[G_2/F_2]_s$	4/4	GGFFFFGG	1.40/0.60	26/22
$[G_3/F]_s$	2/6	GGGFFGGG	0.70/0.90	15/40
$[G_4]_s$	0/8	GGGGGGGG	0.00/1.28	0/54

laminates were derived from the free vibrations. An impulse hammer (PCB 086C03 model) was used to excite the samples and their responses were detected by an accelerometer (PCB 352C23 model) that measures the acceleration of vibrations. Next, the excitation and response signals were digitalised using LMS SCADAS Mobile. More details about the used experimental setup can be found in [23]. Note that the test specimens were supported vertically by two fine rubber threads in such a way to have free-free boundary conditions of the beam. The tested specimens were manually excited at different points. Next, the experimental mode shapes were visualized by using the LMS PolyMAX [33] to be sure that they correspond to bending modes of free-free beam. The tested specimens had a wide of 25 mm and different lengths (230, 250 and 270 mm) which allowed obtaining a variation of their peak frequencies.

In order to determine the natural frequencies and their corresponding damping coefficients from the experimental analysis, the experimental frequency response functions were fitted with the LMS software using the PolyMax method [33]. This fitting was carried out by the least square method by means of the optimisation developed by LMS. This fitting enabled us to derive the values of the natural frequencies f_i and their modal damping coefficients ξ_i (case of damping using viscous damping modelling) or their loss factors η_i (case of damping using the complex stiffness model), related to the specific damping capacity by the relation $\psi_i = 2\pi\eta_i$. The latter is usually used to characterize the ratio of the energy dissipated to the energy stored in a structure or an element of structure.

Ageing Tests

In order to analyse the impact of water ageing on the free vibration behaviour of flax-glass hybrid composites, specimens from each batch of hybrid laminates were subjected to long-term immersion in water at room temperature. After being dried during 24 h, almost three specimens of each batch were immersed in tap water until saturation. Edges perpendicular to the thin direction (z direction) of the damping samples were not sealed in order to accelerate the process of diffusion. Water absorption measurements were performed by gravimetric analysis. During the ageing test and at certain time intervals, specimens were periodically taken out of the water bath. To assess the mass change, they were weighed using an analytical balance to the nearest 1 mg (Ohaus Pioneer, model PA413) after all surfaces were meticulously wiped dry with tissue paper. After weighing, these specimens were again immersed in water. The weighing of the specimens was repeated until the mass reached saturation point, that is to say until the mass gain was constant. To reach this saturation of each hybrid laminate, the immersion duration of one year was necessary.

After an immersion period *t*, the percentage of water absorption M_t in the hybrid laminate was evaluated from its relative uptake of mass according to the equation:

$$M_t = \frac{m_t - m_0}{m_0} \times 100\% \tag{1}$$

where m_0 and m_t are the mass of the specimen before ageing and during ageing at time *t*, respectively.

The moisture absorption behaviour at room temperature in natural fibre composites was usually Fickian in most cases, as was confirmed for all flax-glass fibre hybrid composites of this study. Due to the dimensions of the damping specimens, their width and length were high compared to their thickness. In that case, one-dimensional approach of Fick's laws was sufficient to estimate the diffusion parameters, from the following equation:

$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left(\frac{-(2i+1)^2\pi^2 Dt}{h^2}\right) \tag{2}$$

where M_∞ is the saturation mass uptake, D is the diffusion coefficient and h is the thickness of the specimen.

The diffusion coefficient D was assessed from an optimisation algorithm developed to minimise the quadratic error between the analytical solution and the experimental points, as detailed in [34,35].

Results and Discussion

Diffusion Kinetics of Hybrid Composites

Figure 1 shows the experimental and theoretical percentage moisture content according to the square root of ageing time for the flax-glass hybrid laminates. These composites are divided into two groups, depending on whether flax layers are outer layers (Figure 1(a)) or inner layers (Figure 1(b)). The obtained results show that all curves follow a Fickian behaviour with a linear initial part and an equilibrium plateau. Note that the theoretical water uptake depicted by the solid curve was calculated from Fick's model. After a long-term immersion in water of one year, one can consider that all samples have reached a saturated moisture level. It is worth noting that, for both types of hybrid laminates, the saturated plateau is reached after different time of water immersion: 6, 15 and 25 days were necessary for the $[F/G_3]_s$, $[F_2/G_2]_s$ and $[F_3/G]_s$ laminates, respectively, compared to more than 10 months for the $[G_3/F]_s$, $[G_2/F_2]_s$ and $[G/F_3]_s$ and laminates. Whatever the stacking sequence $[F_m/G_n]_s$ or $[G_n/F_m]_s$, the mass gain at saturation of hybrid composites increase with the flax layers number. This means that the more the number of flax layers added on either side of the glass layers or inserted between them increases, the more the mass of water absorbed by the composite increases. In addition, the kinetics of water absorption are accelerated with the number of flax layers. One can also notice that the position of flax layers in the laminate, either as outer layers or as inner layers, has an impact on the diffusion parameters. For example, the diffusion coefficient of $[F_2/G_2]_s$ laminate is

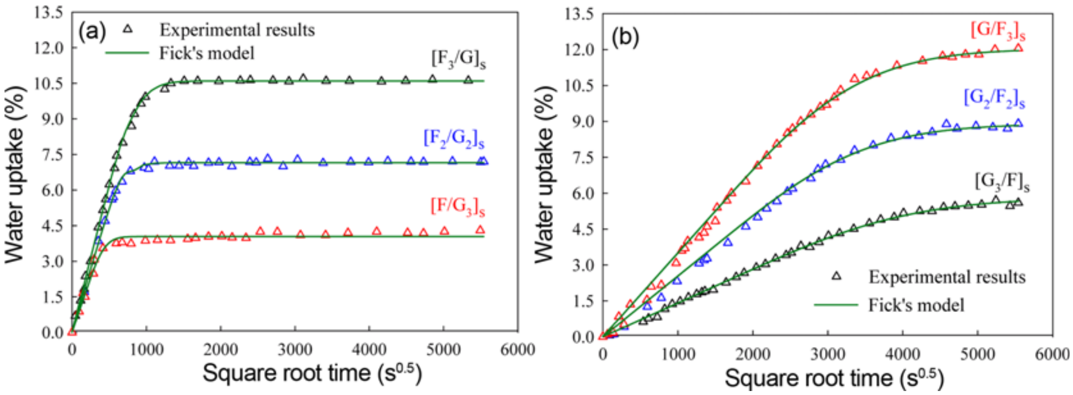

Figure 1. Evolution of water uptake of hybrid laminate composites as a function of the square root of immersion time; (a) $[F_m/G_n]_s$ and (b) $[G_n/F_m]_s$.

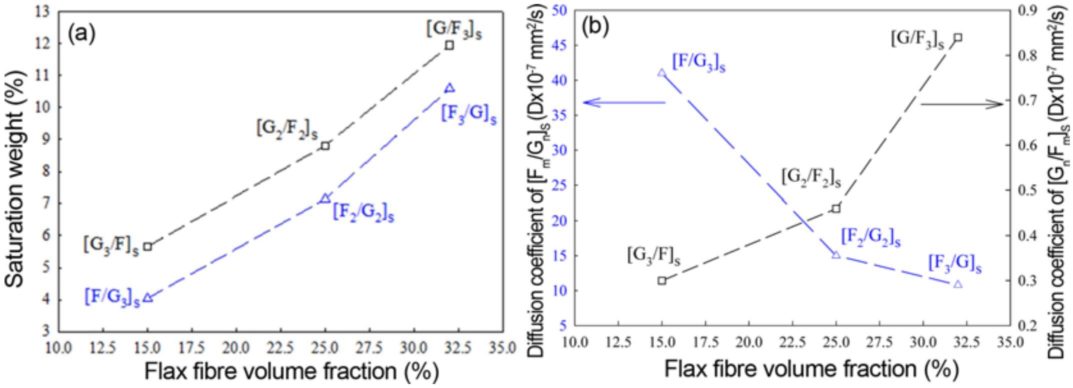

Figure 2. Evolution of the diffusion parameters of hybrid laminate composites as a function of the flax fibre volume fraction; (a) saturated mass uptake M_∞ and (b) diffusion coefficient D.

approximately 32 times higher than that of $[G_2/F_2]_s$ composite. In contrast, the mass uptake at saturation for the $[F_m/G_n]_s$ configuration is approximately 10 % to 40 % lower than that of the $[G_n/F_m]_s$ laminates. To illustrate this, Figure 2 presents the evolution of these parameters (saturated mass uptake M_∞ and diffusion coefficient D) as a function of flax fibre volume fraction, for all hybrid laminates. The saturated mass uptake of hybrid laminates increases quasi-linearly with flax fibre volume fraction and this one is higher for the hybrid laminates with inner flax layers. This increase in mass uptake is attributed to high hydrophilicity of the main components of the flax fibre and to its multi-layered structure with a central cavity (lumen). As regards the diffusion coefficients, the difference between the $[F_m/G_n]_s$ and $[G_n/F_m]_s$ laminates is due to the fact that the glass layers placed outside the laminate slow down the kinetics of water diffusion thanks to their low absorption properties. Although the $[G_n/F_m]_s$ type configurations have a positive effect in terms of diffusion rate, they remain nevertheless less interesting from the point of view of the saturated mass uptake. Indeed, the storage of water inside the material has been found to be more effective in the $[G_n/F_m]_s$ laminates because of the presence of internal flax layers identified as a material being highly hydrophilic. For the $[F_m/G_n]_s$ laminates, where flax layers are outer layers, Figure 2(b) shows that the diffusion coefficients increase as the flax fibre volume fraction decreases. Note that the diffusion rate increases as the number of flax layers decreases, because the thickness of flax layers decreases. This increase results, in part, from the increase of the ratio h/M_∞. Indeed, in the linear part of the water absorption curve, the diffusion coefficient is proportional to the ratio (h/M_∞) [31]. Compared to the $[F_3/G]_s$ laminate, this ratio is 1.5 and 3.1 higher than that of $[F_2/G_2]_s$ and $[F/G_3]_s$ laminates, respectively. This is in accordance with the ratios of the diffusion coefficients.

Mechanical and Damping Properties of Unaged Hybrid Composites

Figure 3 presents the specific bending modulus and loss factor of the unaged flax-glass hybrid composites. The obtained results show that the evolution of these two characteristics are strongly related to the position of glass layer inside the hybrid laminates. For example, the replacement of the external glass layers by the flax ones

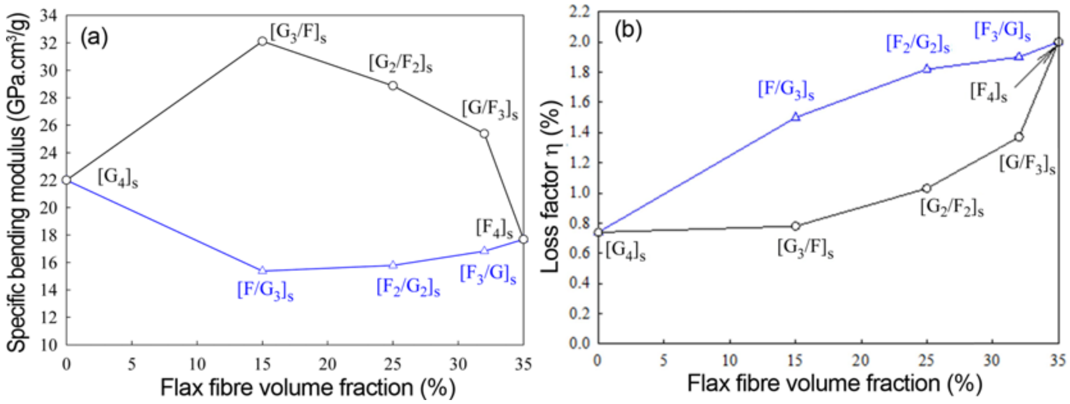

Figure 3. Evolution of (a) the specific bending modulus and (b) the loss factor of unaged hybrid composites as a function of the flax fibre volume fraction.

decreases the specific bending modulus of the hybrid laminates by about 23 % to 30 % compared to the glass-epoxy composite. However, this replacement leads to an enhancement by about 15 % to 46 % of the specific bending modulus when the flax layers are placed inside the hybrid laminates. The difference between the $[G_n/F_m]_s$ and $[F_m/G_n]_s$ configurations results from the layers with higher moduli with are the most distant from the middle plan as reported in [36,37].

On the other hand, the replacement of the glass layers by those of flax enhances the damping properties the hybrid flax-glass laminates. This enhancement is more pronounced when the flax layers are placed outside the hybrid laminate. For example, the damping increases by about 35 % for the $[G_2/F_2]_s$ composite and 138 % for the $[F_2/G_2]_s$ compared to the glass laminate. This difference is attributed firstly to the high damping of the flax fibre compared to glass one and secondly the energy dissipated by the flax and glass layers which depends on their position. Note that, for the same volume fraction of flax fibre, the flax layers lead to higher dissipation energy when placed on outer layers. Indeed, the loss factor is clearly higher for hybrid laminates with outer flax layers than for hybrid laminates with inner flax layers.

Mechanical and Damping Properties of Aged Hybrid Composites

Figures 4 and 5 present the bending modulus and loss factors of the unaged and aged flax-glass hybrid laminates. The bending modulus decreases when the flax layer number increases. This decrease is about 7.86 %, 7.88 % and 19.08 % for the laminates $[G_3/F]_s$, $[G_2/F_2]_s$ and $[G/F_3]_s$, respectively. For the other hybrid laminates, the losses remain more important and reach ~44.04 % for the $[F/G_3]_s$ laminate. On the other hand, these losses are less important compared to the 50 % observed in the case of the $[F_4]_s$ laminate. These results clearly show that the association of flax and glass layers reduces the effect of water ageing on the bending modulus of the hybrid laminates, in particular for the $[G_m/F_n]_s$ configurations.

Contrary to the bending modulus, the loss factor increases after ageing and this is strongly due to position the glass layer inside the hybrid laminate. For example, the loss factor increases by about 150 % for the $[F_3/G]_s$ compared to 50 % for the $[G/F_3]_s$ laminate. This difference between the staking sequences requires analysing the relationship between the loss factor and saturation mass gain of the hybrid laminates.

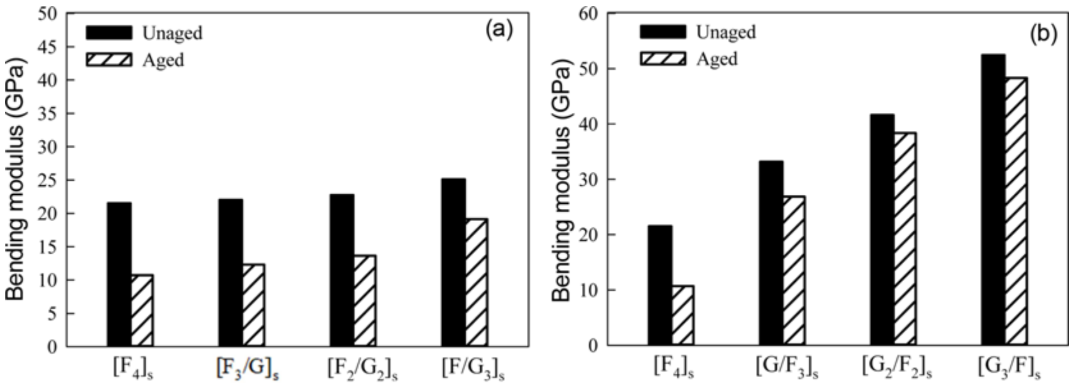

Figure 4. Evolution of bending modulus of unaged and aged flax-glass hybrid composites; (a) $[F_m/G_n]_s$ and (b) $[G_n/F_m]_s$.

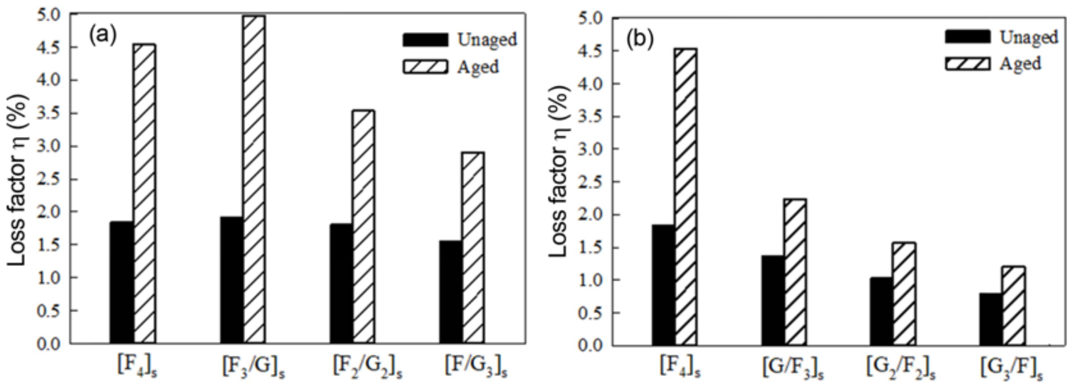

Figure 5. Evolution of loss factor of unaged and aged flax-glass hybrid composites; (a) $[F_m/G_n]_s$ and (b) $[G_n/F_m]_s$.

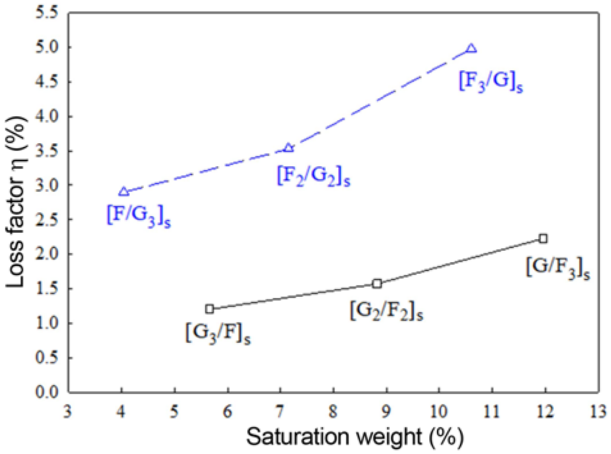

Figure 6. Evolution of loss factor of aged flax-glass hybrid composites $[F_m/G_n]_s$ and $[G_n/F_m]_s$ as a function of the saturation weight.

Figure 6 illustrates the evolution of the loss factor according to the saturation mass gain of the hybrid laminates. These results show that the damping increases with the amount of absorbed water. This is essentially attributed to the plasticization of the hybrid composite constituents caused by the infiltration of water molecules inside them [38,39]. On the other hand, the water absorption can lead to important frictions, firstly at different scale inside the flax fibre and secondly at the fibre-matrix interface, which increase the energy dissipation [40].

Synthesis

This present discussion aims at finding from all tested hybrid composites the one that would present the best compromise between mechanical properties, density, fibre volume fraction and damping properties, taking into account a possible ageing in water. This action was taken for the purpose of finding, with severe ageing conditions, a stiffer composite than the flax/epoxy composite, while increasing its specific bending modulus and keeping its interesting

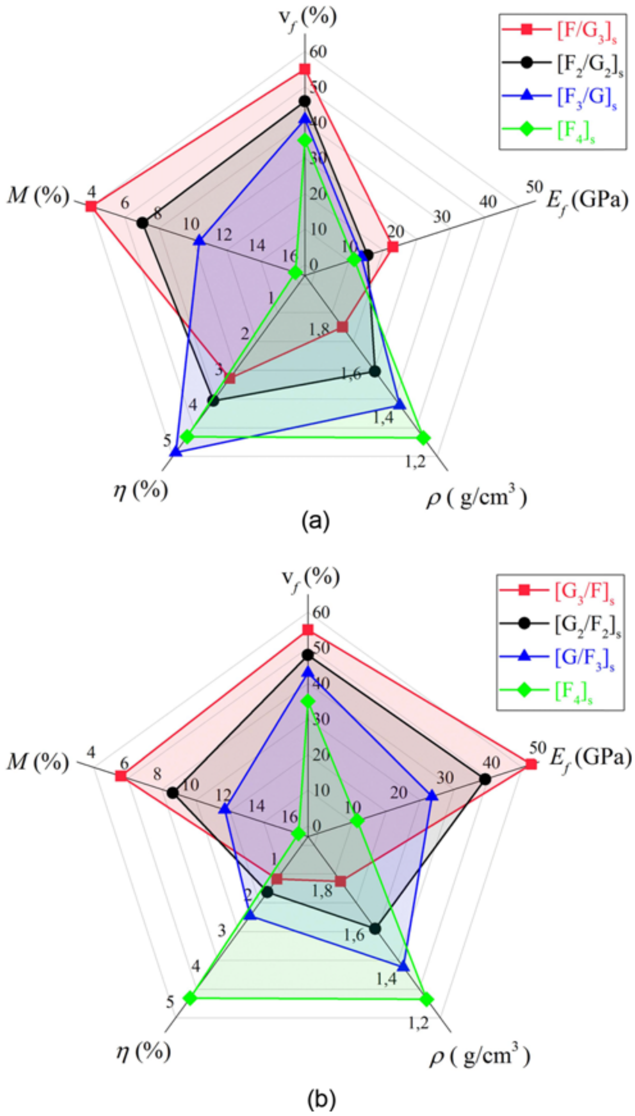

Figure 7. Radar chart according to the five selected features (V_f, *M, η, ρ* and E_f) of aged flax-glass hybrid composites; (a) $[F_m/G_n]_s$ and (b) $[G_n/F_m]_s$.

damping capacity. For this, the influence of the position of flax layers in the hybrid laminate, either as outer layers or as inner layers, was analysed after ageing as well as the number of flax layers. In order to compare these hybrid composites after ageing, the aged flax composite $[F_4]_s$ was used as a reference material. This choice was justified by non-hybrid character of laminate that was the most hydrophilic and having the best damping properties. The variations of the five selected features V_f, M_∞, η, ρ and E_f were summarised in Figure 7 from two radar charts, according to the hybrid composites with outer flax layers ($[F_m/G_n]_s$ configurations) and with inner flax layers ($[G_n/F_m]_s$ configurations). The axes are represented with the most beneficial values towards the outside of the diagram, which means that the larger the area built from the five features, the better the composite materials are considered.

The star diagrams clearly show that the selected features change according to the stacking sequence. Note that the position of flax layers in the hybrid laminate, as outer or inner layers, only has a direct influence on the values of the bending modulus, loss factor and mass gain at saturation. When the flax laminate is turned into the hybrid laminate with outer flax layers (Figure 7(a)), the area increase and shifts to the left in the upper part of the diagram. This is mainly due to the decrease of their loss factor and mass gain at saturation as well as the increase of their density. The hybrid $[F_m/G_n]_s$ laminates did not show significant signs of improvement in terms of bending modulus for aged hybrid laminates, compared to the aged $[F_4]_s$ laminate. For the conversion of the flax laminate into the hybrid one with inner flax layers (Figure 7(b)), the area also increase (but more significantly) and shifts to the upper part of the diagram both on the left and right. This is mainly explained the significant enhancement of the bending modulus. Indeed, the bending modulus of the hybrid $[G_n/F_m]_s$ laminates remains interesting (2.5 to 4.5 times higher than that of aged flax composite) although their mass gain at saturation is higher than that of their corresponding hybrid composites with outer flax layers (Figure 7(b)).

On the other hand, the radar chart show that the $[G_3/F]_s$ configuration became more interesting with ageing, mainly in terms of bending stiffness and mass gain at saturation. This configuration allows firstly an improvement of 4.5 times in the bending modulus compared to the flax composite and secondly, to considerably limit its loss with ageing: 8 % for $[G_3/F]_s$ vs. 50 % for $[F_4]_s$.

In conclusion, in order to improve the mechanical properties of flax fibre composites that are sensitive to ageing, the $[G_2/F_2]_s$ and $[G_3/F]_s$ hybrid configurations are the most efficient. In comparison to the flax composite, it enables an increase in bending modulus and specific modulus, a considerable slowing down of the diffusion phenomenon, while limiting the decrease in damping property. Indeed, the bending modulus and the specific bending modulus are equal to 10.7 GPa and 8.6 GPa·cm^3/g, respectively, for the aged $[F_4]_s$ laminate, to 38.4 GPa and 24.4 GPa·cm^3/g for the aged $[G_2/F_2]_s$ laminate and to 48.4 GPa and 27.1 GPa·cm^3/g for the aged $[G_3/F]_s$ laminate. In the case where the damping preservation of flax fibres is required with ageing, the results show that it is necessary to have a hybrid configuration with a maximum number of flax layers positioned in the outer layers. Thus, the hybrid $[F_3/G]_s$ has the best characteristics with ageing when damping is the main criterion.

In response to the initial aim of the discussion, the hybrid laminate $[G_2/F_2]_s$ offers the best compromise between mechanical properties, density, fibre volume fraction and damping properties, when subjected to water ageing. Its specific bending modulus of 24.4 GPa·cm^3/g is approximatively three times higher than that of the aged $[F_4]_s$ and also higher than the two unaged non-hybrid laminates (17.7 GPa·cm^3/g for the $[F_4]_s$ and 22.7 GPa·cm^3/g for the $[G_4]_s$). The value of its loss factor of 1.6 % remains significantly higher than that of the unaged $[G_4]_s$ (0.75 %) and close to that of the unaged $[F_4]_s$ (2 %). The advantage of this hybrid configuration is based on the bending modulus, which remains high with ageing (38.4 GPa) compared to that of the aged $[F_4]_s$ (10.7 GPa), while being significantly higher than the non-aged $[F_4]_s$ (21.4 GPa). Therefore, for a specification where damping and stiffness are the main criteria, the hybrid laminate $[G_2/F_2]_s$ can meet this requirement, whether in a humid environment or not, while having a strong specific stiffness.

Conclusion

In this paper, the effect of stacking sequence of hybrid composites was investigated through the mechanical and damping properties, taking into account ageing in long-term water immersion. The composites were composed of quasi-unidirectional flax and glass fibre laminate plies with different stacking sequences. Their mechanical and damping properties were measured using free vibrations testing. From the results and discussions presented above, the main findings of this work can be summarised as follows:

1. The saturation mass uptake and the diffusion coefficient of hybrid laminates were strongly dependent on the sequence of fibre reinforcement;
2. The saturated mass uptake of hybrid laminates increases linearly as the flax fibre volume fraction increases and this one is higher for the hybrid laminates with inner flax layers;
3. Less than 25 days were necessary for reaching the water saturation when flax layers were outer layers, whereas it took over 10 months when they were inner layers;
4. The association of flax and glass layers reduces the effect of water ageing on the bending modulus of the hybrid laminates in particular for the $[G_m/F_n]_s$ configurations;
5. The hybridisations with outer flax layers lead to higher loss factor values for both unaged and aged composites. In particular, the hybrid laminate $[F_3/G]_s$ (i.e. three outer flax

layers and one inner glass layers) has the best characteristics with ageing in terms of damping;

6. The loss factor increases with the amount of absorbed water;
7. In comparison with the unaged and aged flax fibre composites, the flax/glass hybrid laminate with two inner flax layers and two outer glass layers was the most efficient for a specification where damping and stiffness are the main criteria. The value of its loss factor remains significantly high with ageing (1.6 %) and close to that of the unaged flax fibre laminate (2 %), while its bending modulus with ageing (38.4 GPa) becomes higher than that of flax fibre laminate (unaged: 21.4 GPa and aged: 10.7 GPa). This one can meet the damping and stiffness requirement, whether in a short- or long-term water immersion or not, while having a strong specific stiffness.

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References

1. P. Wambua, J. Ivens, and I. Verpoest, *Compos. Sci. Technol.,* **63**, 1259 (2003).
2. S. V. Joshi, L. T. Drzal, A. K. Mohanty, and S. Arora, *Compos. Part A-Appl. Sci. Manuf.,* **35**, 371 (2004).
3. L. Yan, N. Chouw, and K. Jayaraman, *Fiber. Polym.*, **15**, 1270 (2014).
4. S. Prabhakaran, V. Krishnaraj, M. Senthil Kumar, and R. Zitoune, *Proc. Eng.*, **97**, 573 (2014).
5. A. Monti, A. El Mahi, Z. Jendli, and L. Guillaumat, *Compos. B-Eng.,* **110**, 466 (2017).
6. F. Duc, P. E. Bourban, C. J. G. Plummer, and J. A. E. Manson, *Compos. Part A-Appl. Sci. Manuf.*, **64**, 115 (2014).
7. F. Duc, P. E. Bourban, and J. A. E. Manson, *J. Reinf. Plast. Compos.*, **33**, 1625 (2014).
8. N. Saba, M. Jawaid, O. Y. Alothman, and M. T. Paridah, *Construct. Build. Mater.,* **106**, 149 (2016).
9. M. Z. Rahman, K. Jayaraman, and B. R. Mace, *Fiber. Polym.*, **18**, 2187 (2017).
10. M. Z. Rahman, K. Jayaraman, and B. R. Mace, *Fiber. Polym.*, **19**, 375 (2018).
11. M. J. Le Guen, R. H. Newman, A. Fernyhough, G. W. Emms, and M. P. Staiger, *Compos. Part B-Eng.,* **89**, 27 (2016).
12. S. C. Furtado, A. L. Araújo, and A. Silva, *Compos. Struct.,* **189**, 529 (2018).
13. Y. Li, S. Cai, and X. Huang, *Compos. Sci. Technol.*, **143**, 89 (2017).
14. J. Vanwalleghem, I. De Baere, S. Huysman, L. Lapeire, K. Verbeken, A. Nila, S. Vanlanduit, M. Loccufier, and W. Van Paepegem, *Polym. Test.,* **55**, 269 (2016).
15. L. Yan, *J. Reinf. Plast. Compos.,* **31**, 887 (2012).
16. A. Bourmaud, C. Morvan, A. Bouali, V. Placet, P. Perré, and C. Baley, *Ind. Crop. Prod.*, **44**, 343 (2013).
17. A. Lefeuvre, A. Le Duigou, A. Bourmaud, A. Kervoelen, C. Morvan, and C. Baley, *Ind. Crop. Prod.,* **76**, 1039 (2015).
18. S. Mahmoudi, A. Kervoelen, G. Robin, L. Duigou, E. M. Daya, and J. M. Cadou, *Compos. Struct.*, **208**, 426 (2019).
19. M. Bayart, F. Gauvin, M. R. Foruzanmehr, S. Elkoun, and M. Robert, *Fiber. Polym.*, **18**, 1288 (2017).
20. A. Chilali, W. Zouari, M. Assarar, H. Kebir, and R. Ayad, *Compos. Struct.,* **183**, 309 (2018).
21. H. Wang, G. Xian, H. Li, and L. Sui, *Fiber. Polym.*, **15**, 1029 (2014).
22. M. Assarar, D. Scida, A. El Mahi, C. Poilâne, and R. Ayad, *Mater. Des.*, **32**, 788 (2011).
23. K. Cheour, M. Assarar, D. Scida, R. Ayad, and X. L. Gong, *Compos. Struct.,* **152**, 259 (2016).
24. G. Ma, L. Yan, W. Shen, D. Zhu, L. Huang, and B. Kasal, *Compos. Part B-Eng.*, **153**, 398 (2018).
25. L. Yan and N. Chouw, *Constr. Build. Mater.,* **99**, 118 (2015).
26. D. Zhao, Y. Dong, J. Xu, Y. Yang, K. Fujiwara, E. Suzuki, T. Furukawa, Y. Takai, and H. Hamada, *Fiber. Polym.*, **17**, 2131 (2016).
27. S. Panthapulakkal and M. Sain, *J. Compos. Mater.*, **41**, 1871 (2007).
28. E. H. Saidane, D. Scida, M. Assarar, H. Sabhi, and R. Ayad, *Compos. Part A-Appl. Sci. Manuf.*, **87**, 153 (2016).
29. H. N. Dhakal, Z. Y. Zhang, R. Guthrie, J. MacMullen, and N. Bennett, *Carbohyd. Polym.,* **96**, 1 (2013).
30. R. V. Silva, E. M. F. Aquino, L. P. S. Rodrigues, and A. R. F. Barros, *J. Reinf. Plast. Compos.,* **28**, 1857 (2009).
31. D. Scida, M. Assarar, C. Poilane, and R. Ayad, *Compos. Part B-Eng.,* **48**, 51 (2013).
32. A. Chilali, W. Zouari, M. Assarar, H. Kebir, and R. Ayad, *J. Reinf. Plast. Compos.*, **35**, 1217 (2016).
33. B. Peeters, H. Van Der Auweraer, and P. Guillaume, *Shock Vib.*, **11**, 395 (2004).
34. E. H. Saidane, D. Scida, M. Assarar, and R. Ayad, *Compos. Part A-Appl. Sci. Manuf.,* **80**, 451 (2016).
35. A. Chilali, M. Assarar, W. Zouari, H. Kebir, and R. Ayad, *Compos. Part A-Appl. Sci. Manuf.*, **95**, 75 (2017).
36. J. M. Berthelot, “Matériaux Composites. Comportement mécanique et analyse des Structures”, 5th eds., Tec & Doc, Paris, 2012.
37. J. M. Berthelot, “Composite Materials. Mechanical Behavior and Structural Analysis”, Springer, New York, 1999.
38. A. Le Duigou, P. Davies, and C. Baley, *Polym. Degrad. Stab.,* **94**, 1151 (2009).
39. H. M. Akil, L. W. Cheng, Z. A. M. Ishak, A. Abu Bakar, and M. A. Abd Rahman, *Compos. Sci. Technol.,* **69**, 1942 (2009).
40. M. Assarar, W. Zouari, H. Sabhi, R. Ayad, and J. M. Berthelot, *Compos. Struct.,* **132**, 148 (2015).