Journal of Composite Materials
http://jcm.sagepub.com/

Effect of jute fibre loading on the mechanical and thermal properties of oil palm–epoxy composites

M Jawaid, HPS Abdul Khalil, A Abu Bakar, Azman Hassan and Rudi Dungani

Journal of Composite Materials published online 12 June 2012
DOI: 10.1177/0021998312450305

Article

JOURNAL OF COMPOSITE MATERIALS

Journal of Composite Materials
0(0) 1–9

DOI: 10.1177/0021998312450305
jcm.sagepub.com
SAGE

Effect of jute fibre loading on the mechanical and thermal properties of oil palm–epoxy composites

M Jawaid[1], HPS Abdul Khalil[2], A Abu Bakar[3], Azman Hassan[1] and Rudi Dungani[4]

Abstract

Bilayer hybrid composites fabricated by hand lay-up technique by impregnating oil palm empty fruit bunch and jute fibre mats with epoxy resin and cured at 100°C for 1 h followed by post curing at 105°C. Bilayer hybrid composites were prepared by varying the relative weight fraction of the two fibres. The mechanical, morphological and thermal properties of oil palm/jute bilayer hybrid composites were carried out. When the jute fibre loading is increased in the bilayer hybrid composites, flexural strength and modulus of the hybrid composites will be higher. The hybridization of the jute fibres with oil palm composite decreased the impact strength of the bilayer hybrid composites. Analysis of variance statistical of flexural and impact properties were also carried out; there is a statistically significant difference between the mean flexural strength, flexural modulus and impact strength from one level of composite to another at the 95.0% confidence level. Thermogravimetric analysis showed that thermal stability of oil palm composites increased with development of bilayer hybrid composites. Scanning electron micrographs of impact fracture samples are taken to study the failure mechanism, and fibre/matrix interface adhesion.

Keywords

Hybrid composite, flexural properties, impact properties, thermal analysis, scanning electron microscope

Introduction

The combination of natural fibres, such as oil palm, kenaf, hemp, flax, jute, henequen, pineapple leaf, sisal, wood and various grasses with polymer matrices, has been often proposed to produce composite materials.[1–3] Hybrid composites reinforced with natural fibres, combined with synthetic fibres such as glass fibres, are also used in view of a sounder mechanical performance and a better water absorption profile.[4–8] Addition of natural fibre with other natural fibres reinforced polymer composites are also potentially useful materials with respect to environmental concerns.[3] Natural fibre reinforced hybrid composites are initially aimed at the replacement of glass fibre reinforced composites.[9] In order to enhance mechanical and water resistance of natural fibre thermoset composites, glass fibres are used to hybridize the composites.[4,10] Research carried out on jute/glass hybrid composites indicated that hybrid composites have intermediate mechanical properties than those of jute and glass composites.[11]

Recently, work has been done to evaluate the flexural and impact performances of glass/sisal hybrid composites with different fibre loadings and different volume ratios of sisal and glass fibres.[12] The water absorption behaviour of the sisal/cotton, jute/cotton and ramie/cotton hybrid fabric reinforced composites is also evaluated.[13] The results obtained show that the hybrid sisal/cotton fabric has a higher water affinity

---

[1]Department of polymer Engineering, Faculty of Chemical Engineering, Universiti Teknologi Malaysia, Malaysia
[2]School of Industrial Technology, Universiti Sains Malaysia, Malaysia
[3]School of Materials and Mineral Resources Engineering, Engineering Campus, Universiti Sains Malaysia, Malaysia
[4]School of Life Sciences and Technology, Gandung Labtex XI, Institut Teknologi Bandung, Indonesia

Corresponding author:
HPS Abdul Khalil, School of Industrial Technology, University Sains Malaysia, 11800 Penang, Malaysia.
Email: akhalilhps@gmail.com

than jute/cotton and ramie/cotton fabrics. An attempt to study the moisture uptake characteristics of hybrid systems was performed and it was observed that water uptake of hybrid composites were less than that of unhybridized composites. In an interesting study, thermal properties of sisal/oil palm hybrid fibre reinforced natural rubber composites was performed,[14] and thermal stability of the composites was seen to increase upon fibre loading. Hybrid composites with fibre/matrix ratio of 25:75 wt% (25% bamboo and 75% glass fibres) showed better physiomechanical properties than other combination.[15] Thermal properties of sisal/glass hybrid polypropylene (PP) investigated by Jarukumjorn and Suppakarn,[16] observed that addition of glass fibre has improved the thermal properties of sisal/PP composites. Similar study on thermal properties of sisal/glass hybrid composites was done, and it also confirm higher thermal stability in the case of hybrid composites.[17]

Mechanical properties such as tensile and flexural test of hybrid glass/natural fibre reinforced epoxy - composites are reported to be enhanced by hybridization of hemp/kenaf/flax with glass fibres.[18] Santulli[19] conducted comprehensive study on impact properties of glass/plant fibres hybrid composites to find structural applications of hybrid composites. Recently reported work on sisal/glass reinforced epoxy composites indicated that the mechanical properties of sisal–epoxy composite improved by hybridization with glass fibres.[20] The flax/glass hybrid composites based on continuous reinforcement showed good tensile and flexural properties as compared to flax composite.[21] In another study, Hanifawati et al.[22] evaluated the tensile and flexural strengths of banana/glass hybrid composites and results indicated that the incorporation of small fraction of glass fibres in banana–polymer composite show enhancement in tensile and flexural properties.

In this study a thorough investigation has been carried on the effect of jute fibre on flexural, and impact properties of oil palm empty fruit bunch (EFB) epoxy composites. The studies were done by varying jute fibre loading. Morphological studies have been carried out to get an insight into fibre/matrix interaction.

Experimental

Materials

Oil palm EFB fibre mat were supplied by Ecofibre Technology Sdn. Bhd., Malaysia. Jute fibre mat was procured from Indarsen Shamlal Pvt. Ltd (jute house since 1948), Kolkata, India. The physical and mechanical properties of oil palm EFB and jute fibre are given in Table 1.[1,23–30] The epoxy A331 (diglycidyl ether of bisphenol A) and epoxy hardener A062 (reactive polyamide) were used in this study. Both the epoxy resin and commercial curing agent were obtained from Zarm Scientific & Supplies Sdn. Bhd., Malaysia. Benzyl alcohol used as diluents and silicone oil used as releasing agent were supplied by Aldrich Company.

Table 1. Physical and mechanical properties of oil palm EFB and jute fibre

Properties	Oil palm EFB fibre	Jute fibre
Density (g/cm^3)	0.7–1.55	1.3
Tensile strength (MPa)	50–400	393–773
Young's modulus (GPa)	1–9	10–30
Elongation at break (%)	8–18	1.5–1.8
Cellulose content (%)	49.6	58–63
Hemicellulose (%)	18	12
Lignin content (%)	21.2	12–14
Microfibril angle (°)	46	8
Lumen size (μm)	6.90	3.40

EFB: empty fruit bunch.

Preparation of hybrid composites

For the preparation of composite, a stainless steel mould with dimensions of $304 \times 203\,mm^2$ was used. The mould cavity was coated with a thin layer of silicone oil solution, which acts as a releasing agent. In order to make the composites, epoxy resin and polyamide with 100:60 ratios were mixed and benzyl alcohol was added as diluents and the mixture was mixed thoroughly by mechanical stirrer for 15 min. Hybrid composites were developed using hand lay-up technique for making test sample. Keeping the different weight ratio of oil palm EFB and jute and total fibre loading at 40% by weight, bilayer hybrid composites were prepared by hybridizing of oil palm EFB fibres with jute fibres and, both fibre mats were impregnated in epoxy matrix in a mould.

This process was continued until the filling of the mould was complete. Air bubbles were removed carefully with a roller. Then, the mould was closed for curing and the mould was left to cure at 105°C for 1 h in a hot press. An open mould method was used in this research. The mould was compressed at a constant pressure of 275 bars while squeezing out the excess resin. Once the composite was cured, it was removed from the mould and followed by post curing in an oven at 105°C for 30 min. Finally, bilayered laminated composites were cooled in a cold press under constant pressure of 250 bars for 15 min to prevent warpage of the hybrid composites.

Characterizations

Flexural properties. Flexural analysis was carried out at room temperature through three-point bending testing as specified in ASTM D790, using Gotech universal tester-GT-A1-7000L machine. The rectangular samples of dimension 160 × 20 mm^2 were cut using circular saw. The speed of the crosshead was 2 mm/min. Five composite specimens were tested for each sample.

Impact properties. In this study, Izod notched impact testing was carried out using Gotech testing machine, Model GT-7045-MDL. The Izod impact test samples with a dimension of 70 × 15 mm^2 were cut by circular saw. In each type, five samples were tested at ambient condition according to ASTM D 256 and their average load at first deformation was noted and average value was tabulated as impact strength.

Thermal properties. A Perkin Elmer thermal gravimetric analyzer (TGA-6) was used to investigate the thermal stability of the composites. The powder of EFB, jute, and hybrid composites (about 4–5 mg) were heated from 30°C to 900°C under nitrogen at a heating rate of 20°C/min.

Morphological properties. Morphology of the impact fracture of hybrid composites was investigated using SEM (Leo Supra, 50 VP, Carl Ziess, SMT, Germany). The samples were mounted onto SEM holder using double sided electrically conducting carbon adhesive tapes to prevent surface charge on the specimens when exposed to the electron beam. The fracture surfaces of the EFB, jute, and hybrid composites obtained from impact testing were sputtered with gold prior to their morphological observation. The scanning electron micrographs were obtained under conventional secondary electron imaging conditions with an acceleration voltage of 5 kV.

Results and discussion

Flexural properties

The effect of fibre loading on flexural strength and modulus of the hybrid composites having weight fraction of oil palm EFB and jute of 4:1, 1:1, 1:4, EFB and jute composites are given in Table 2. In the case of bilayer hybrid composites, the flexural stress was applied in such a manner that when bending took place, the jute fibre layer was put as outer surface and as a result the jute fibre had to take more stress. Jute fibre has higher strength compared to oil palm EFB fibre and because of that it will withstand higher stress during flexural testing. Flexural strength is a combination of the tensile and compressive strengths which directly varies with the interlaminar shear strength and flexural modulus is a measure of resistance to deformation of the composite in bending.[23,31] In flexural testing, different mechanisms take place simultaneously such as tension, compression, shearing, etc.[23] Hence, increased flexural strength and modulus of bilayer hybrid composite with further loading of jute fibres is mainly due to increased resistance to shearing of the bilayer hybrid composites. Therefore, when the jute fibre loading is increased in the bilayer hybrid composites, flexural strength and modulus of the hybrid composites will be higher. During flexural testing, it was observed that none of the specimens were completely broken at peak load. It may be assumed that failure occurs due to matrix cracking or greater extensibility of jute fibres compared to oil palm EFB fibres.[32]

All hybrid composites are found to be stronger and stiffer than the EFB composite but weaker than jute composite. It is observed that the flexural properties of the EFB composite was considerably lower than jute composite and hence, with the addition of jute fibre to the EFB composite increase the flexural strength and modulus (Figure 1). Oil palm EFB fibre is unable to withstand heavy load which leads to the failure of fibre resulting in the lower flexural strength of EFB composite. Flexural strength and modulus of

Table 2. Flexural and impact properties of oil palm EFB, hybrid and jute composites having 40% fibre by weight oil palm, hybrid, and jute

Composites	Flexural strength (MPa)	Flexural modulus (GPa)	Impact strength (J/m)
EFB	41.7 ± 0.43[a]	2.30 ± 0.05[a]	92.7 ± 1.32[a]
EFB:Jute (4:1)	45.5 ± 1.03	3.42 ± 0.08	58.2 ± 3.29
EFB:Jute (1:1)	56.3 ± 0.99	3.63 ± 0.11	44.7 ± 2.50
EFB:Jute (1:4)	59.4 ± 2.21	4.20 ± 0.21	39.7 ± 1.35
Jute	75.5 ± 1.11	4.32 ± 0.04	32.0 ± 0.85

EFB: empty fruit bunch.
[a] SE.

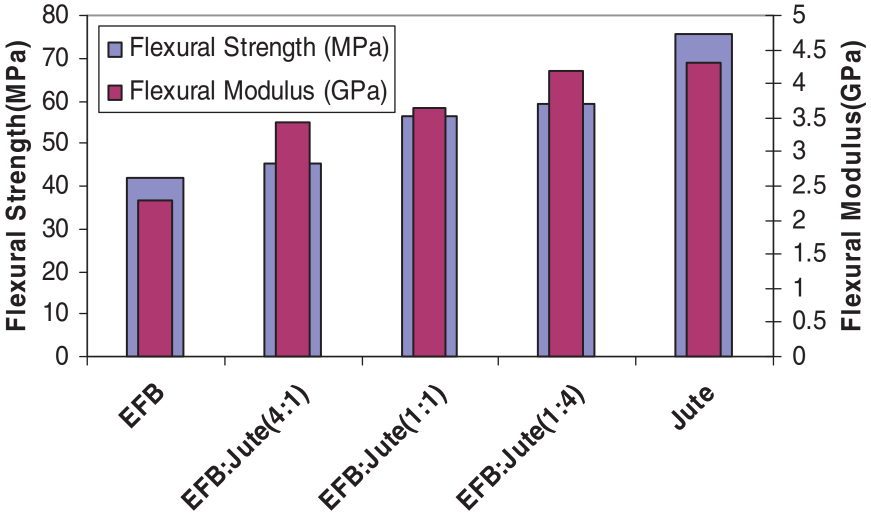

Figure 1. Flexural strength and modulus of oil palm EFB, hybrid and jute composites.
EFB: empty fruit bunch.

hybrid composites increases as the jute fibre loading increases in EFB composite due to better tensile properties of jute fibre and increased resistance to shearing. At all fibre loading, flexural strength and modulus is maximum when the relative weight fraction of oil palm EFB and jute in the composite is 1:4. Flexural strength of jute composite is much higher than oil palm EFB and jute 1:4 hybrid composite. On the other hand, flexural modulus values of jute composite are more or less similar to that of the oil palm EFB and jute 1:4 hybrid composite. It would be possible to prepare high strength materials from oil palm EFB and jute hybrid composites with proper selection of fabrication techniques. Flexural strength is found to be higher in oil palm EFB and jute (4:1) bilayer hybrid composites as compared to trilayer EFB/jute/EFB due to different lamination mechanism in trilayer and bilayer hybrid composites.[33] Flexural modulus is also found to be the highest in the bilayer composites as compared to trilayer hybrid composites. Similar study conducted on flexural strength and modulus of banana and sisal hybrid composites has reported that the highest flexural strength was found in the bilayer composite and the lowest was in intimate mix composites.[34]

Statistical analysis has been carried out by one-way analysis of variance (ANOVA) and the results are presented in Tables 3 and 4 for the difference between the samples regarding flexural strength and modulus, respectively.

ANOVA analysis presented in Table 3 decomposes the variance of flexural strength into two components: a between group (BG) and within group (WG) components. The *F*-ratio, which in this case equals 54.55, is a ratio of the BG estimate to the WG estimate. Since the *p*-value of the *F*-test is less than 0.05, there is a statistically significant difference between the mean flexural strength from one level of composite to another at the 95.0% confidence level.

Table 3. ANOVA test for flexural strength of oil palm EFB, hybrids and jute composites

Source	SS	DF	MS	*F*-ratio	*p*-Value
BG	3569.74	4	892.434	54.55	0.0000
WG	327.182	20	16.3591		

ANOVA: analysis of variance; EFB: empty fruit bunch; BG: between group; WG: within group; SS: sum of squares; DF: degree of freedom; MS: mean square; and *F*: *F*-test for ANOVA.
Number of observations = 25.
Number of samples = 5.

Table 4. ANOVA test for flexural modulus of oil palm EFB, hybrids and jute composites

Source	SS	DF	MS	*F*-ratio	*p*-Value
BG	12.9604	4	3.2401	46.47	0.0000
WG	1.3946	20	0.06973	–	–

ANOVA: analysis of variance; EFB: empty fruit bunch; BG: between group; WG: within group; SS: sum of squares; DF: degree of freedom; MS: mean square; and *F*: *F*-test for ANOVA.
Number of observations = 25.
Number of samples = 5.

ANOVA analysis presented in Table 4 decomposes the variance of flexural modulus into two components: a BG and WG components. The *F*-ratio, which in this case equals 46.47, is a ratio of the BG estimate to the WG estimate. Since the p-value of the F-test is less than 0.05, there is a statistically significant difference between the mean flexural modulus from one level of composite to another at the 95.0% confidence level.

Impact properties

The impact strength is a measure of the fracture toughness of materials when they are subjected to an impact load. The impact properties of composite materials are directly related to its overall toughness which is highly influenced by the nature of the constituent materials, fibre/matrix interface, construction and geometry of the composites, and it also depend upon the test conditions.[35] The natural fibres play an important role in the impact resistance of fibre-reinforced composites as they interact with the crack formation and act as stress transferring medium.

Table 2 presents the effect of jute fibre loading on the impact strength of the hybrid composites. It is observed that EFB composite show higher impact strength compared to that of the jute composite. Polymer composites with natural fibres having a high microfibril angle indicated a higher composite fracture toughness than those with small spiral angles.[34] Bledzki and Gassan[32] also reported that microfibril angle of the fibrils and the content of cellulose affect the mechanical properties of cellulose-based natural fibres. EFB composite containing oil palm EFB fibres (microfibril angle 46°) show good impact properties. The microfibril angle of jute fibre is 8° (Table 1), which has got lower fracture toughness compared to oil palm EFB fibre. In the case of bilayer hybrid composites, the impact load was applied in such a manner that when impact took place, the EFB fibre layer was put as outer surface because EFB fibre has better impact properties. It could be observed that hybrid composites show less impact strength compared to EFB composites, i.e. 92.7 J/m because EFB and jute fibres are comprised primarily of cellulose, hemicellulose and lignin. Hence, the chemical composition and the architecture of cell wall (primary wall, secondary wall and middle lamella) that gives composites higher impact properties. The lumen size of oil palm EFB fibre is higher than jute fibres, as presented in Table 1, which increases the porous nature of the fibre as well as the impact strength. It is reported that sisal fibre reinforced polymer composites have higher impact strength than banana fibre based composite because sisal fibres have higher spiral angle and lumen size compared to banana fibre.[36]

The hybridization of the jute fibres with EFB composite decreased the impact strength of the bilayer hybrid composites significantly, as presented in Table 2. It is observed that on increasing the relative weight fraction of jute fibre, the impact strength of the oil palm EFB/jute hybrid composite is decreased. In an interesting study, it was reported that impact strength of the oil palm EFB/glass hybrid composite increased with the addition of glass fibres.[4] The highest impact strength is observed for hybrid composite having oil palm EFB and jute fibre of ratio 4:1. Bilayer oil palm EFB and jute fibre of ratio 4:1 shows higher impact strength than jute/EFB/jute trilayer but lower than EFB/jute/EFB trilayer hybrid composites.[33] In another interesting study, trilayer and bilayer banana/sisal hybrid composites have almost the same impact strength.[34] It is already reported that high tensile strength offered to jute composite due to better stress transfer from fibre to matrix is the reason for the low impact strength. Many studies have been reported on the impact behaviour and factors affecting the impact strength of hybrid composites.[37–41]

Table 5. ANOVA test for impact strength of oil palm EFB, hybrids and jute composites

Source	SS	DF	MS	F-ratio	p-Value
BG	11630.2	4	2907.56	23.78	0.0000
WG	2445.1	20	122.255		

ANOVA: analysis of variance; EFB: empty fruit bunch; BG: between group; WG: within group; SS: sum of squares; DF: degree of freedom; MS: mean square; and F: F-test for ANOVA.
Number of observations = 25.
Number of samples = 5.

Statistical analysis has been carried out by one-way ANOVA and the results are presented in Table 5 for the difference between the samples regarding impact strength.

ANOVA analysis presented in Table 5 decomposes the variance of impact strength into two components: a BG and WG components. The F-ratio, which in this case equals 23.78, is a ratio of the BG estimate to the WG estimate. Since the p-value of the F-test is less than 0.05, there is a statistically significant difference between the mean tensile strength from one level of composite to another at the 95.0% confidence level.

Thermal properties

From TGA thermograms (Figure 2), it is observed that decomposition of hybrid composites started at higher temperature compared to EFB composite. All composites show two-stage thermal degradation, the thermal degradation temperature in both the stages for the hybrid composites was comparatively higher than EFB composite. It was observed that the initial

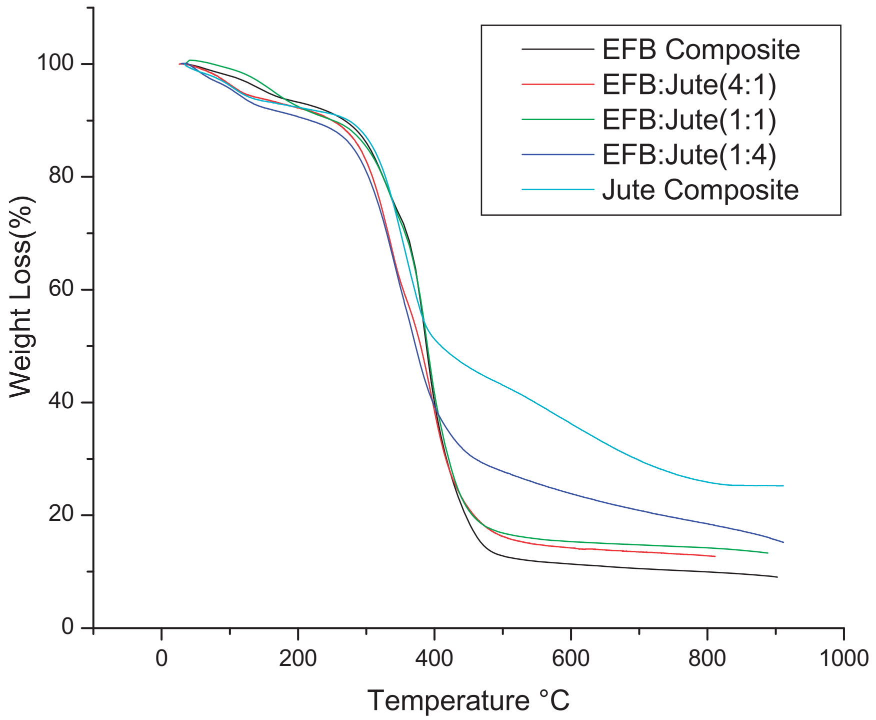

Figure 2. Variation of thermal degradation of oil palm EFB composite with varying weight fractions of jute fibre. EFB: empty fruit bunch.

degradation temperature of hybrid composites is within the range 263–286°C as compared to EFB composite (260°C). Final degradation temperature of EFB composites also increased from 433°C to 463°C due to hybridization with jute fibres. The result shows that the thermal stability of the EFB composite increases as the jute fibre content increased. Incorporation of jute fibre has resulted in considerable increase in the thermal stability of hybrid composites which is possibly due to higher thermal stability of jute fibre than oil palm EFB fibre.

It can be seen from Table 6 that even after complete degradation, char residue is around 12–15% for hybrid composites whereas for EFB char residue is only 9.04%. It may be due to the presence of thermally stable jute fibre. The char residue remaining after 800°C is increased with jute fibre content because the char residue is mainly coming from the lignin component of oil palm fibres in the case of EFB composite, whereas jute fibre is also responsible in the case of hybrid composites. Thermal stability of bilayer composites, oil palm EFB and jute (4:1) show similar results as trilayer hybrid composites of oil palm and jute hybrid composites.[40] In an interesting research on thermal properties of bamboo/glass hybrid composites, it was reported that hybrid composite system shows higher char residue as compared to bamboo fibre reinforced composite due to higher flame retardancy of the systems.[41] Similar work was reported on sisal/glass hybrid composites and it was indicated that the increase in thermal stability of hybrid composite is due to higher thermal stability of glass fibre as compared to sisal fibre.[42]

Table 6. Thermal properties of oil palm EFB, jute and hybrid composites

	Degradation temperature (°C)		
Composites	T^{IDT}	T^{FDT}	Char residue (%)
EFB	260	433	9.04
EFB:Jute (4:1)	263	440	12.73
EFB:Jute (1:1)	283	459	13.25
EFB:Jute (1:4)	286	463	15.35
Jute	288	499	25.20

EFB: empty fruit bunch; IDT: initial decomposition temperature; and FDT: final decomposition temperature.

Morphological properties

Scanning electron microscope (SEM) images of impact fracture surface of EFB, hybrid and jute composites are shown in Figure 3. Fibre/matrix interfacial failure is evident from the SEM. Impact fracture of composites shows both fibres pull out and breakage. Fibres pull out are visible in Figure 3(b) and (c). The difference in the impact fracture of oil palm EFB and jute fibre can be seen from the SEM micrograph of hybrid composite (Figure 3(d)). SEM observation of the fracture surfaces

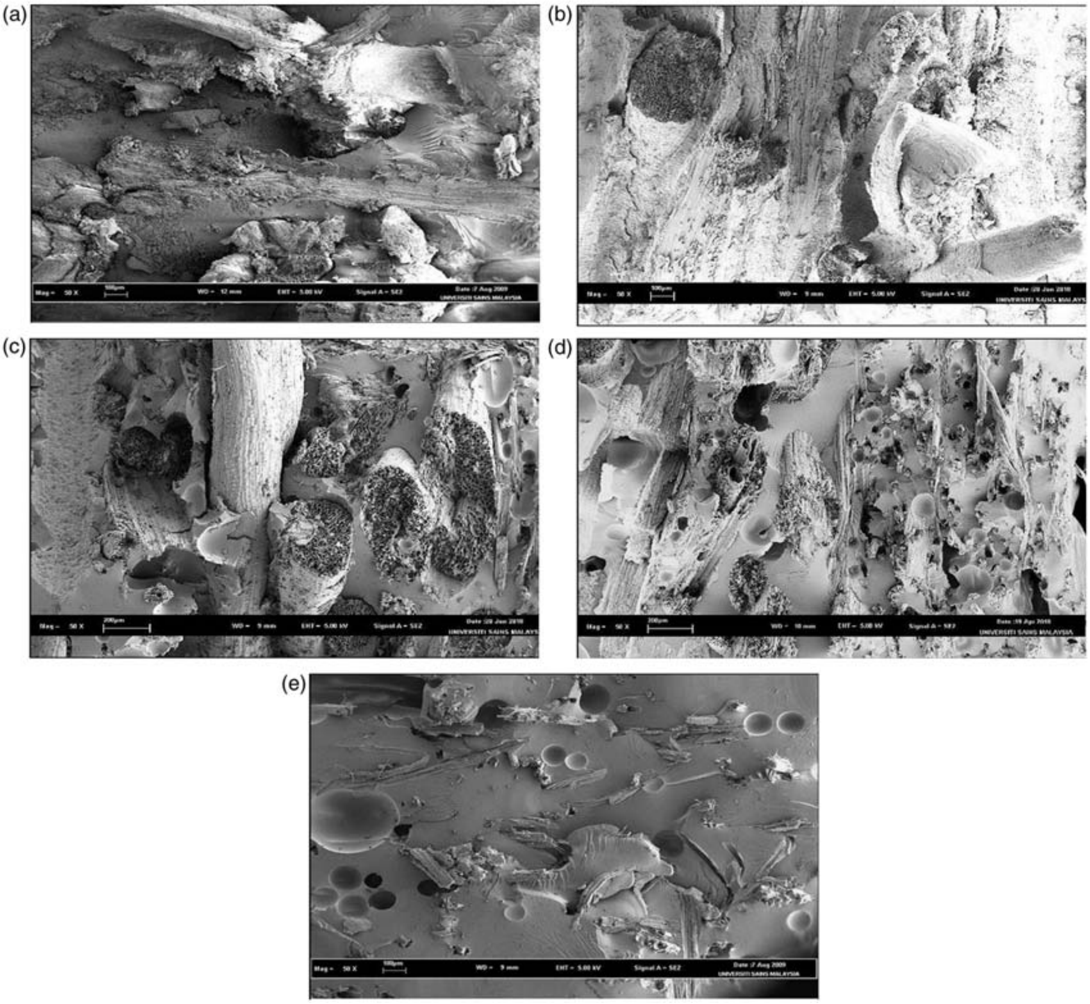

Figure 3. SEM micrograph of impact fracture of (a) EFB composite; (b) EFB and jute hybrid composite (ratio of 4:1); (c) EFB and jute hybrid composite (ratio of 1:1); (d) EFB and jute hybrid composite (ratio of 1:4); and (e) Jute composite.
SEM: scanning electron microscope; EFB: empty fruit bunch.

of the oil palm EFB composite showed fibre fracture as the predominant failure mechanism (Figure 3(a)). As the oil palm EFB composite is subjected to a high speed impact load, the sudden stress transferred from the matrix to fibre exceeds the fibre strength, hence resulting in the fracture of the oil palm EFB fibres at the cracks plane without any fibre pull out.[4] Oil palm EFB fibre breakage is also observed. Compared to EFB composite, jute fibre composite impact fracture shows the presence of fibres pull out and broken fibre (Figure 3(e)).

Conclusions

Flexural strength and modulus of bilayer hybrid composite increased with the further loading of jute fibres are mainly due to increased resistance to shearing of the bilayer hybrid composites. Impact strength of oil palm EFB: jute (4:1) is higher due to higher microfibril angle and lumen size of oil palm EFB fibre compared to jute fibre. Incorporation of jute fibre results in considerable increase in the thermal stability of the hybrid composites which is possibly due to higher thermal stability of jute fibre than oil palm EFB fibre. It is anticipated that these studies will optimize the use of oil palm EFB fibres and its utilization in development of unique cost-effective advanced composites possessing good mechanical properties, dimensional stability, appropriate stiffness and thermal stability.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgements

The authors thank the Universiti Sains Malaysia, Penang, for providing facilities that has made this study possible.

Conflicts of interest

None declared.

References

1. Hassan A, Adam Salema A, Ani FN, et al. A review on oil palm empty fruit bunch fiber-reinforced polymer composite materials. *Polym Compos* 2010; 31: 2079–2101.
2. Akil HM, Omar MF, Mazuki AAM, et al. Kenaf fiber reinforced composites: a review. *Mater Des* 2011; 32: 4107–4121.
3. Jawaid M and Abdul Khalil HPS. Cellulosic/synthetic fibre reinforced polymer hybrid composites: a review. *Carbohydr Polym* 2011; 86: 1–18.
4. Abu Bakar A, Hariharan and Abdul Khalil HPS. Lignocellulose-based hybrid bilayer laminate composite: part I - studies on tensile and impact behavior of oil palm fiber-glass fiber-reinforced epoxy resin. *J Compos Mater* 2005; 39: 663–684.
5. Abdul Khalil HPS, Kang CW, Khairul A, et al. The effect of different laminations on mechanical and physical properties of hybrid composites. *J Reinf Plast Compos* 2009; 28: 1123–1137.
6. De Rosa IM, Santulli C, Sarasini F, et al. Post-impact damage characterization of hybrid configurations of jute/glass polyester laminates using acoustic emission and IR thermography. *Compos Sci Technol* 2009; 69: 1142–1150.
7. Akil HM, De Rosa IM, Santulli C, et al. Flexural behaviour of pultruded jute/glass and kenaf/glass hybrid composites monitored using acoustic emission. *Mater Sci Eng A* 2010; 527: 2942–2950.
8. Kong K, Hejda M, Young RJ, et al. Deformation micromechanics of a model cellulose/glass fibre hybrid composite. *Compos Sci Technol* 2009; 69: 2218–2224.
9. Joshi SV, Drzal LT, Mohanty AK, et al. Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Composites Part A* 2004; 35: 371–376.
10. Abdul Khalil HPS, Hanida S, Kang CW, et al. Agro-hybrid composite: the effects on mechanical and physical properties of oil palm fiber (EFB)/glass hybrid reinforced polyester composites. *J Reinf Plast Compos* 2007; 26: 203–218.
11. Koradiya SB, Patel JP and Parsania PH. The preparation and physicochemical study of glass, jute and hybrid glass-jute bisphenol-C-based epoxy resin composites. *Polym Plast Technol Eng* 2010; 49: 1445–1449.
12. Ornaghi HL Jr, Bolner AS, Fiorio R, et al. Mechanical and dynamic mechanical analysis of hybrid composites molded by resin transfer molding. *J Appl Polym Sci* 2010; 118: 887–896.
13. Alsina OLS, De Carvalho LH, Filho FGR, et al. Immersion temperature effects on the water absorption behavior of hybrid lignocellulosic fiber reinforced-polyester matrix composites. *Polym Plast Technol Eng* 2007; 46: 515–520.
14. Jacob M, Jose S, Thomas S, et al. Stress relaxation and thermal analysis of hybrid biofiber reinforced rubber biocomposites. *J Reinf Plast Compos* 2006; 25: 1903–1917.
15. Dieu TV, Liem NT, Mai TT, et al. Study on fabrication of BMC laminates based on unsaturated polyester resin reinforced by hybrid bamboo/glass fibers. *JSME Int J Ser A* 2004; 47: 570–573.
16. Jarukumjorn K and Suppakarn N. Effect of glass fiber hybridization on properties of sisal fiber-polypropylene composites. *Composites Part B* 2009; 40: 623–627.
17. Nayak SK and Mohanty S. Sisal glass fiber reinforced PP hybrid composites: effect of MAPP on the dynamic mechanical and thermal properties. *J Reinf Plast Compos* 2010; 29: 1551–1568.
18. Cicala G, Cristaldi G, Recca G, et al. Properties and performances of various hybrid glass/natural fibre composites for curved pipes. *Mater Des* 2009; 30: 2538–2542.
19. Santulli C. Impact properties of glass/plant fibre hybrid laminates. *J Mater Sci* 2007; 42: 3699–3707.
20. Hashmi SAR, Naik A, Chand N, et al. Development of environment friendly hybrid layered sisal-glass-epoxy composites. *Compos Interfaces* 2011; 18: 671–683.
21. Adekunle K, Cho S-W, Richard K, et al. Mechanical properties of natural fiber hybrid composites based on renewable thermoset resins derived from soybean oil, for use in technical applications. *J Appl Polym Sci* 2012; 124: 4530–4541.
22. Hanifawati AN, Azmah Hanim MA, Sapuan SM, et al. Tensile and flexural behaviour of hybrid banana pseudostem/glass fibre reinforced polymer composites. *Key Eng Mater* 2011; 471–472: 686–691.
23. Sreekala MS, George J, Kumaran MG, et al. The mechanical performance of hybrid phenol-formaldehyde-based composites reinforced with glass and oil palm fibres. *Compos Sci Technol* 2002; 62: 339–353.
24. Abdul Khalil HPS. *Acetylated plant fibres reinforced composites*. Bangor, UK: University of wales, 1999.
25. Bledzki AK and Gassan J. Composites reinforced with cellulose based fibres. *Prog Polym Sci* 1999; 24: 221–274.
26. Ahmed Z, Haque MS and Akhter F. Study of the chemical composition of different pipeline varieties of jute fibres. *Pak J Biol Sci* 2003; 6: 1463–1467.
27. Munikenche Gowda T, Naidu ACB and Chhaya R. Some mechanical properties of untreated jute fabric-reinforced polyester composites. *Composites Part A* 1999; 30: 277–284.
28. Shinoj S, Visvanathan R, Panigrahi S, et al. Oil palm fiber (OPF) and its composites: a review. *Ind Crops Prod* 2011; 33: 7–22.
29. Majumder A, Samajpati S, Ganguly PK, et al. Swelling of jute: heterogenity of crimp formation. *Text Res J* 1980; 50: 575–578.
30. Munawar RF, Zakaria S, Radiman S, et al. Properties of magnetic paper prepared via in situ synthesis method. *Sains Malaysiana* 2010; 39: 593–598.
31. Ahmed KS, Vijayarangan S and Rajput C. Mechanical behavior of isothalic polyester-based untreated woven jute and glass fabric hybrid composites. *J Reinf Plast Compos* 2006; 25: 1549–1569.
32. Bledzki AK and Gassan J. Composites reinforced with cellulose based fibres. *Prog Polym Sci* 1999; 24: 221–274.

33. Jawaid M, Abdul Khalil HPS and Abu Bakar A. Mechanical performance of oil palm empty fruit bunches/jute fibres reinforced epoxy hybrid composites. *Mater Sci Eng A* 2010; 527: 7944–7949.
34. Idicula M, Neelakantan NR, Oommen Z, et al. A study of the mechanical properties of randomly oriented short banana and sisal hybrid fiber reinforced polyester composites. *J Appl Polym Sci* 2005; 96: 1699–1709.
35. Joseph S, Sreekala MS, Oommen Z, et al. A comparison of the mechanical properties of phenol formaldehyde composites reinforced with banana fibres and glass fibres. *Compos Sci Technol* 2002; 62: 1857–1868.
36. Idicula M, Joseph K and Thomas S. Mechanical performance of short banana/sisal hybrid fiber reinforced polyester composites. *J Reinf Plast Compos* 2010; 29: 12–29.
37. De Medeiros ES, Agnelli JAM, Joseph K, et al. Mechanical properties of phenolic composites reinforced with jute/cotton hybrid fabrics. *Polym Compos* 2005; 26: 1–11.
38. Mwaikambo LY and Bisanda ETN. Performance of cotton-kapok fabric-polyester composites. *Polym Test* 1999; 18: 181–198.
39. Paiva Junior CZ, De Carvalho LH, Fonseca VM, et al. Analysis of the tensile strength of polyester/hybrid ramie-cotton fabric composites. *Polym Test* 2004; 23: 131–135.
40. Jawaid M and Abdul Khalil HPS. Effect of layering pattern on the dynamic mechanical properties and thermal degradation of oil palm-jute fibers reinforced epoxy hybrid composite. *BioResources* 2011; 6: 2309–2322.
41. Nayak SK, Mohanty S and Samal SK. Influence of short bamboo/glass fiber on the thermal, dynamic mechanical and rheological properties of polypropylene hybrid composites. *Mater Sci Eng A* 2009; 523: 32–38.
42. Yuan X, Zhang Y and Zhang X. Maleated polypropylene as a coupling agent for polypropylene–waste newspaper flour composites. *J Appl Polym Sci* 1999; 71: 333–337.