The Effects of Orientation on the Mechanical and Morphological Properties of Woven Kenaf-reinforced Poly Vinyl Butyral Film

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Kenaf is one of the important plants cultivated for natural fibres globally and is regarded as an industrial crop in Malaysia for various applications. This study was conducted to determine the effects of orientation on the tensile and flexural strengths, Charpy impact test, and morphological properties of kenaf fibre-reinforced poly vinyl butyral (PVB) composites. Laminates of 40% fibre weight fraction were manufactured using the hot press manufacturing technique at 0°/90° and 45°/−45° orientations, and eight specimens were prepared for each test. The mechanical properties of the composites were variably affected by the fibre orientation angle. The results showed that the composites at 0°/90° had the highest tensile strength, flexural strength, and flexural modulus, while the elongation at break was almost the same. Additionally, tests were carried out on the composites to determine their impact energy and impact strength. The results revealed that impact properties were affected in markedly different ways by different orientations. The composite at 45°/−45° offered better impact properties than the composites at 0°/90°. In addition, scanning electron microscopy for impact specimens was employed to demonstrate the different failures in the fracture surfaces.

Keywords: Kenaf fibres; PVB film; Mechanical properties; Different orientation; Morphological properties

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INTRODUCTION

The advantages of natural fibre-reinforced composites in comparison with those reinforced with synthetic fibres include enhanced energy recovery, carbon dioxide sequestration, abundance, low cost, low weight, good relative mechanical properties, and lower dermal and respiratory irritation (Salman *et al.* 2015a). One of the popular natural fibres is kenaf fibre, which possesses moderately high specific strength and stiffness and can be utilized as a reinforcing material in polymeric resins to make useful structural composite materials(Aji *et al.* 2009). The use of the weave technique can add structural strength to the material because it increases strength, flexibility, formability, and energy absorption capacity (Salman *et al.* 2015c).

While several investigations have focused on the overall properties of kenaf fibre-reinforced composites (Khan 2010; Qatu 2011; Ali *et al.* 2014; Saba *et al.* 2015), the authors have concluded that a specific article on the effect of orientation on the mechanical properties of kenaf fibre-reinforced PVB composites has not yet been published. However, many experimental studies have been performed by Ochi (2008) and El-Shekeil *et al.*(El-Shekeil *et al.* 2012a,b,c,2014); however, the results of these works cannot be compared because they all used different resins, fibre contents, and orientations.

One of the significant parameters that affects the mechanical performance of composites is fibre orientation (Akil *et al.* 2011). From reported works on the mechanical properties of polymeric composites based on kenaf fibres, Alavudeen *et al.*(2015) experimentally investigated the effect of weaving patterns and random orientation on the mechanical properties of kenaf and banana fibre-reinforced polyester composites. Generally, it was reported that the plain weaving patterns and composite properties showed improved mechanical properties compared with the random type. Moreover, the maximum increase in mechanical strength was observed in the plain woven composites rather than in randomly oriented composites. When naturally reinforced polymer composite are subjected to loading, the fibres act as carriers of load and stress (stiffness and strength). Therefore, the orientation of natural fibres has an important effect on the mechanical properties in composite materials (Ku *et al.* 2011).

However, only limited work has been done using woven patterns of kenaf fibre to reinforce either epoxy or polyester composites (Chow *et al.* 2000; Ramaswamy *et al.* 2003; Sgriccia *et al.* 2008). Hence, in this study, composites of kenaf fibre-reinforced PVB composites at orientations of 0°/90° and 45°/−45° were developed. Moreover, the effect of the orientation of kenaf fibre on tensile, flexural, and impact properties was investigated to inform guidelines for the future development of kenaf fibres with PVB film. The influence of orientation on tensile test samples was analysed through scanning electron microscopy (SEM) images.

EXPERIMENTAL

The effect of orientation of kenaf fibres at $0^o/90^o$ and $45^o/-45^o$ reinforced PVB composites were investigated. Kenaf fibre is the main fibre used in this study, with the properties as reported in Table 1 and shown in Fig. 1.

Table 1. Properties of Woven Kenaf

Characterization	Woven Kenaf
Thickness, *t* (mm)	2 ± 0.2
Weight (g/m^2)	890
Density (g/cm^3)	1.2
Warp density (warp/inch)	12
Weft density (weft/inch)	12
Wavelength, λ (mm)	4.2
Inter-yarn fabric porosity (ε)	0.274
Moisture Content (%)	8.353
Water Uptake (%)	148.86
Average breaking strength (MPa)	100.64
Average maximum strain (%)	17.3

Fig. 1. Kenaf fibre

Poly vinyl butyral (PVB) film is now employed in a wide array of industrial and commercial applications due to its impressive mechanical performance and outstanding versatility. The tensile strength of the PVB film is ≥ 20 MPa, and breaking elongation is ≥ 200% (manufacturer data sheet).

Fabrication of the Composite Sample

The composite samples were made with 40% kenaf fibre weight content using a hot hydraulic press technique, which led to better fibre-to-resin bonding, as shown in Fig. 2. The plain woven kenaf fibre and PVB film were cut into 300mm by 300mm sheets. The stacks of five layers of kenaf fabric and six layers of PVB film were centered between two stainless-steel molds and hot plates of a compression moulding press. Subsequently, the platens were closed, the hot press plates were heated to 165 °C for 20 min, and the compression pressure was set to 8 MPa, as shown in Figs. 3(a) and (b). Once the temperature of the platens reached 165 °C, the compression pressure was increased to 8 MPa and held constant for 15 min. After this compression cycle, the platen temperature was reduced to room temperature (25 °C), while the pressure was maintained at 8 MPa until the temperature reached 25 °C. Once the platen temperature reached 25 °C, the woven kenaf-reinforced PVB film composite laminate was taken out of the compression moulding frame. Forty-eight specimens were fabricated for each composite, and five replications were considered. Plates of these composites with five layers of woven kenaf-reinforced polymers were fabricated at $0^o/90^o$ and $45^o/-45^o$ directions, then press-molded and allowed to complete inner curing.

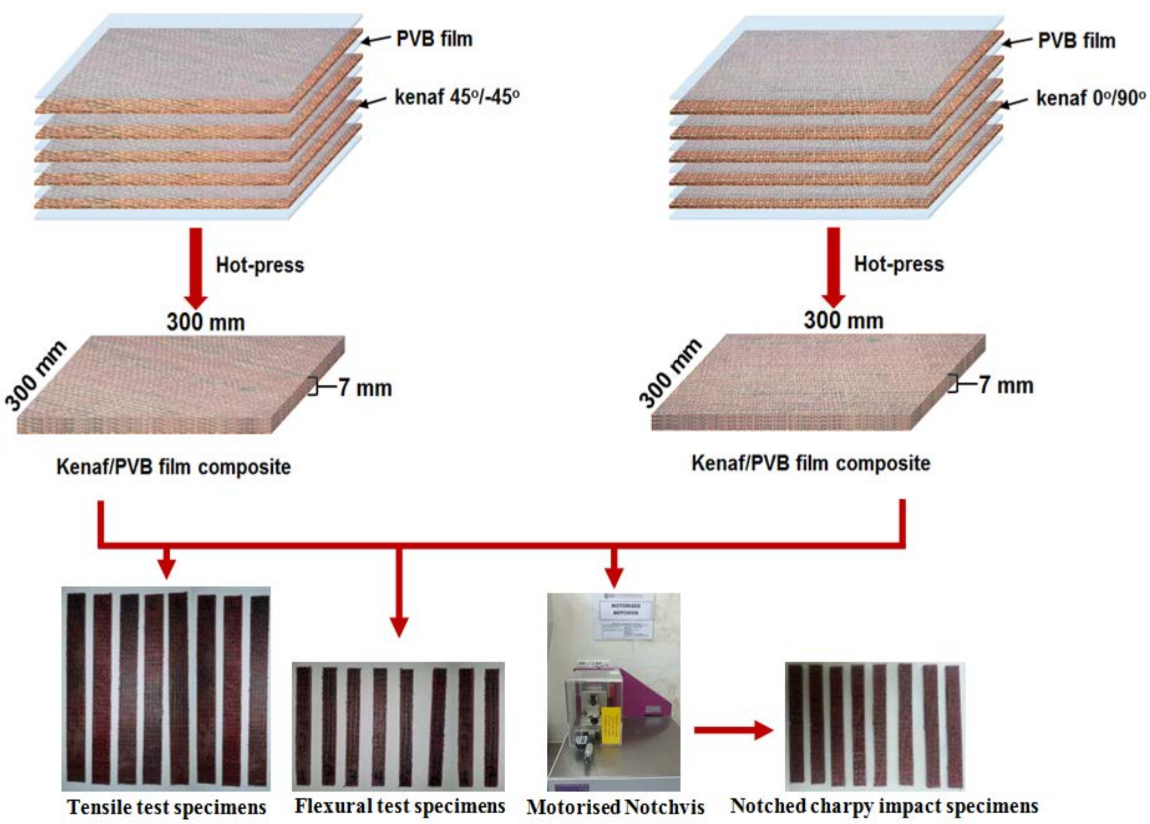
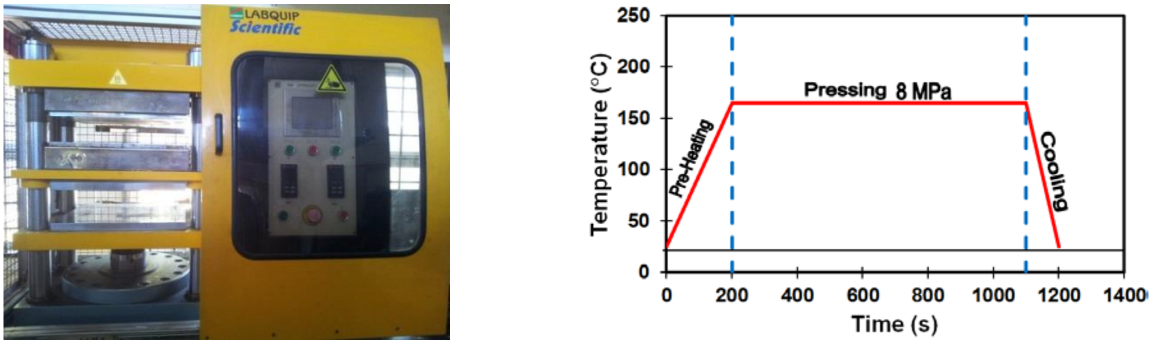


Fig. 2. The composite specimens prepared using the hot press technique



(a) Hot press (b) Processing cycle

Fig. 3. Compression moulding hot press and temperature profile

Mechanical Properties of Composites

Tests to determine the influence of orientation on the tensile and flexural properties of kenaf fibre-reinforced PVB composites were carried out in the composite laboratory of the Mechanical Engineering Department, Universiti Putra Malaysia, according to the standards of ASTM D3039/D3039M-10 (2010) and ASTM D790-10 (2010). Using a wheel saw machine, the specimens were carefully cut from the composite to prepare specimens of the appropriate size. Tensile specimens were cut to a 250mm× 25mm ×7 mm rectangular sectional area flat strip and a gage length of 170mm for both $0^o/90^o$ and $45^o/-45^o$ composites. The rectangular three-point bending specimens were prepared with dimensions of 127mm× 12.7mm× 7mm for both $0^o/90^o$ and $45^o/-45^o$ composites. The distance between supports (span length) was calculated as per the standard, with a ratio of 16:1. Both tests were conducted using a universal testing machine model Instron 3365 (Instron Company, USA), with a capacity of 100 kN and a crosshead speed of 2 mm/min, with a replication of eight times (Figs. 4(a) and (b)). These tests were conducted until a specimen fractured to measure the ultimate tensile strength and ultimate flexural strength of the composites; the average value of five results was used.

(a) (b) (c)

Fig. 4. The specimen under (a) tensile test; (b) flexural test; and (c) Charpy impact test

The impact strength of the specimens was measured using a Charpy impact test machine, according to the ASTM D6110-10 standard (2010). The Charpy impact test was performed on eight notched specimens using a pendulum impact tester model CEAST 9050 (Instron Company, USA), with various hammer energies (0.5, 2.7, 5.4, and 21.6 J, as shown in Fig. 4(c). Impact specimens were cut to a 127 mm × 12.7 mm × 7 mm rectangular sectional area flat strip for both $0^o/90^o$ and $45^o/-45^o$ composites. They were notched in the middle with a radius of curvature of 0.25R mm to 2.54 mm using a CEAST motorised Notchvis machine, (Instron Company, USA), as shown in Fig. 2.

Morphological Observation

The influence of orientation on the fracture surface of both tensile and Charpy impact tests specimens was analysed through scanning electron microscopy images, using the scanning electron microscope (SEM) instrument model HITACHI S-3400N, (HITACHI Company, Japan). All the fractured specimens were coated with a thin layer of gold by low-vacuum sputter coating, model EMITECH K550X (Quorum Technologies Limited Company, UK) to avoid electron charge accumulation and were subjected to a voltage of 10 to 15 kV.

RESULTS AND DISCUSSION

Figures 5, 6, and 7 show the average and ultimate tensile strength, tensile modulus, and strain for the composites at $0^o/90^o$ and $45^o/-45^o$ orientations. Between these two fibre orientations, the $0^o/90^o$ composite showed the highest tensile strength and modulus. The average tensile strength of the composite at the $0^o/90^o$ orientation was 19.19 MPa, which is 79.1% higher than that of the $45^o/-45^o$ composite (10.716 MPa) (Salman *et al.* 2015b). A similar trend has been reported in the study done by Alavudeen *et al.* (2015) on banana and kenaf fibre-reinforced polyester composites. There was a decline in the tensile properties of the composite samples with a random orientation, while there were higher tensile properties of woven fabric composites. This could be caused by a uniform distribution of stress transfer with the application of tensile load in both the longitudinal and transverse directions, whereas this was not found in the $45^o/-45^o$ orientation. Furthermore, it can be seen that the values of the tensile modulus of the $0^o/90^o$ composite were much higher than those of the $45^o/-45^o$ composite as a result of the high strain value of the $45^o/-45^o$ orientation. The average tensile modulus of the composite at the $0^o/90^o$ orientation was 889.22 MPa, while it was 57.87 MPa for the $45^o/-45^o$ composite. As a result of the elongation of the $45^o/-45^o$ composite, it yielded the highest tensile strain (18.52%). This is in agreement with the findings of Alavudeen *et al.* (2015), who found similar trends for plain woven and random kenaf fibre-reinforced polyester composites. However, noticeable improvements in the strength of polymer composites can be achieved, while reinforcing natural fibres under different orientations makes the composites stronger and comparable to those of synthetic fibres (Dittenber and GangaRao 2012; Faruk *et al.* 2012). Generally, the increase in the tensile strength and modulus of kenaf composites with $0^o/90^o$ is indicated by the initiation and propagation of microscopic cracks through the matrix, which depends on the orientation of the kenaf fibres. Thus, $0^o/90^o$ orientation could result in a capacity for greater stress uptake composites, which leads to higher tensile strength. Therefore, when composite materials are designed, the reinforcement is always oriented in the load direction (Sapuan *et al.* 2006; Hojo *et al.* 2014; Karimi *et al.* 2014), and if it is variable, it becomes important to predict the ply mechanical behaviour. The tensile strain of the 0°/90° composites was much lower than the tensile strain of the 45°/−45° composites, which indicates minimum stress development at the interface of composites because of the distribution of load transfer along the fibre direction, and the composite's properties were affected by the PVB resin properties.

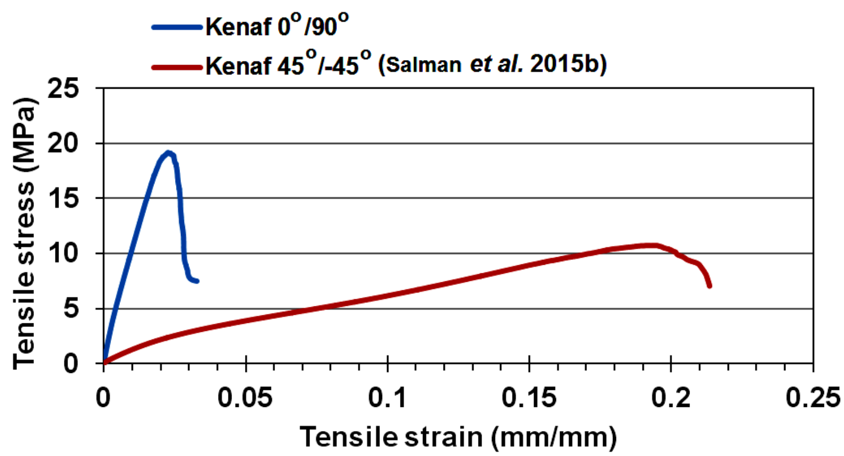


Fig. 5. Average values of tensile stress-deformation diagram of the kenaf fibre-reinforced PVB film at $0^o/90^o$ and $45^o/-45^o$ composites

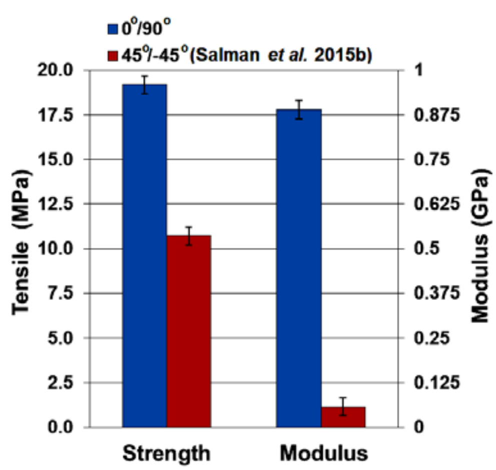


Fig. 6. Average tensile strength and modulus of the composites at $0^o/90^o$ and $45^o/-45^o$ orientations

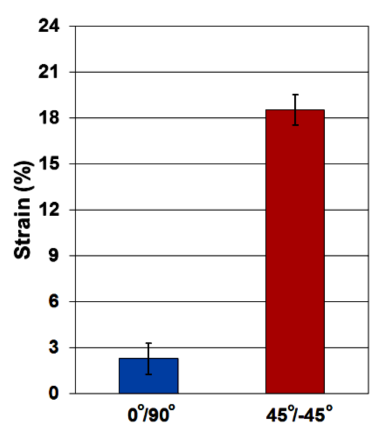


Fig. 7. Average tensile strain of the composites at $0^o/90^o$ and $45^o/-45^o$ orientations

A similar finding was also observed in the flexural strength and flexural modulus for the composites at $0^o/90^o$ and $45^o/-45^o$orientations using a three-point flexural test (as shown in Figs. 8, 9, and 10). Like the tensile strength and modulus values of the $0^o/90^o$ composite, the orientation angle seems to have had a marked influence on the flexural strength and modulus. The average ultimate flexural strength of the composite at the 0°/90° orientation was 11.77 MPa, while it was 3.67 MPa for the 45°/−45° composite (Salman *et al.* 2015b). As a result of the deflection of the 45°/−45° composite, it yielded the highest flexural strain (13.1%). As previous studies have reported, the flexural properties not only depend on the type of polymer, but fibre orientation is also a critical factor on the mechanical properties of the composites (Sapuan *et al.* 2007; Shibata *et al.* 2008). These authors reported that a significant difference in the flexural properties was observed between cross ply and longitudinal arrangements in banana, kenaf, and bamboo fibre-reinforced polyester composites. Generally, in previous works on natural fibre/polymer composites, the low flexural properties were caused by the orientations of the natural fibres in the matrix (Omar *et al.* 2010; Mylsamy and Rajendran 2011; Rassmann *et al.* 2011).

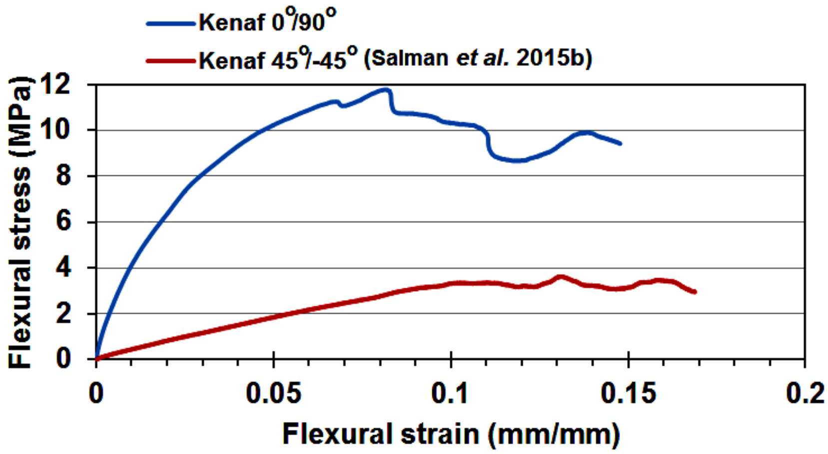


Fig. 8. Average values of the flexural stress-deformation diagram of the kenaf fibre-reinforced PVB film at 0°/90° and 45°/−45° composites

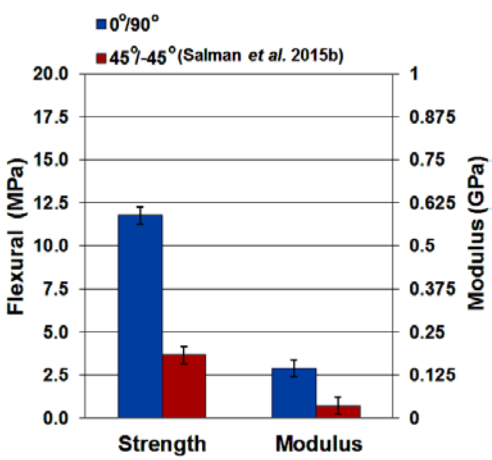


Fig. 9. Average flexural strength and modulus of the composites at 0°/90° and 45°/−45° orientations

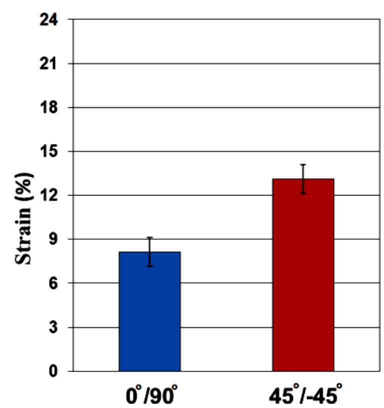
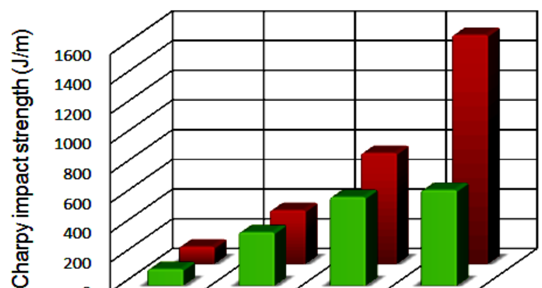


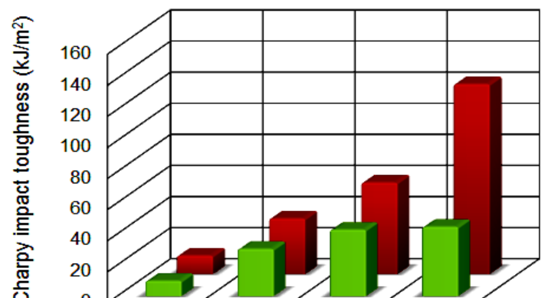
Fig. 10. Average flexural strain of the composites at 0°/90° and 45°/−45° orientations

Unlike both the tensile and flexural behaviour of the composites at 0°/90° and 45°/−45° orientations, the Charpy impact behaviour at different energy levels (0.5, 2.7, 5.4, and 21.6 J) seems to show contrasting results, as represented in Figs. 11 and 12. It can be clearly seen that the 45°/−45° composite had a greater impact strength and toughness than the impact strength and toughness of the 0°/90° composite, especially at high energy levels. This means that the 45°/−45° composite absorbed the most energy before failure, while the 0°/90° composite absorbed the least. Furthermore, the average impact strength of 0°/90° and 45°/−45° composites showed almost same behaviour when tested with a low energy level (0.5 J). Similarly, the average impact toughness of the composites at 0°/90° and 45°/−45° orientations was 9.9 kJ/m^2 and 11.93 kJ/m^2, respectively, whereas the average impact strength of the two composites exhibited a high difference when tested at high energy levels, approximately three times that of the 0°/90° composite value at 21.6 J. Ultimately, the average impact toughness of the two composites showed the same behaviour when tested at high energy levels, approximately four times that of the 0°/90° composite value at 21.6 J. It can be concluded that for the same type of reinforcing fibre, the impact strength of composites differs with different orientation angles of fibre reinforcement. As stated by others (de Albuquerque *et al.* 2000; Yousif *et al.* 2012), both the fibre orientation angles and geometry of the composites are accountable for deciding the impact strength of the composites. This implies that both the effect of interlaminar delimitation and interfacial strength between the fibre and matrix considerably affect impact strength, especially in the case of the weaving pattern, as stated by others (Joseph *et al.* 2003; Mahdi *et al.* 2014).



	0.5 J	2.7 J	5.4 J	21.6 J
Av. 0°/90°	109.67	357.7	595.09	642.280
Av. 45°/-45°	113.67	359.11	744.38	1540.07

Fig. 11. Impact strength of the composites at 0°/90° and 45°/−45° orientations

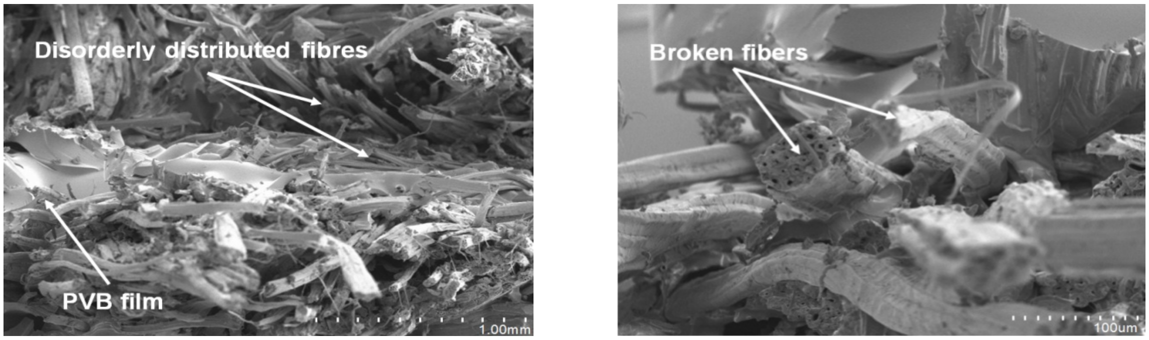


	0.5 J	2.7 J	5.4 J	21.6 J
Av. 0°/90°	9.9	30.42	42.81	44.650
Av. 45°/-45°	11.93	35.77	58.87	122.23

Fig. 12. Impact toughness of the composites at 0°/90° and 45°/−45° orientations

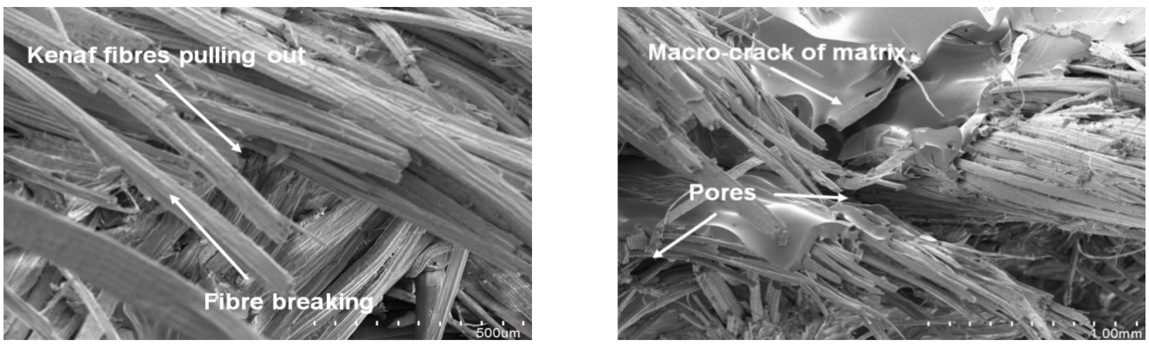
Morphological Properties

Morphological changes of the fractured specimens after tensile testing are shown in SEM images in Figs. 13 and 14. Figures 13(a) and (b) show the fractured surface of the 0°/90° composite, which indicated higher tensile strength behaviour than that of the 45°/−45° composite (as shown in Figs. 14(a) and (b)). The reasons why the 0°/90° composite had better tensile properties are clearly evident in the SEM micrographs. The kenaf fibres in the 0°/90° composite, based on the morphology achieved, are distributed in a disorderly fashion in the matrix and broken at the interface, whereas the fracture mechanism of the 45°/−45° composite appears to involve both fibre pull-out and fibre breaking, as well as crack propagations through the matrix. A tortuous path in crack propagation through the fibre/matrix interface and many hollow portions after the fracture can be seen in the micrograph of the 45°/−45° composite, indicating that the phenomenon of fibre pull-out occurred to a considerable extent.



(a) (b)

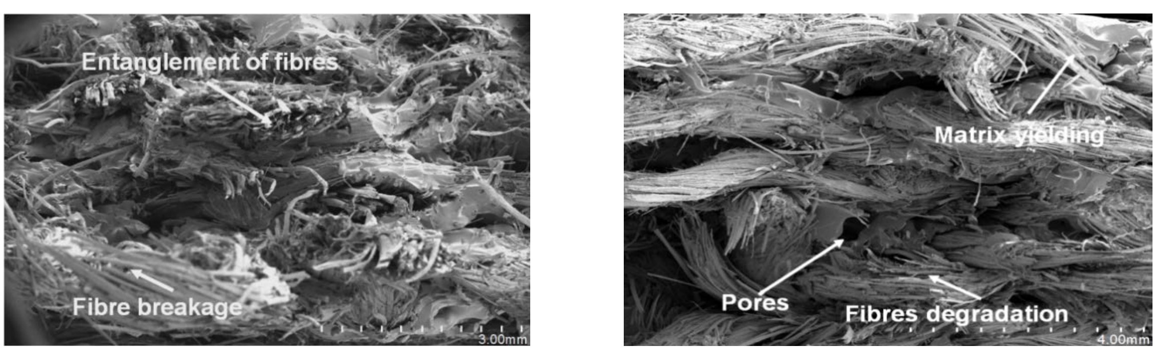
Fig. 13. SEM micrographs of the tensile failure surfaces of the 0°/90° composite: (a) broken kenaf fibre; (b) disorderly distribution of kenaf fibre



(a) (b)

Fig. 14. SEM micrographs of the tensile failure surfaces of the 45°/−45° composite: (a) kenaf fibre pulling out; (b) macrocrack of PVB matrix

To assess the behavioural changes of the interfacial mechanisms in terms of fibre orientation angle, SEM micrographs of the impact fractured surface of the 0°/90° and 45°/−45° composites are presented in Figs. 15(a) and (b), respectively. The appearance of transverse cross-sections of the kenaf fibre end reflects the absence of kenaf fibre pullout and ensures enhanced interfacial adhesion, which leads to high impact resistance for the 45°/−45°composite (as shown in Fig. 15(b)).



(a) (b)

Fig. 15. SEM micrographs of the impact failure surfaces of (a) the 0°/90° composite; and (b) the 45°/−45° composite

Figure 15(a) shows a hollow cross-section of a 0°/90° kenaf fibre along the crack propagation direction, which leads to the complete removal of kenaf fibre bundles along the direction of loading. Generally, the strength of the composite is governed by the initiation and propagation of microscopic cracks through the matrix, which depends on the shape and orientation of the kenaf fibre reinforcement. The entanglement of kenaf fibre could create complex load sharing behaviour between the kenaf fibre and PVB film, which is initially taken up by the kenaf fibre oriented along the horizontal direction and then to the transverse direction with the load after the final failure occurs.

CONCLUSIONS

An experimental study was conducted to determine the best laying angles (fibre orientation) for kenaf fibre/PVB composites in terms of the mechanical and morphological properties. All the examined specimens consisted of five layers of kenaf fibres with two laying angles, $0^o/90^o$ and $45^o/-45^o$ reinforced composites. The findings of this research can be summarized as follows:

1. The mechanical properties of the composite were affected by the fibre orientation angle. The results showed the advantage of the using the $0^o/90^o$ orientation in terms of the tension and flexural properties compared with the $45^o/-45^o$ orientation.
2. The flexural strength of the composite at the $45^o/-45^o$ orientation was found to be lower than the flexural strength of the composite at the $0^o/90^o$ orientation. Moreover, the results indicated that the Young's modulus of the kenaf/PVB composites strongly depended on the fibre orientation angles.
3. The $45^o/-45^o$ composite showed higher impact strength at different energy levels because of the high interlocking of kenaf fibres in the resin.
4. SEM examinations of tensile test specimens show that the $0^o/90^o$ composite failed by fibre fracture, while the $45^o/-45^o$ composite failed by a combination of fibre pull-out and fibre fracture. On the other hand, fractrography studies of the impact test specimens showed that the $45^o/-45°$ composite failed by fibre fracture because of strong entanglement of the fibres.

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REFERENCES CITED

Aji, I., Sapuan, S., Zainudin, E., and Abdan, K. (2009). "Kenaf fibres as reinforcement for polymeric composites: A review," *International Journal of Mechanical and Materials Engineering* 4(3), 239-248.

Akil, H. M., Omar, M. F., Mazuki, A. A. M., Safiee, S., Ishak, Z. A. M., and Abu Bakar, A. (2011). "Kenaf fiber reinforced composites: A review," *Materials and Design* 32(8-9), 4107-4121. DOI: 10.1016/j.matdes.2011.04.008

Alavudeen, A., Rajini, N., Karthikeyan, S., Thiruchitrambalam, M., and Venkateshwaren, N. (2015). "Mechanical properties of banana/kenaf fiber-reinforced hybrid polyester composites: Effect of woven fabric and random orientation," *Materials and Design* 66(A), 246-257. DOI: 10.1016/j.matdes.2014.10.067

Ali, I., Jayaraman, K., and Bhattacharyya, D. (2014). "Implications of fiber characteristics and mat densification on permeability, compaction and properties of kenaf fiber panels," *Industrial Crops and Products* 61, 293-302. DOI: 10.1016/j.indcrop.2014.07.018

ASTM D790-10 (2010). "Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials," ASTM International, West Conshohocken, PA. DOI: 10.1520/D0790-10

ASTM D3039/D3039M-10 (2010). "Standard test method for tensile properties of polymer matrix composite materials," ASTM International, West Conshohocken, PA.

ASTM D6110-10 (2010). "Standard test method for determining the charpy impact resistance of notched specimens of plastics," ASTM International, West Conshohocken, PA. DOI: 10.1520/D6110-10

Chow, P., Lambert, R. J., Bowers, C., and McKenzie, N. (2000). "Physical and mechanical properties of composite panels made from kenaf plant fibers and plastics," *Proceedings of the 2000 International Kenaf Symposium*, Yasuura, Hiroshima, Japan,pp. 139-143.

de Albuquerque, A. C., Joseph, K., Hecker de Carvalho, L., and d'Almeida, J. R. M. (2000). "Effect of wettability and aging conditions on the physical and mechanical properties of uniaxially oriented jute-roving-reinforced polyester composites," *Composites Science and Technology* 60(6), 833-844. DOI: 10.1016/S0266-3538(99)00188-8

Dittenber, D. B., and GangaRao, H. V. S. (2012). "Critical review of recent publications on use of natural composites in infrastructure," *Composites Part A: Applied Science and Manufacturing* 43(8), 1419-1429. DOI: 10.1016/j.compositesa.2011.11.019

El-Shekeil, Y., Sapuan, S., Khalina, A., Zainudin, E., and Al-Shuja'a, O. (2012a). "Influence of chemical treatment on the tensile properties of kenaf fiber reinforcedthermoplastic polyurethane composite," *eXPRESS Polymer Letters* 6(12). DOI: 10.3144/expresspolymlett.2012.108

El-Shekeil, Y., Sapuan, S., Khalina, A., Zainudin, E., and Al-Shuja’a, O. (2012b). "Effect of alkali treatment on mechanical and thermal properties of kenaf fiber-reinforced thermoplastic polyurethane composite," *Journal of Thermal Analysis and Calorimetry* 109(3), 1435-1443. DOI: 10.1007/s10973-012-2258-x

El-Shekeil, Y. A., Sapuan, S. M., Abdan, K., and Zainudin, E. S. (2012c). "Influence of fiber content on the mechanical and thermal properties of Kenaf fiber reinforced

thermoplastic polyurethane composites," *Materials and Design* 40, 299-303. DOI: 10.1016/j.matdes.2012.04.003
El-Shekeil, Y. A., Sapuan, S. M., and Algrafi, M. W. (2014). "Effect of fiber loading on mechanical and morphological properties of cocoa pod husk fibers reinforced thermoplastic polyurethane composites," *Materials and Design* 64, 330-333. DOI: 10.1016/j.matdes.2014.07.034
Faruk, O., Bledzki, A. K., Fink, H. P., and Sain, M. (2012). "Biocomposites reinforced with natural fibers: 2000–2010," *Progress in Polymer Science* 37(11), 1552-1596. DOI: 10.1016/j.progpolymsci.2012.04.003
Hojo, T., Xu, Z., Yang, Y., and Hamada, H. (2014). "Tensile properties of bamboo, jute and kenaf mat-reinforced composite," *Energy Procedia* 56, 72-79. DOI: 10.1016/j.egypro.2014.07.133
Joseph, P. V., Mathew, G., Joseph, K., Groeninckx, G., and Thomas, S. (2003). "Dynamic mechanical properties of short sisal fibre reinforced polypropylene composites," *Composites Part A: Applied Science and Manufacturing* 34(3), 275-290. DOI: 10.1016/S1359-835X(02)00020-9
Karimi, S., Tahir, P. M., Karimi, A., Dufresne, A., and Abdulkhani, A. (2014). "Kenaf bast cellulosic fibers hierarchy: A comprehensive approach from micro to nano," *Carbohydrate Polymers* 101, 878-885. DOI: 10.1016/j.carbpol.2013.09.106
Khan, A. R. (2010). "Kenaf, a fibre for the future: The Harusmas experience," *JEC Composites Magazine*59, 21.
Ku, H., Wang, H., Pattarachaiyakoop, N., and Trada, M. (2011). "A review on the tensile properties of natural fiber reinforced polymer composites," *Composites Part B: Engineering* 42(4), 856-873. DOI: 10.1016/j.compositesb.2011.01.010
Mahdi, E., Hamouda, A. M. S., and Sebaey, T. A. (2014). "The effect of fiber orientation on the energy absorption capability of axially crushed composite tubes," *Materials and Design* 56, 923-928. DOI: 10.1016/j.matdes.2013.12.009
Mylsamy, K., and Rajendran, I. (2011). "The mechanical properties, deformation and thermomechanical properties of alkali treated and untreated agave continuous fibre reinforced epoxy composites," *Materials and Design* 32(5), 3076-3084. DOI: 10.1016/j.matdes.2010.12.051
Ochi, S. (2008). "Mechanical properties of kenaf fibers and kenaf/PLA composites," *Mechanics of Materials* 40(4-5), 446-452. DOI: 10.1016/j.mechmat.2007.10.006
Omar, M. F., Md Akil, H., Ahmad, Z. A., Mazuki, A. A. M., and Yokoyama, T. (2010). "Dynamic properties of pultruded natural fibre reinforced composites using split Hopkinson pressure bar technique," *Materials and Design* 31(9), 4209-4218. DOI: 10.1016/j.matdes.2010.04.036
Qatu, M. S. (2011). "Application of kenaf-based natural fiber composites in the automotive industry," SAE Technical Paper 2011-01-0215. DOI: 10.4271/2011-01-0215
Ramaswamy, G. N., Sellers, T., Tao, W., and Crook, L. G. (2003). "Kenaf nonwovens as substrates for laminations," *Industrial Crops and Products* 17(1), 1-8. DOI: 10.1016/S0926-6690(02)00040-7
Rassmann, S., Paskaramoorthy, R., and Reid, R. G. (2011). "Effect of resin system on the mechanical properties and water absorption of kenaf fibre reinforced laminates," *Materials and Design* 32(3), 1399-1406. DOI: 10.1016/j.matdes.2010.09.006

Saba, N., Jawaid, M., Hakeem, K. R., Paridah, M. T., Khalina, A., and Alothman, O. Y. (2015). "Potential of bioenergy production from industrial kenaf (*Hibiscus cannabinus* L.) based on Malaysian perspective," *Renewable and Sustainable Energy Reviews* 42, 446-459. DOI: 10.1016/j.rser.2014.10.029

Salman, S. D., Leman, Z., Sultan, M. T., Ishak, M. R., and Cardona, F. (2015a). "Kenaf/synthetic and Kevlar®/cellulosic fiber-reinforced hybrid composites: A review," *BioResources* 10(4). DOI:10.15376/biores.10.4.Salman

Salman, S. D., Leman, Z., Sultan, M. T., Ishak, M. R., and Cardona, F. (2015b). "Mechanical and morphological properties of 45°/−45° woven kenaf reinforced PVB-phenolic resin produced using a hot press technique," *Malaysia Polymer International Conference 2015 (MPIC 2015)*,10–11 June 2015, Palm Garden Hotel, IOI Resort, Putrajaya, Kuala Lumpur, Malaysia.

Salman, S. D., Sharba, M. J., Leman, Z., Sultan, M., Ishak, M., and Cardona, F. (2015c). "Physical, mechanical, and morphological properties of woven kenaf/polymer composites produced using a vacuum infusion technique," *International Journal of Polymer Science* 2015, 894565.

Sapuan, S. M., Leenie, A., Harimi, M., and Beng, Y. K. (2006). "Mechanical properties of woven banana fibre reinforced epoxy composites," *Materials and Design* 27(8), 689-693. DOI: 10.1016/j.matdes.2004.12.016

Sapuan, S., Harun, N., and Abbas, K. (2007). "Design and fabrication of a multipurpose table using a composite of epoxy and banana pseudostem fibres," *Journal of Tropical Agriculture* 45(1–2), 66-68.

Sgriccia, N., Hawley, M. C., and Misra, M. (2008). "Characterization of natural fiber surfaces and natural fiber composites," *Composites Part A: Applied Science and Manufacturing* 39(10), 1632-1637. DOI: 10.1016/j.compositesa.2008.07.007

Shibata, S., Cao, Y., and Fukumoto, I. (2008). "Flexural modulus of the unidirectional and random composites made from biodegradable resin and bamboo and kenaf fibres," *Composites Part A: Applied Science and Manufacturing* 39(4), 640-646. DOI: 10.1016/j.compositesa.2007.10.021

Yousif, B. F., Shalwan, A., Chin, C. W., and Ming, K. C. (2012). "Flexural properties of treated and untreated kenaf/epoxy composites," *Materials and Design* 40, 378-385. DOI: 10.1016/j.matdes.2012.04.017

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