Effect of stacking sequence and hybridization on the tensile and flexural properties of natural fibres based hybrid laminated composites

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Abstract: *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 have been investigated experimentally. It was found that stacking sequence is not highly significant on tensile properties, contrasting with flexural strength and modulus which were strongly dependent on the hybrid configuration between sandwich-like (SL) and intercalation (IC) sequences. Specific modulus based on the variation densities of the hybrid laminates was 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 Fibre, hybrid, stacking sequence, tensile and flexural*

I. Introduction

In the 21st century, the development of eco-friendly, biodegradable, sustainable and renewable resources of materials gains attention exclusively. This kind of green technology development is very crucial to cope with global warming and highly concern with environmental issues. New perspectives have arisen on the usage of natural fibres due to the special attributes offered and potentially low cost together with their good mechanical performance, such as basalt fibre which is capable to resist at high temperature [1]. The idea to fill these fibres into a polymer matrix is relatively recent and the development of hybrid laminated composites using synthetic and natural fibres could offer very interesting perspectives that have not yet been sufficiently investigated. Furthermore, composite materials are broadly used in various fields and applications currently due to unique properties and characteristics that cannot be realized by conventional material. Hybridization of composite laminates with natural fibres gain attention widely due to the lower density of materials offered, yielding relatively light weight composites with specific properties, low cost, acceptable specific properties, ease of separation, enhanced energy recovery and biodegradability [2,3]. However, composite materials also have their own sphere of applications and limitations, therefore selection combination of different materials should be done in a judicious way in order to achieve the desired properties. A number of studies have been performed recently, which suggest that mechanical properties can be possibly tailored using hybridization between synthetic and natural fibres of basalt, jute and flax [4 - 9]. Effect of stacking sequence between jute/glass reinforced polyester resin on flexural loading was studied and it was found that incorporation of glass in jute fibre composites enhances the properties of hybrid composites [4]. Empty fruit bunches (EFB)/jute reinforced epoxy with different layering pattern was investigated and the result indicated that the arrangement of woven jute as a skin and oil palm EFB fibre as a core leads to enhance in flexural strength and modulus [5]. Hybrid composites with different stacking sequences of glass/carbon [6], carbon/basalt [7], jute/glass [8] on the mechanical loadings significantly affected the properties of the laminates. The objectives of the present work are to investigate the effect of stacking sequences and hybridization of E-glass/basalt, E-glass/jute and E-glass/flax on tensile and flexural loadings. In addition, fracture analysis will be characterized using scanning electron microscopy (SEM) to identify the type of failure modes exhibit by the specimens after testing.

II. Materials and methods

II.1. Material

Hybrid composite laminates were produced using reinforcements and matrix as shown in Table 1. Natural fibres were supplied by Creative Composite, United Kingdom. Material data sheets were also provided for references. Synthetic fibre of E-glass 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.

Table 1: Material properties

Fibre	Arial weight (g/m^2)	Density (g/cm^3)	Tensile strength (MPa)	Tensile Modulus (GPa)	Elongation (%)
E-glass	600	2.5	2000 – 3500	63 ± 5	0.5
Flax	200	1.5	500 ± 130	50 ± 10	2.0
Jute	290	1.46	400 ± 120	40 ± 10	1.8
Basalt	200	2.7	571 ± 219	63 ± 18	0.9 ± 0.3
Epoxy	-	1.17	85 ± 10	10.5 ± 4	0.8

II.2. Sample 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 sucked resin into the dry fabric lay-up via carefully placing of spiral tubing as shown in Fig.1. 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, then post- curing 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 (SL) and intercalation (IC) sequences with the total of seven plies comprising of E-glass and natural fibres. Details about the hybrid laminated samples as shown in Table 2.

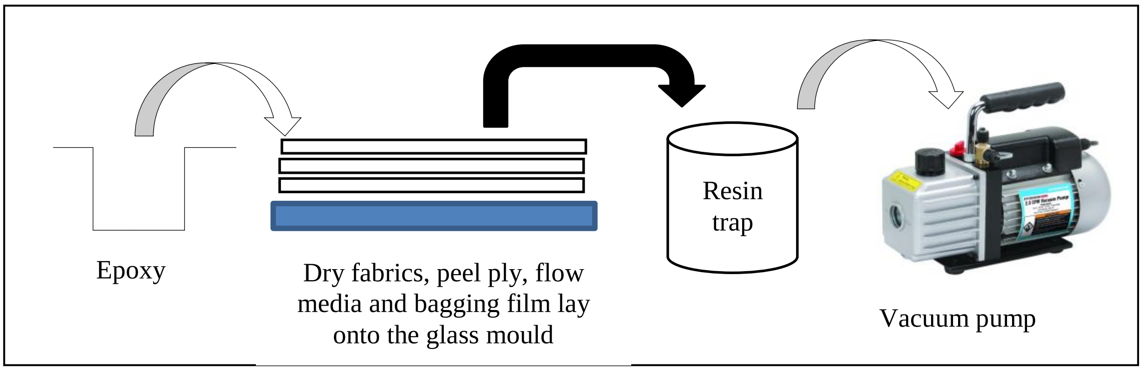


Fig. 1 : Schematic of VIP

Table 2 : Hybrid laminated composites

Symbol	Stacking sequence	Thickness (mm)	Density (g/cm^3)
S1	$[G_2/B_3/G_2]$ - (SL)	2.1	1.85
S2	$[G_2/J_3/G_2]$ - (SL)	4.2	1.43
S3	$[G_2/F_3/G_2]$ - (SL)	3.0	1.56
S4	$[G/B/G/B]_S$ - (IC)	2.3	1.87
S5	$[G/J/G/J]_S$ - (IC)	4.2	1.42
S6	$[G/F/G/F]_S$ - (IC)	2.8	1.51

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

II.3. Tensile testing

Tensile test was done according to ASTM D638-10 using universal testing machine, Instron Model 5969 with a load cell of 10 kN at a 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 the test, specimens were inspected to ensure all the cutting edges are in good conditions and free from defects such as notch and et cetera. 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 configurations and the average result is obtained [9]

II.4. Flexural testing

ASTM D790-03 standard was strictly followed for three-point bending test and used also 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 2.0 mm/min at room temperature [10]. At least five identical specimens were tested for each sample. Flexural strength was calculated using the following equation [10] ;

$$\sigma_f = 3PL/2bd^2 \quad \text{A} \qquad (1)$$

where σ_f is the flexural strength (MPa), *P* is the maximum load (N), *L* is support span (mm), *b* is width of beam tested (mm) and *d* is depth of beam tested (mm). Flexural modulus, E_f was calculated using Tangent Modulus of Elasticity using following equation [10] ;

$$E_f = L^3 m/4bd^3 \qquad (2)$$

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 slope of the tangent to the initial straight-line portion of the load-deflection curve (N/mm).

II.5. Morphology study

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

III. Results and discussion

III.1. Effect of stacking sequences on tensile loading

Effect of stacking sequences of hybrid composite laminates on tensile strength and modulus will be analysed in this section. As seen in the Fig. 2 and Fig.3, it can be concluded that there is no substantial difference in the tensile strength between (SL) and (IC) sequence of the hybrid laminates. Tensile strength of glass/basalt with (SL) sequence (S1) only shows approximately less than 5% higher compared with E-glass/basalt with (IC) sequence (S4). E-glass/jute (S2) and (S4) show tensile strength and modulus of 151 MPa, 4.68 GPa and 143 MPa, 4.47 GPa, respectively. The effect of stacking sequences is not highly significant on the E-glass/jute hybrid laminates since sample (S2) only shows 5.3% and 4.49% higher on tensile strength and modulus compared with sample (S4). This trend was similarly observed on hybrid laminate of E-glass/flax (S3) versus (S6). These findings can be explained due to the probability of equivalent effect of fibre loading acting on the cross-sectional area of the hybrid laminate perpendicular to the direction of applied load. Although the sequences are different, but hybrid laminates were constructed to keep maintain the equal percentage of fibre weight fraction, W_f between synthetic and natural fibre, which comprising E-glass and natural fibre with the fibre weight fraction of 40% and 30%, respectively. Hence, the effect of stacking sequence in this present study has not significantly contributed to withstand tension load. This finding agreed with the previous study on the effect of lay-up architecture on the plain-weave flax[11] and hybrid composite laminates of glass/carbon with different sequences[6]

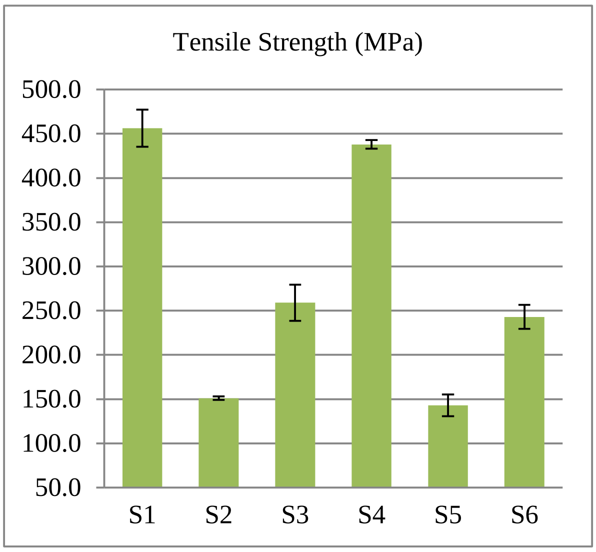


Fig. 2 : Tensile strength of hybrid laminates

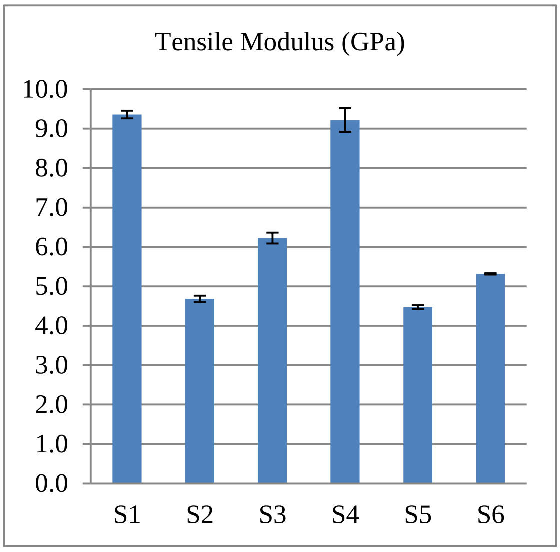


Fig. 3 : Tensile modulus of hybrid laminates

III.2. Effect of hybridization on tensile loading

Effect of hybridization between hybrid laminated composites of E-glass/basalt, E-glass/jute and E-glass/flax was compared based on specific tensile strength and specific tensile modulus as shown in Fig. 4 and Fig. 5. Specific properties were calculated based on the density value of the hybrid laminates as mention in Table 2. E-glass/basalt (S1) exhibits the highest specific tensile strength and modulus, followed by E-glass/flax (S3) and E-glass/jute (S2). Even though basalt fibre shows the highest density value of 2.7 g/cm^3 compared with jute and flax, but E-glass/basalt (S1) displays 57 % and 36 % higher in term of specific tensile strength and modulus compared with E-glass/jute (S2). Laminated composites of E-glass/jute (S2) and E-glass/flax (S3) exhibit specific tensile strength and modulus of 106 MPa, 3.3 GPa and 166 MPa, 4.0 GPa, respectively. The same trend was similarly observed on hybrid laminated composites with an (IC) sequence of E-glass/basalt (S4), E-glass/jute (S5) and E-glass/flax (S6). It is interesting to note that the density value of hybrid laminates plays a significant role in representing the specific properties of the hybrid laminates, hence it's become a valuable guide to select an appropriate material for constructing hybrid laminated composites, particularly when its application highly concerns on the strength to weight ratio.

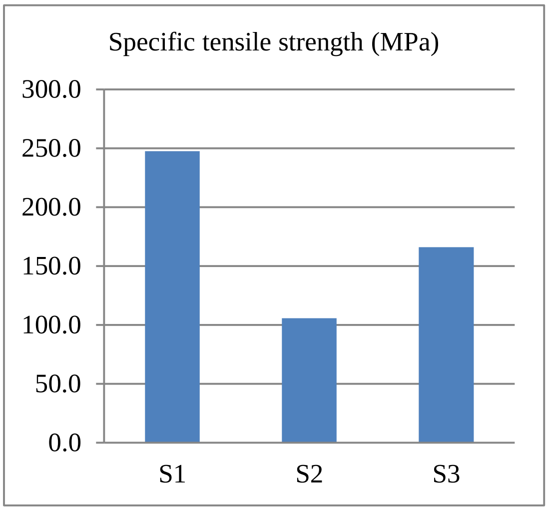


Fig. 4 : Specific tensile strength of (SL) laminates

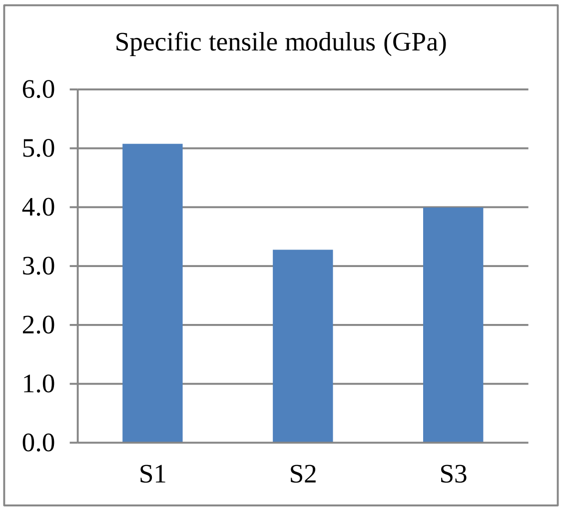


Fig. 5 : Specific tensile modulus of (SL) laminates

III.3. Effect of stacking sequences on flexural loading

Generally, hybrid laminates which comprising two layers of E-glass as a face sheet and three layers of natural fibres either basalt, jute or flax as a core exhibit higher flexural strength and modulus compared with (IC) sequence as shown in Fig. 6 and Fig. 7. (SL) sequence of E-glass/basalt (S1) shows 9.7% and 14.3 % higher of flexural strength and modulus compared with (IC) sequence (S4). This pattern was similarly observed on E-glass/jute (S2) versus (S5) and E-glass/flax (S3) versus (S6). E-glass/jute (S2) and (S5) show flexural strength and modulus of 340 MPa, 17 GPa and 298 MPa, 15 GPa, respectively. E-glass/flax (S3) with a (SL) sequence shows 10.5 % and 6 % higher of flexural strength and modulus than (IC) sequence (S6). Hybrid laminate of E-glass/jute highly influenced on the effect of stacking sequence based on the results shown in Fig. 6 and Fig. 7 compared with E-glass/basalt and E-glass/flax. Sandwich-like sequence of hybrid laminated composites highly significant on flexural loadings and these can be explained due to the behaviour of the hybrid specimens under bending load, whereas upper and lower sides are in tension and compression modes. Two layers of E-glass put at the extreme sides on (SL) sequence enable the hybrid laminates to withstand higher on flexural loading since the core of natural fibres seem at a neutral position, only withstand smaller load caused from the bending. This investigation revealed that the arrangement of fibre in hybrid composite structure strongly affects its flexural strength and modulus. It was similarly found in the previous study on the effect of stacking sequence of carbon/basalt reinforced epoxy [7], hybrid composite laminates for load bearing structure [6], effects of interply hybridization on the damage resistance [12], mechanical behaviour of stacking sequence in kenaf and banana fibre reinforced polyester [13] and hybrid composite laminates reinforced with kevlar/carbon/glass woven fabrics for ballistic impact testing [14].

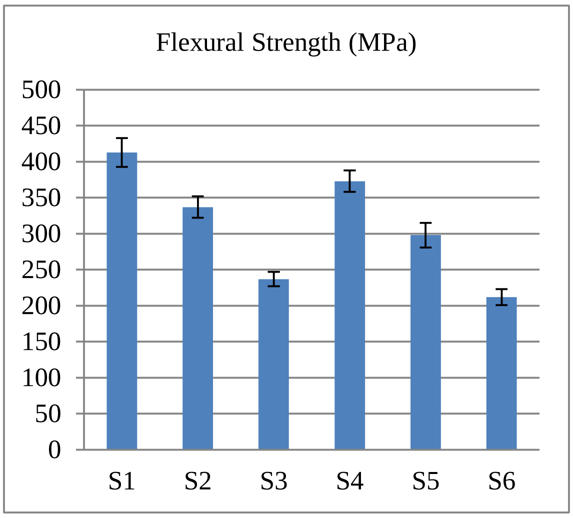


Fig .6 : Flexural strength of the hybrid laminates

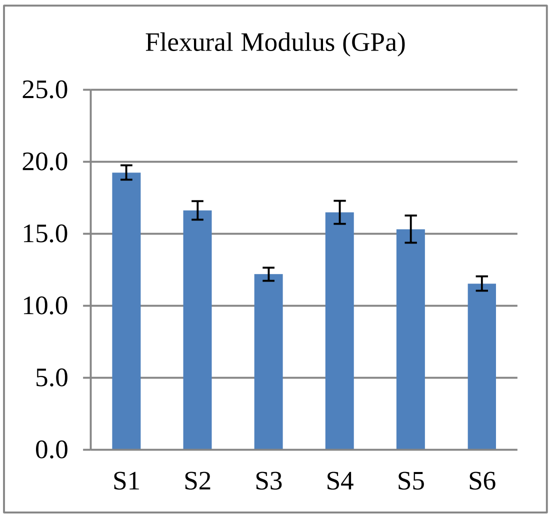


Fig. 7 : Flexural modulus of the hybrid laminates

III.4. Effect of hybridization on flexural loading

Effect of hybridization between E-glass/basalt, E-glass/jute and E-glass/flax was compared based on specific flexural strength and modulus as shown in Fig. 8 and Fig. 9. E-glass/jute (S2) shows the highest specific flexural strength compared to E-glass/basalt (S1) and E-glass/flax (S3) with the different value of 5.1 % and 35.6 %, respectively. In terms of stiffness, also E-glass/jute shows the highest stiffness value. These can be explained due to the lowest density of jute fibre which is 1.46 g/cm^3, compared to basalt and flax which are 2.70 g/cm^3 and 1.50 g/cm^3 respectively. This result makes the jute fibre amongst the best selected material for high strength and stiffness to weight-ratio i.e. in structural applications where bending loading is predominant. The present study agreed with the effect of hybridization on the materials selection as found by Reis et.al [15] in investigating the flexural behaviour of hybrid laminated composites using glass/hemp reinforced PP, effects of hybridization of glass/coir on tensile and flexural loadings [2], hybridization on the damage resistance of woven glass, woven carbon and UD carbon using drop impact [12], and mechanical characterization of hybrid composite laminates using basalt, flax, hemp and glass fibres [16].

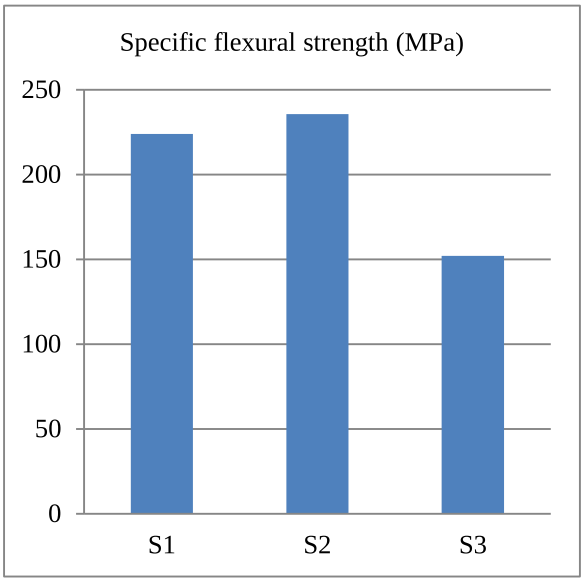


Fig. 8 : Specific flexural strength of (SL)

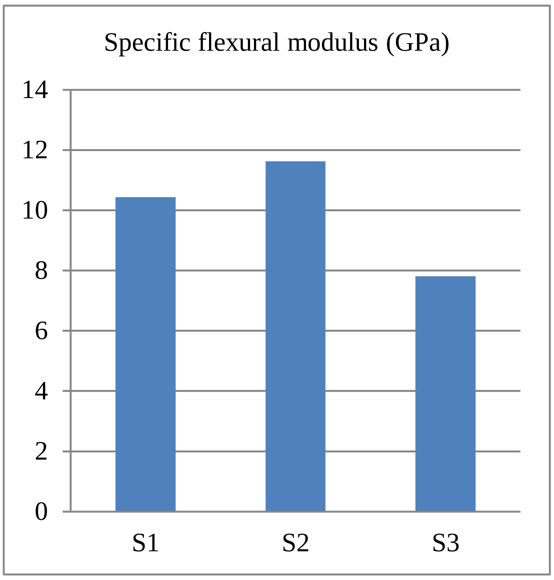
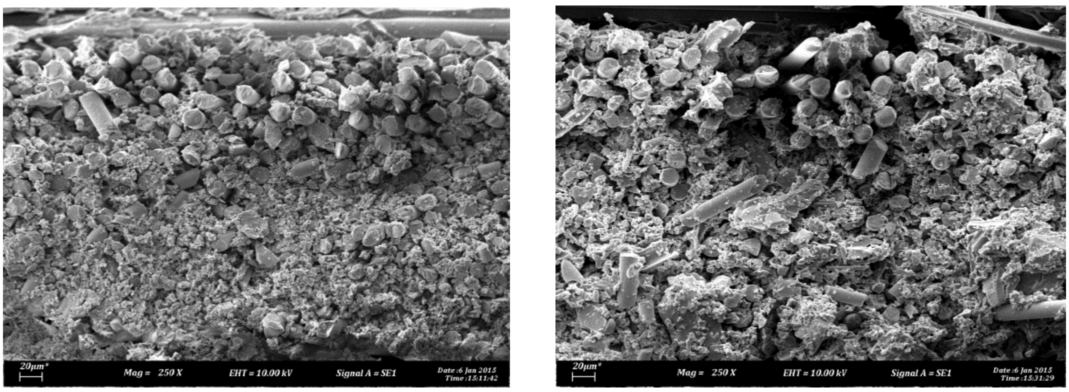


Fig. 9 : Specific flexural modulus of (SL)

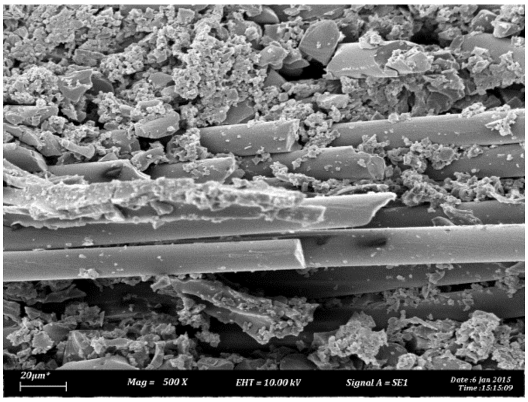
III.5. Fracture characteristics of hybrid composites

III.5.1. Tensile fracture analysis

The tensile strengths and modulus of hybrid structures of E-glass/basalt, E-glass/jute and E-glass/flax are insignificant between (SL) and (IC) sequences. For this loading configuration, almost of the tested structures fail due to the fibre breakage as evidenced in Fig.10. E-glass/basalt hybrid laminate shows the failure interests with the first failure of E-glass layer followed by basalt layer as shown in Fig.10(a) and Fig.10(b). However, hybrid composite laminates of E-glass/jute and E-glass/flax exhibit the dominant failure mode caused from the weakness of jute and flax fibres, respectively. Failure of hybrid composite laminates with (IC) sequence are governed by the extensive degree of fibre pull-outs and fibre breakage as evidenced in hybrid laminate of E-glass/basalt [Fig.10(b)], E-glass/jute [Fig.10(d)] and E-glass/flax [Fig.10(f)] compared with (SL) sequences. These can be explained due to the poor interfacial bonding between natural fibres of basalt, jute and flax compared with better surficial adhesion of E-glass fibre with epoxy resin. In addition, composite with two layers of E-glass at the extreme site mostly did not break into two halves for all the type of hybrid configurations investigated here. Emergence two layers of E-glass fibres contribute 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 [6] on the E-glass/carbon woven fabrics for light weight bearing structures.



a **b**



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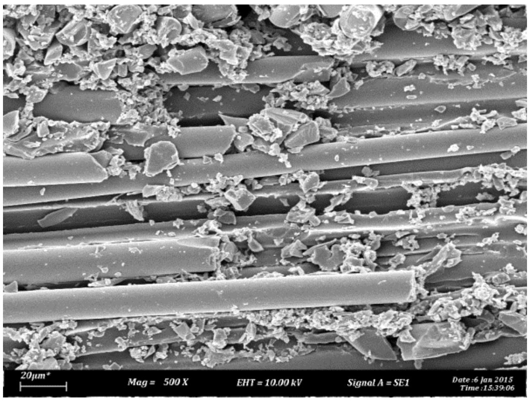

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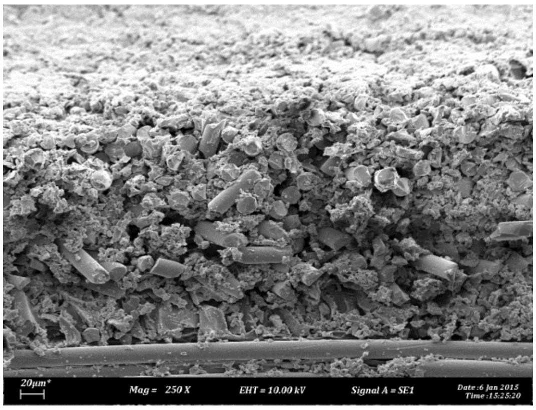

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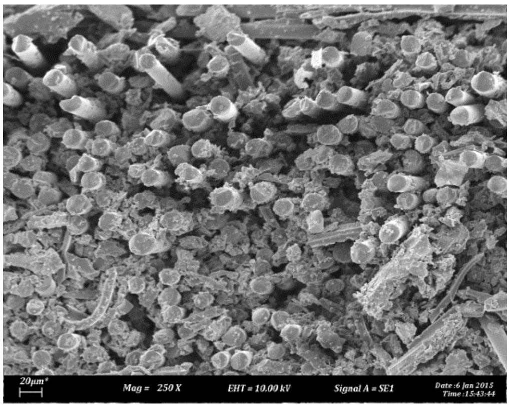

f

Fig. 10: SEM micrographs of tensile fracture of (a) E-glass/basalt with (SL) sequence, (b) E-glass/basalt with (IC) sequence, (c) E-glass/jute with (SL) sequence, (d) E-glass/jute with (IC) sequence, (e) E-glass/flax with (SL), (f) E-glass/flax with (IC) sequence

III.5.2. Flexural fracture analysis

The flexural strengths and modulus of hybrid structures of E-glass/basalt, E-glass/jute and E-glass/flax with (SL) sequence are higher than (IC) sequence and these can be explained by considering the failure mechanism as shown in Fig.11. E-glass/basalt [Fig.11(b)] shows a laminate fail for a premature delamination at the interface between the basalt and E-glass layer caused by internal failure of the layer's interface. This kind of failure was similar as evidenced in the E-glass/flax laminate [Fig.11(f)]. It is interesting to note that delamination mechanism seems not happened as the presence of two E-glass layers rather than one in all hybrid structures [Fig.11(a), Fig.11(c) and Fig.11(e)] which leads the stress gap between the E-glass layers and natural fibre layers to decrement. Delamination is one of the most common and dangerous failure mechanisms of the composite laminates under bending load which has been discovered in previous studies [17 - 18]. E-glass/jute with (IC) sequence exhibits an extensive degree of fibre pull-out and apparent that fibres have also been peeled from the fracture surface [Fig.11(d)]. Matrix cracking and fracture lines were performed on the surfaces that exhibited poor interfacial bond with the cracking at the early stages damage the matrix and E-glass layers then transfer to the jute fibre. The presence of E-glass on the next layer which adjacent to jute layer will slow down and blunted the damage propagation as shown in Fig.12.

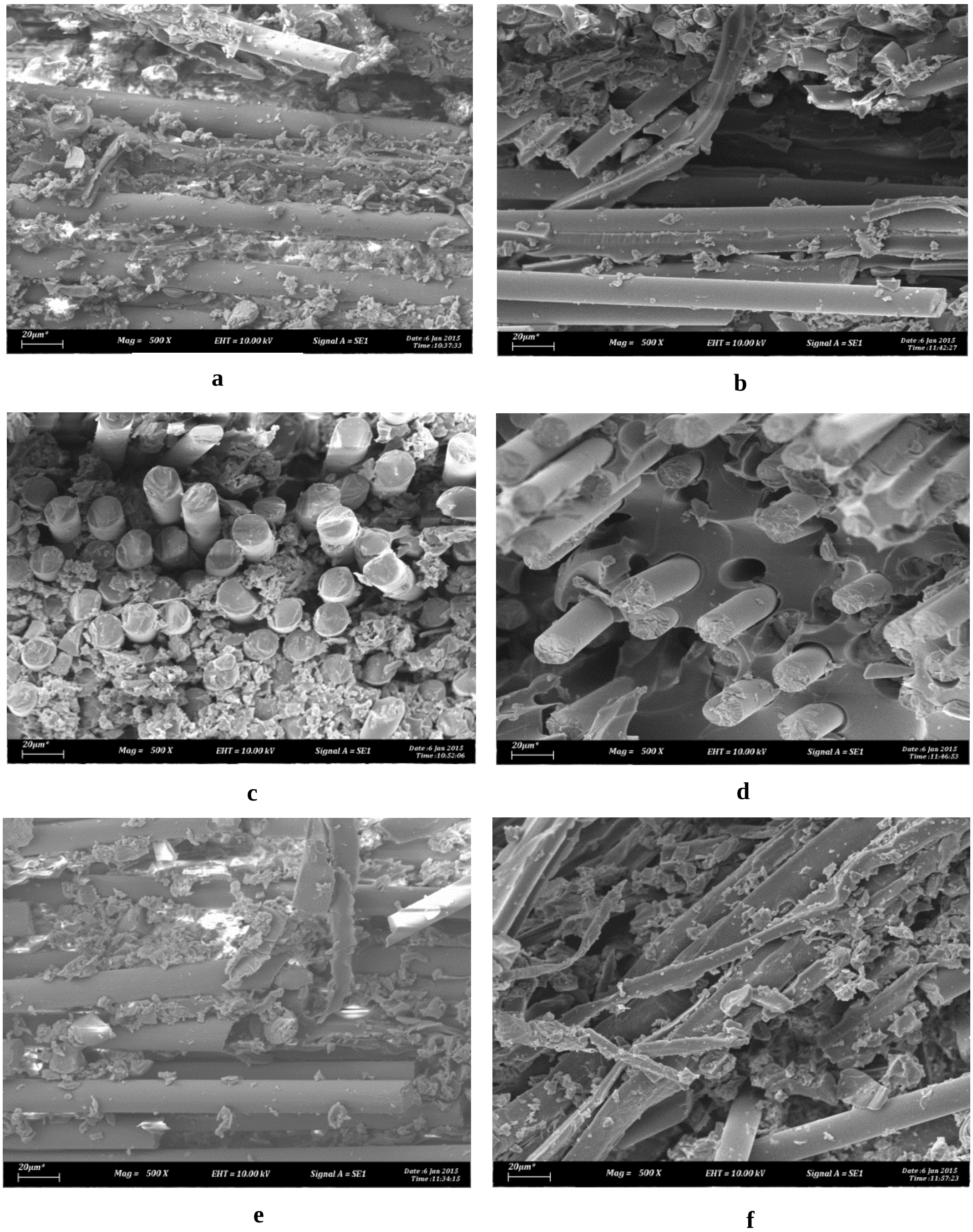

Fig. 11: SEM micrographs of bending fracture of (a) E-glass/basalt with (SL) sequence, (b) E-glass/basalt with (IC) sequence, (c) E-glass/jute with (SL) sequence, (d) E-glass/jute with (IC) sequence, (e) E-glass/flax with (SL), (f) E-glass/flax with (IC) sequence

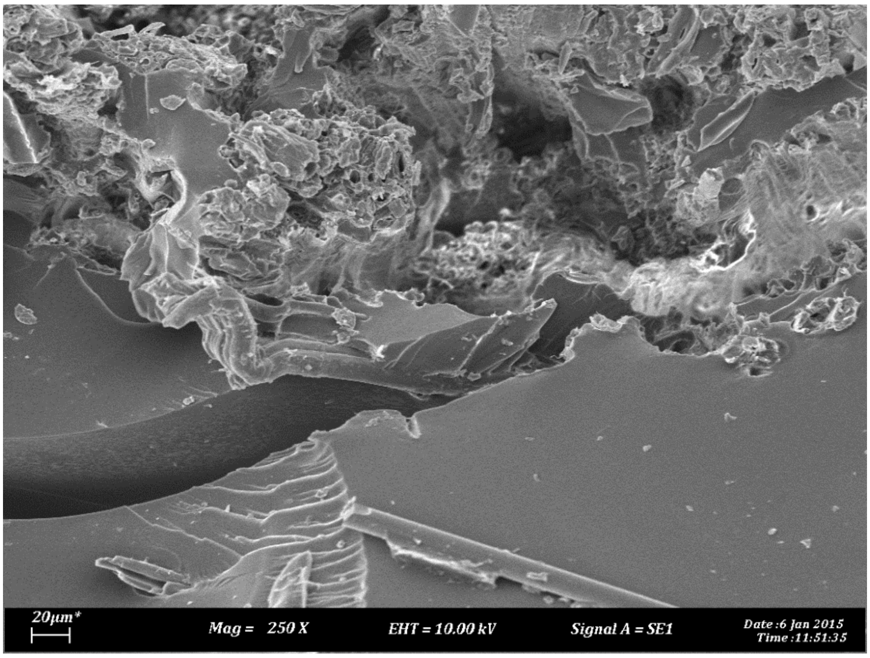

Fig.12: Matrix cracking of E-glass/jute hybrid laminate under flexural loading

IV. Conclusions

The effects of stacking sequences of E-glass/basalt, E-glass/jute and E-glass/flax reinforced epoxy on tensile and flexural loadings have been experimentally investigated with two different configurations, (SL) and (IC) 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 (SL) and (IC) sequence is not highly significant on tensile loading for all hybrid configurations between E-glass/basalt, E-glass/jute and E-glass/flax since the difference on the tensile strength and modulus are less than 5%.
2) E-glass/basalt (S1) and (S4) show 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 E-glass were put at the extreme sides compared with (IC) sequence.
4) On the effect of hybridization, the highest on specific flexural strength and modulus was achieved on E-glass/jute (S2), showing an increase of 5.1 % and 35.6 % from E-glass/basalt (S1) and E-glass/flax (S3).
5) Scanning electron micrographs (SEM) 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 applications. 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 E-glass/basalt, E-glass/jute and E-glass/flax.

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