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Effect of Stacking Sequence on the Tensile and Flexural Properties of Glass Fibre Epoxy Composites Hybridized with Basalt, Flax or Jute Fibres

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Abstract

The effect of stacking sequence and hybridization on the tensile and flexural properties of composite laminates between basalt, jute and flax with E-glass reinforced epoxy has been investigated experimentally. It was found that the stacking sequence has a limited significance over tensile properties, whereas flexural strength and modulus appeared to change considerably between sandwich-like and intercalation hybrid sequences. Specific modulus measurements based on the different densities of the various hybrid laminates produced were used to discover the best combination either basalt, jute or flax with E-glass exhibits superior properties concerning on the strength to weight-ratio. Hence, stacking sequences and material selection are among predominant factors that influence on mechanical properties and very crucial in designing composite hybrid system to meet the desired requirements.

Keywords: Natural fibres, Hybrid composites, Stacking sequence, Tensile properties, Flexural properties.

Introduction

In a number of industrial sectors, the use of thermosetting matrices reinforced with glass fibres is still prevalent and this trend is likely to continue in the near future. However, the introduction of other fibres, such as vegetable (e.g., flax, jute, sisal, etc.) or mineral (basalt) ones, together with glass fibres, therefore obtaining hybrid composite laminates, is likely in many cases to reduce the environmental impact of composite production. This will be obtained as the consequence of the renewable character of the fibres, in the case of plant-extracted ones, and of the limited amounts of sizing agents needed for fabrication, in the case of basalt ones [1]. Moreover, the production of hybrid composites including both glass fibres and vegetable fibres does reduce the density of materials, therefore the attention is more focused on yielding acceptable specific properties [2-3]. On the other side, composite materials also have their own sphere of applications and limitations, therefore selection of the combination of different

materials should be performed in a judicious way if the desired properties are to be achieved. A number of studies have been performed recently, which suggest that mechanical and impact properties can be possibly tailored using hybridization between glass fibres and other fibres, such as of basalt, jute and flax [4-6]. The effect of stacking was clearly assessed for glass/basalt fibre hybrid laminates, where intercalation of glass and basalt layers, with the latter as outer layers, offered improved impact energy absorption capacity and enhanced damage tolerance capability with respect to glass fibre laminates [7]. In jute/glass fibre reinforced polyester composites, stacking sequence has greater effect on flexural and interlaminar shear properties than tensile properties on flexural loading: in general terms, the sequence with glass fibre layers disposed externally performed better [8]. This is basically confirmed in Pandita SD, et al [9], where the effect of the outer layers of fibreglass was also significant in terms of modifying water absorption profile. However, concerns about the predictability of residual performance following impact damage of glass/jute/glass fibre hybrid laminates are raised elsewhere [10]. It needs to be noticed that jute fibre laminates are not always necessarily used as the core of other laminates: for example arrangement of woven jute as a skin and oil palm EFB fibre as a core leads to enhanced flexural strength and modulus [11].

Dealing with the use of basalt fibre in hybrid laminates, the highest increase in mechanical properties over pure glass fibre reinforced laminates is related to the application of basalt fibre layers externally to these, though with non negligible delamination problems under flexural loading [12]. More complex hybrids have also been fabricated, such as in [6], involving basalt fibres, however the emphasis was more put on the types of fibres employed, rather than on the effect of stacking sequence.

The objectives of the present work, focusing on the partial replacement of glass fibres with other fibres, are to investigate and compare the effect of stacking sequences and hybridization of glass/basalt, glass/jute and glass/flax on tensile and flexural

loadings. In addition, fracture surfaces are characterized using scanning electron microscopy (SEM) to identify the type of failure modes exhibited by the specimens after testing.

Materials and methods

Material

Hybrid composite laminates were produced using different fibres as reinforcements and using epoxy matrix throughout: the characteristics of these materials are listed in Table 1. All natural fibres were supplied by local third-party supplier, which is responsible to arrange and deliver from United Kingdom to our place in good conditions. E-glass fibres and epoxy resin were supplied by Chemrex Corporation Sdn.Bhd, Selangor Malaysia. Epoxy resin DM15F3 (A) cured with hardener DM15F3 (B) in the ratio of 5:1 was used as a matrix. To allow for comparison, all the fibres were supplied in the form of plain weave, although with different areal weight.

Table 1: Material properties as declared by manufacturers

Fibre	Areal weight (g/m ²)	Density (g/cm ³)	Tensile strength (MPa)	Tensile Modulus (GPa)	Elongation (%)
E-glass	600	2.5	3200 ± 300	63 ± 5	5 ± 0.3
Flax	200	1.5	500 ± 130	50 ± 10	2.5 ± 0.5
Jute	290	1.46	400 ± 120	15 ± 6	4.5 ± 2
Basalt	200	2.7	571 ± 219	63 ± 18	3.5 ± 0.3
Epoxy	-	1.17	85 ± 10	10.5 ± 4	3.2 ± 0.5

Samples fabrication

Composite panels have been produced using vacuum infusion process (VIP). A stack of dry reinforcements are laid onto the glass mould, which are then sealed with vacuum bag. The applied vacuum creates a pressure differential which is used to literally suck resin into the dry fabric lay-up via placement of spiral tubing. During infusion stage, vacuum pressure was maintained at 78 ± 10 kPa using vacuum pump model ECVP425 provided by Easy Composite, United Kingdom. Laminates were cured at room temperature for 24 hours and then post-cured in an oven at 60°C for 3 hours. For this study, two types of stacking sequences were considered during sample preparation, namely sandwich-like and intercalation sequences with a total of seven plies comprising E-glass and other fibres, either jute, flax and basalt. Details about the hybrid laminate samples are shown in Table 2.

Table 2: Hybrid laminated composites

Symbol	Stacking sequence	Thickness (mm)	Density (g/cm ³)
S1	[G ₂ /B ₃ /G ₂] - sandwich-like	2.1	1.85
S2	[G ₂ /J ₃ /G ₂] - sandwich-like	4.2	1.43
S3	[G ₂ /F ₃ /G ₂] - sandwich-like	3.0	1.56
S4	[G/B/G/B] _G - intercalation	2.3	1.87
S5	[G/J/G/J] _G - intercalation	4.2	1.42
S6	[G/F/G/F] _G - intercalation	2.8	1.51

Legend : G – glass, B – basalt, J – jute, F – flax

Tensile testing

Tensile tests were performed according to ASTM D638-10 using universal testing machine, Instron Model 5969 with a load cell of 10 kN at cross-head speed of 2 mm/min. Specimens were cut using 2-axis milling machine, Rolland MDX-40A according to dumbbell shape (Type I) at adjustable parameters such as speed rate, depth of cut and feed rate to suit with the types of reinforcement and resin used. Prior to test, specimens were inspected to ensure all the cutting edges are in good conditions and free from defects such as notch, etc. Testing specimens were positioned vertically in the grips using recommended grip face based on the sample thickness and were tightened firmly to prevent any slippage. During testing, gauge length was kept at 100 mm for all the specimens and at least five identical specimens were tested for each of the configuration and the average result is obtained [13].

Flexural testing

ASTM D790-10 standard was followed for three-point bending tests, performed using a universal testing machine, Instron Model 5969. During testing, specimens were loaded in three-point bending mode with recommended span to depth ratio of 16:1 with a load cell of 10kN at a cross-head speed of 2 mm/min at room temperature [15]. At least five identical specimens were tested for each sample. Flexural strength was calculated using the following equation [14]:

$$\sigma_f = 3PL/2bd^2 \tag{1}$$

where σ_f is the flexural strength (MPa), P is the maximum load (N), L is support span (mm), b is the width and d the depth in mm of the beam tested. Flexural modulus, E_f , was calculated using tangent modulus of elasticity using the following equation [15];

$$E_f = L^3 m / 4bd^3 \tag{2}$$

Where E_f is modulus of elasticity in bending (MPa), L is support span (mm), b is width of beam tested (mm), d is depth of beam tested (mm), and m is the slope of the tangent to the initial straight-line portion of the load-deflection curve (N/mm).

Morphology study

A Scanning Electron Microscope (SEM) EVO 50 (CarlZeiss, UK) was used to analyze the morphological images of the hybrid composites. Prior to morphological examination, the fractured specimens were sputter-coated with gold and SEM micrographs were obtained under conventional secondary electron imaging conditions with an acceleration voltage of 5 KV.

Results and discussion

Effect of stacking sequences on tensile loading

The effect of stacking sequences of hybrid composite laminates on the tensile strength and modulus will be analysed in this section. All the six hybrids were realised trying to keep constant the general amount of reinforcement fibres, in particular to around 40 wt.% of glass fibres and around 30 wt. % of other fibres (basalt, jute or flax), for a total of around 70 wt.% fibres.

However, in general terms, the comparison needs to take into account the relevant thickness of the laminates, therefore a comparison between the whole set of six hybrid laminates, three sandwich-like and three with intercalated structure, does not

make sense. Therefore the three couples formed by laminates with the same fibres, hence glass/basalt (S1 vs. S4), glass/jute (S2 vs. S5) and glass/flax (S3 vs. S6), and approximately the same thickness, will be carried out against each other.

As seen in Figure 1, it can be concluded that a slight decrease both of tensile strength and tensile modulus is observed throughout when passing from sandwich-like to intercalated one. Only in the case of glass/flax hybrid laminates, the decrease is more significant, amounting at almost 20%. In general terms, it can be concluded that the effect of stacking sequence has not significantly contributed to better withstanding tension load. On the other side, it can be suggested that the presence of a larger number of interfaces, such as in hybrids with intercalated structure, may be detrimental on the final properties of the laminates, especially on their stiffness. This finding only partially agreed with previous study on the effect of lay-up architecture on the plain-weave flax laminates. In that case, it was suggested that the effect of the amount of fibres oriented in the load direction was absolutely predominant and exclusive [15].

Effect of stacking sequences on flexural loading

Generally, hybrid laminates comprising two layers of glass as a face sheet and three layers of natural fibres either basalt, jute or flax as a core exhibited higher flexural strength and modulus compared those with intercalated sequence, as shown in Figure 2. The differences were considerably larger than in the case of tensile loading, this time especially for laminates including basalt fibres and jute fibres. Comparing with tensile results and bearing in mind that flexural loading implies tensile loading on the upper side and compressive one on the lower side of the laminates, it may be also suggested that the main detrimental effect of intercalation would come from reduced compressive strength. Hence, the investigation revealed that the arrangement of fibres in hybrid composite structure strongly affects its flexural strength and modulus. This might be due to the predominance of compressive mode of failure on the properties of the laminate. This has been observed wherever vegetable fibres are involved (e.g., in glass/coir fibre composites, where small delaminations were clearly forming around the fractured coir fibres, but not around glass

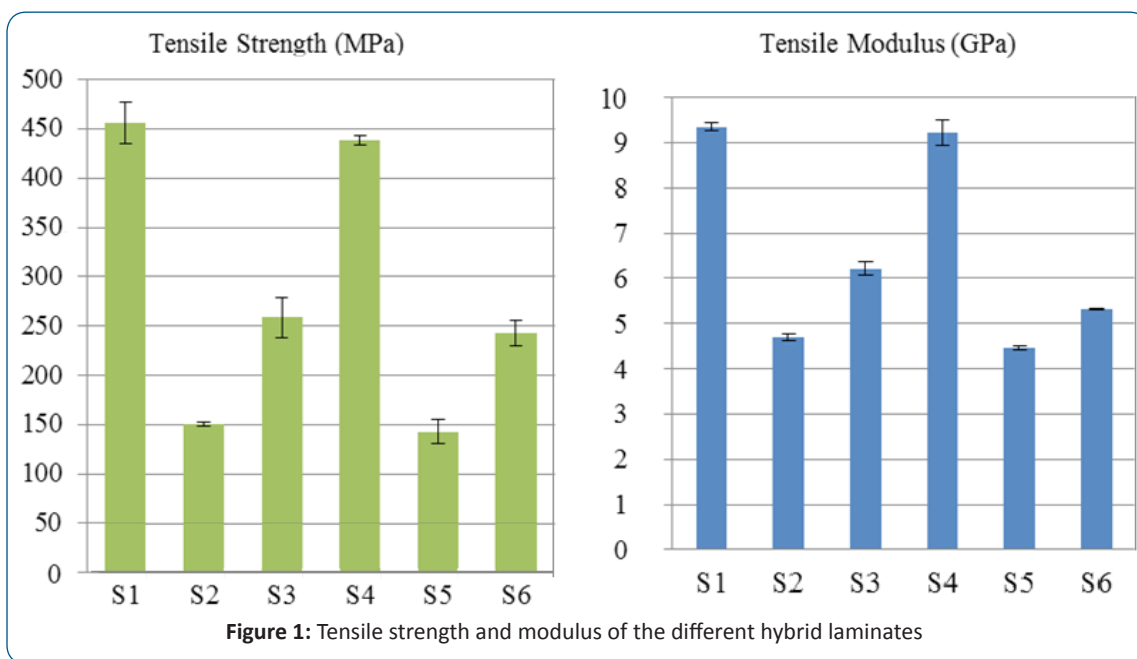


Figure 1: Tensile strength and modulus of the different hybrid laminates

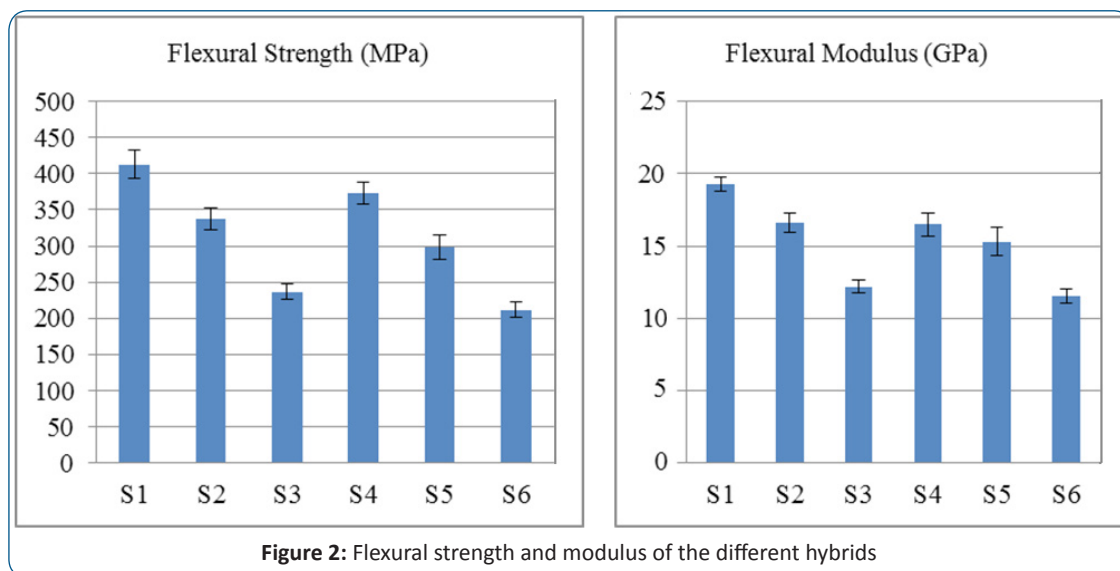
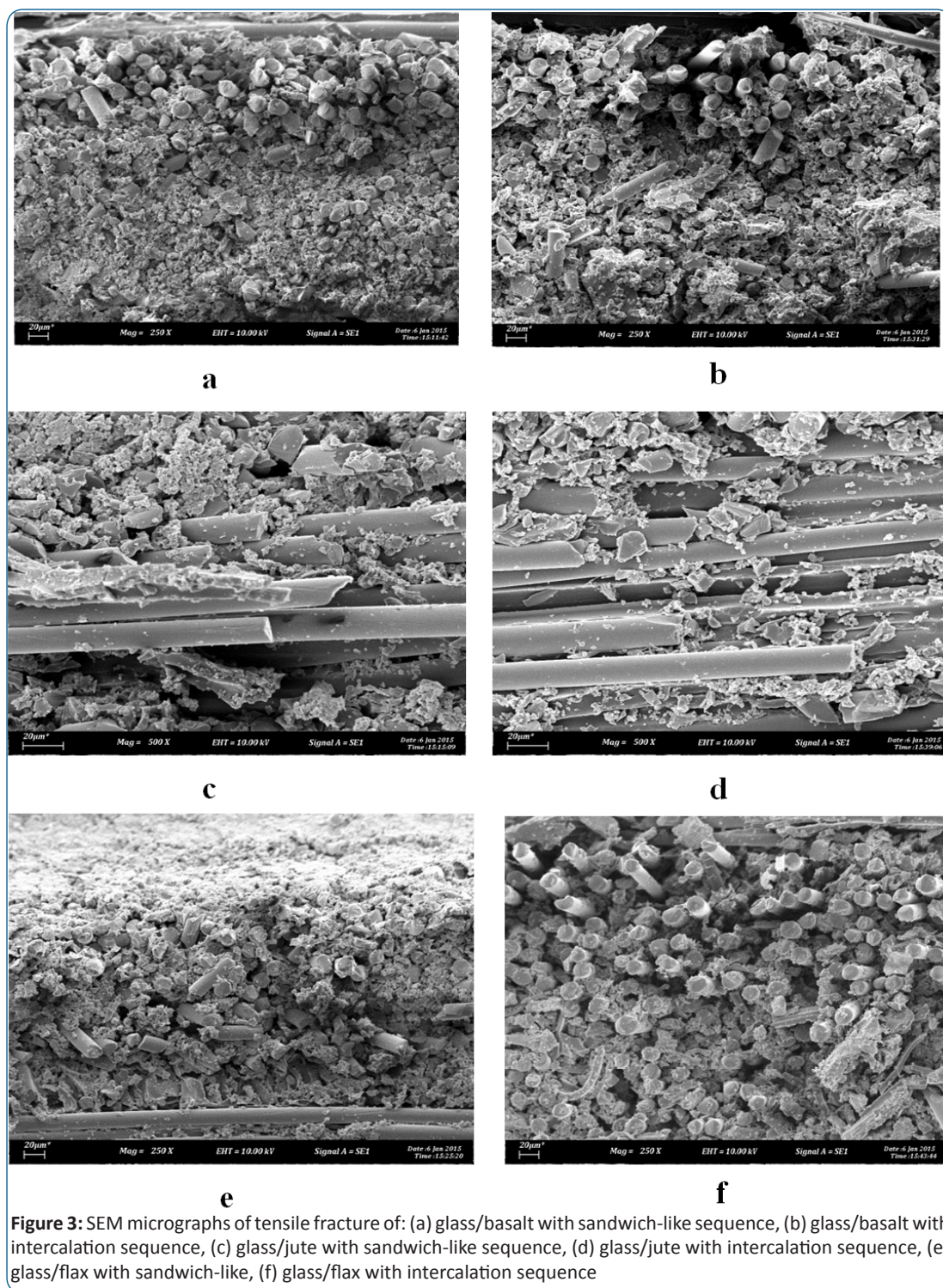


Figure 2: Flexural strength and modulus of the different hybrids

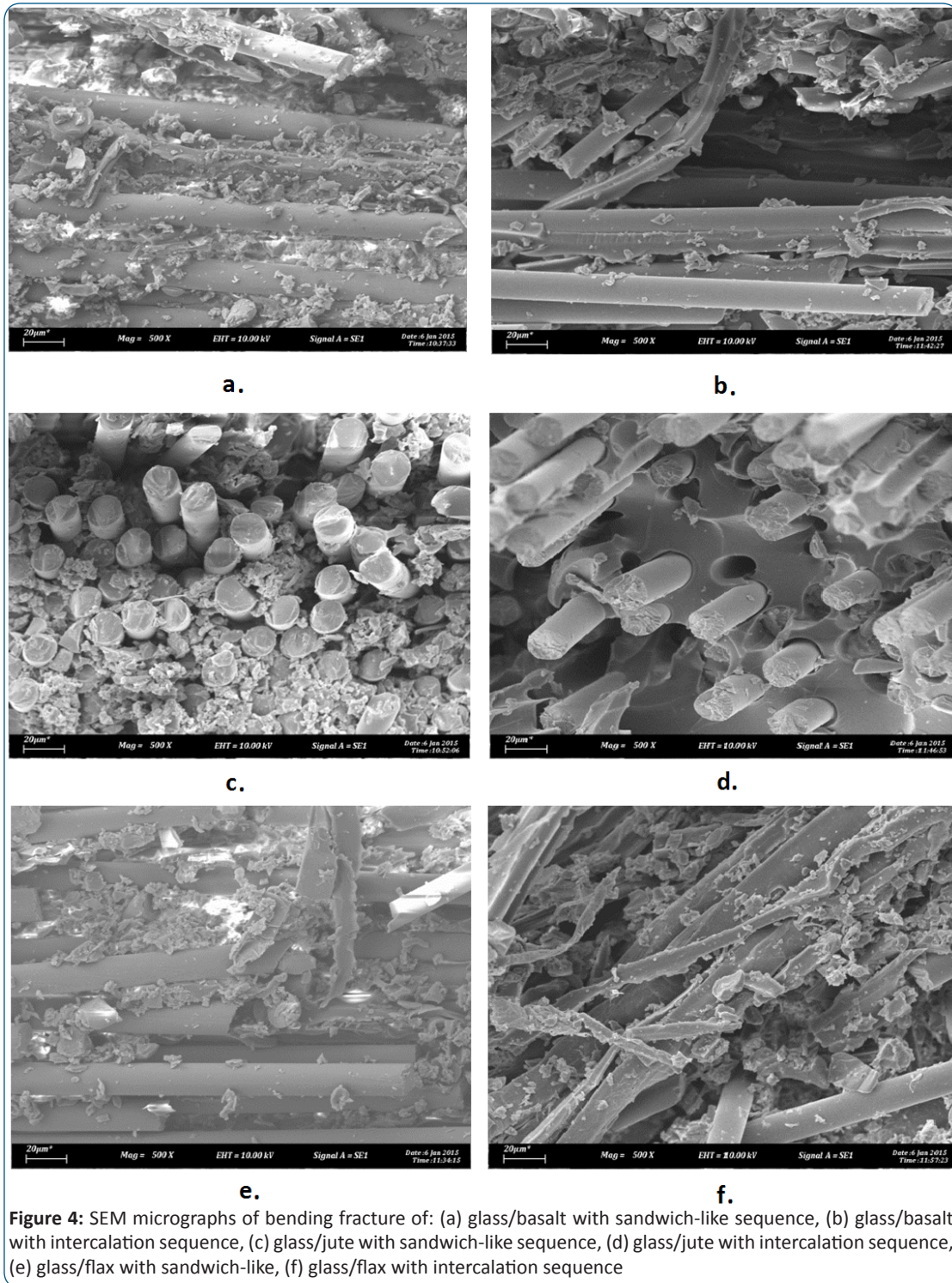


ones) [16]. Compressive mode is also predominant in the case of basalt fibres, while this is not the case for carbon fibres [17]. As a matter of fact, whenever compressive loading is predominant, though localised, such as in falling weight impact tests, it is important to notice that selecting different fibres to fabricate the core may have significant effects in delaying the onset of damage [18]. Another consideration can be done on the fact that using jute offered a lower decrease in flexural performance than it was the case with flax, considering that basalt is obviously superior, but entails a considerable weight penalty, while the opposite is true for tensile performance, where flax is clearly superior. This result was observed already with composites with other matrices,

such as polypropylene [19]. This is likely to be attributed to the presence of fibrillation (i.e., separation of the different filaments during loading), which is very diffuse in jute, also due to the need for alkali treatment [20]. Fibrillation appears a limiting factor for tensile performance, whereas it provides a larger bonding surface between fibre and matrix, which may improve flexural properties [21].

Fracture characteristics of hybrid composites

Tensile fracture analysis: In the case of tensile loading, almost all the tested structures fail due to the fibre breakage, as evidenced in Figure 3. Glass/basalt hybrid laminate shows the failure first in



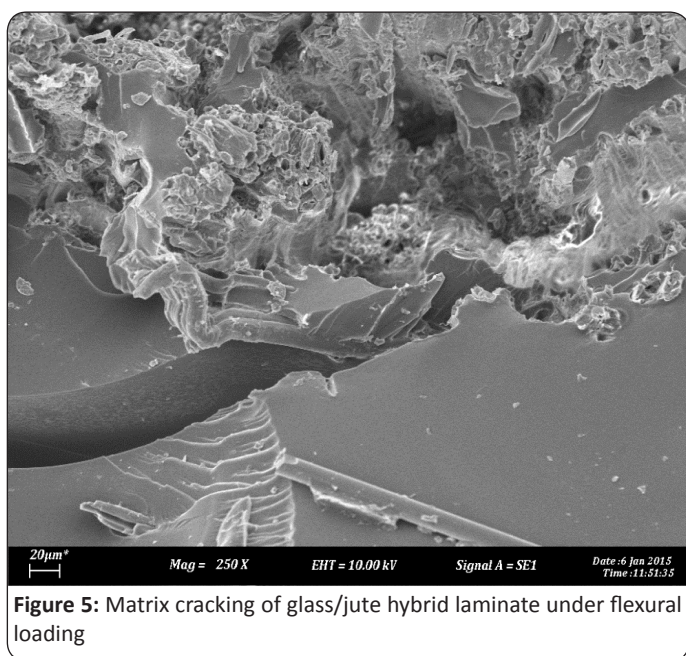
correspondence with the failure of glass layer followed by basalt layer, as shown in Figure 3a and 3b. However, hybrid composite laminates of glass/jute and glass/flax exhibit the dominant failure mode caused from the weakness of jute and flax fibres, respectively. Failure of hybrid composite laminates with intercalation sequence are governed by the extensive degree of fibre pull-outs and fibre breakage as evidenced in hybrid laminate of glass/basalt (Figure 3b), glass/jute (Figure 3d) and glass/flax (Figure 3f) compared with sandwich-like sequences. This can be explained due to the poor interfacial bonding between natural fibres of basalt, jute and flax compared with better surface adhesion of glass fibre with epoxy resin. In addition, composite with two layers of glass at the extremities mostly did not break into two halves for all the

type of hybrid configurations investigated here. The outer layers of glass fibres contributed to create the stronger bridging rupture and reduce stress distribution to the natural fibres of basalt, jute and flax. This phenomenon agreed with Zhang et al [12] on the glass/carbon woven fabrics for light weight bearing structures.

Flexural fracture analysis: The flexural strengths and modulus of hybrid structures of glass/basalt, glass/jute and glass/flax with sandwich-like sequence are higher than for intercalation sequence and these can be explained by considering the failure mechanism as shown in Figure 4. Glass/basalt (Figure 4b) shows a laminate failing for premature delamination at the interface between the basalt and glass layer caused by internal failure of the layers interface. This kind of failure was similar as evidenced

in the glass/flax laminate (Figure 4f). It is interesting to note that delamination mechanism seems not happened as the presence of two glass layers rather than one in all hybrid structures (Figure 4a, 4c and 4e), which leads the stress gap between the glass layers and natural fibre layers to decrease. Delamination is one of the most common and dangerous failure mechanisms of hybrid composite laminates under bending load, such as indicated in previous studies particularly on hybrids including vegetable fibres [22-24]. Glass/jute with intercalation sequence exhibits an extensive degree of fibre pull-out and apparent that fibres have also been peeled from fracture surface (Figure 4d).

In the particular case of glass/jute fibre laminates, matrix cracking and fracture lines were clearly revealed on the surfaces that exhibited poor interfacial bond with the cracking at the early stages damage the matrix and glass layers then transfer to the jute fibre. On the other side, the presence of glass on the next layer adjacent to jute layer will slow down and blunt the damage propagation, as shown in Figure 5.



Conclusions

The effects of stacking sequences of glass/basalt, glass/jute and glass/flax reinforced epoxy on tensile and flexural loadings have been experimentally investigated with two different configurations, sandwich-like and intercalation sequence. Specific properties were used to study the effect of hybridization between E-glass and natural fibres based on specific tensile strength, specific tensile modulus, specific flexural strength and specific flexural modulus due to the different densities of the hybrid laminates considered here.

From the results of the experimental test, it can be concluded that:

1. Effect of stacking sequences of hybrid laminates between sandwich-like and intercalation sequence is not highly significant on tensile loading for all hybrid configurations between glass/basalt, glass/jute is limited, less so on tensile strength and especially modulus of glass/flax hybrids, where the sandwich configurations were superior.
2. Glass/basalt hybrids in both configurations showed the highest value on the specific tensile strength and modulus even though

natural fibre of basalt exhibits the highest density compared with jute and flax.

3. The stacking sequence was found to affect the flexural properties of the hybrid composites. Higher flexural strengths and modulus were obtained when two layers of glass were put at extreme sides compared with intercalation sequence.
4. Comparing the effect of the introduction of jute and flax fibres in fibreglass, the former was more suitable for flexural performance, while the latter performed better under tension.
5. Scanning electron micrographs showed that the predominant failure modes of tensile tests are fibre pull out and fibre breakage, whereas almost of the composite laminates exhibit delamination and matrix cracking under flexural loadings.

By varying the stacking sequences of the components of the hybrid composite, we can tailor the mechanical properties of the resulting hybrid material according to our target of applications. In this regard, a future investigation on hybrids including both jute and flax fibres would be suggestive, as these two fibres showed quite complementary properties, mechanically speaking (see above point 4). However, more extensive work on the above lines with differing material parameters are needed to take full advantage of excellent strength and stiffness properties of all the hybrid configurations between glass/basalt, glass/jute and glass/flax. In particular, it could be indicated that a study of static properties, such as tensile and flexural performance, alongside e.g., with impact performance and especially residual properties post-impact damage would be needed.

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