Physical and Mechanical Properties of Woven Kenaf/Bamboo Fiber Mat Reinforced Epoxy Hybrid Composites

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Research interest has shifted from synthetic fiber to natural fiber due to environmental concerns and government regulation. This study evaluated the physical and mechanical properties of kenaf(K)/bamboo(B) fiber mat reinforced epoxy hybrid composites. Kenaf, bamboo, and kenaf/bamboo hybrid composites were prepared using the hand lay-up method at 40% wt total fiber loading. Different ratios of kenaf to bamboo fibers, such as 70:30(3B7K), 50:50(BK), and 30:70(7B3K), were used to fabricate the hybrid composites. Kenaf composite and bamboo composite were fabricated as controls. Mechanical (flexural and impact), morphological, and physical properties (thickness swelling, water absorption, and density) were examined. The density, water absorption and thickness swelling of the composites increased as the kenaf weight ratio increased. The flexural properties of kenaf composites were improved by hybridization with bamboo fiber, whereas the impact properties of bamboo were improved by hybridization with a woven kenaf mat. Hybrid composites with a 50:50 ratio showed the highest flexural and impact strength. Scanning electron microscopy (SEM) of flexural fracture showed that 50:50(BK) displayed better interfacial adhesion than the other two ratios. The woven kenaf/bamboo hybrid composite is suitable for use in the fabrication of automotive components.

Keywords: Composite; Kenaf; Bamboo; Natural fiber polymer composite; Physical properties; Flexural properties; Impact properties

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INTRODUCTION

Fiber-reinforced polymer composites (FRPC) are used in various fields. Usually, FRPC contain synthetic fibers, which produce composites with superior properties. Synthetic fibers have been used in the aerospace, automotive, and wind energy industries (Rana and Fangueiro 2016). However, there are a number of environmental issues related to the industrial use of synthetic fibers, which include energy consumption during their production and products that are difficult to dispose. For example, production of glass fibers consumes a lot of fossil fuels (Abdul Khalil *et al.* 2007a). There are no suitable ways to dispose of FRPC, even with energy recovery using an incinerator (Okubo *et al.* 2004).

As a petroleum-based material, synthetic fibers are non-renewable. Increasing interest in green and renewable material has encouraged researchers to study the properties of natural fiber in order to replace or reduce the use of synthetic fibers and polymers. Incorporation of natural fibers can improve the properties of composites, reduce polymer usage, and decrease production cost. In the automotive industries, natural fiber reinforced polymer composites have been used for various for interior and exterior components of vehicles (Holbery and Houston 2006).

There are three sources of natural fibers: animal, plant, and mineral. Plant fibers are commonly used as reinforcement in composite materials. Kenaf, hemp, and jute are examples of natural fibers sourced from plants. These fibers are readily and commercially available in the market. Additionally, these fibers are cheaper than synthetic fibers that are currently being used. In 1940, kenaf fiber was used to make carpet backing, packing materials, papers, and fencing (Tiwari and Srivastava 2012). Kenaf bast fibers possess striking mechanical properties that make them suitable reinforcing materials to replace glass fiber in polymer composites (Faruk *et al.* 2012; Paridah *et al.* 2011). Bamboo has been used as a structural element in pre-industrial architecture in Asian and South American countries (Tara Sen and Reddy 2011). Natural fiber reinforced polymer composite has comparable mechanical properties to glass reinforced polymer composite (Faruk *et al.* 2012; Krishna and Kanny 2016; Sanjay *et al.* 2018). The properties of natural fiber reinforced polymer composites depend on fiber selection, matrix selection, interfacial strength, fiber dispersion, fiber orientation, composite manufacturing process, and porosity (Pickering *et al.* 2016). Additionally, properties of natural fibers depend on the type of plant, extraction process, maturity of fiber, and locality where it is grown. Fiber selection is important since every fiber has its own unique properties. The two reinforcing elements ought to provide unique combinations of properties or synergistic effects as a “hybrid composite”, which then can be used for different applications (Hubbe 2017).

El-Shekeil *et al.* (2012) studied the influence of fiber content (20%, 30%, 40%, and 50%) on the mechanical properties of kenaf fiber reinforced polyurethane. This study showed that the tensile strength of the composite increased as fiber loading increased, up to 30% of fiber loading. Composites with 40% fiber loading showed the second highest tensile strength. The tensile modulus, flexural strength, and modulus increased with each increment in fiber loading. Mahjoub *et al.* (2014) reported that continuous unidirectional kenaf fiber reinforced epoxy composites with different fiber volumes have variable tensile strength. The 40% fiber volume, which was the highest fiber content that was tested, yielded optimum tensile properties for the composite. Similar findings were documented in their analytical analysis using the rule of mixtures (ROM). Researchers reported studies using bamboo fibre as reinforcement for fabrication of natural fiber reinforced polyester composites (Ratna Prasad and Mohana Rao 2011). Different types of fiber were used such as jowar, sisal, and bamboo. The effect of different volume fractions were evaluated and 0.4 volume fraction showed the optimum mechanical properties.

Researchers investigated how the use of more than one type of reinforcement affected the performance of different composites. Hybrid composites can be made either using natural fibers or natural fibers with synthetic fibers depending on the application. Maleque *et al.* (2012) studied the flexural and impact properties of kenaf/glass hybrid composites with different ratios. In this study, untreated and treated kenaf were used. Treated kenaf/glass hybrid with a ratio of 50:50 showed the highest flexural strength, while untreated kenaf/glass hybrid with a ratio of 50:50 showed the highest value of impact strength. Asim *et al.* (2017) studied the effect of hybridization on the mechanical properties of pineapple leaf fiber (PALF)/kenaf (K) phenolic hybrid composite. Different ratios of pineapple leaf fiber to kenaf fiber (PALF:K) were used (100:0, 70:30, 50:50, 30:70, and 0:100). It was shown that the optimum mechanical properties of hybrid composite was obtained when a 30:70 ratio of pineapple leaf fiber to kenaf fiber was used. Researchers have studied the effect of bamboo fiber on the physical and mechanical properties of glass/polyester composites (Vaghasia and Rachchh 2018). The percentage of glass fiber was maintain at 19%, and the percentage of bamboo was varied at 3%, 6%, 9%, 12%, and 15%. In general terms, the physical and mechanical properties increased as the percentage of bamboo fiber was increase up to 9%.

Bamboo has been utilised in composites as reinforcement; it has comparable mechanical properties to glass fiber (Rawi *et al.* 2013). Its high mechanical properties have attracted the interest of researchers to explore the potential for kenaf and bamboo fiber as reinforcement. This research work was intended to develop and characterize woven kenaf/bamboo hybrid composites for use in the automotive industries. In this study, bamboo mat was used to improve the properties of woven kenaf reinforced epoxy composite. Woven kenaf/bamboo reinforced epoxy hybrid composites were fabricated using the hand lay-up method with different ratios of kenaf and bamboo fibers. Mechanical properties such as flexural and impact properties were evaluated. In addition, density, water absorption, and thickness swelling of composites were carried out to study the effect of hybridization of kenaf and bamboo on physical properties.

EXPERIMENTAL

Materials

The woven kenaf fiber mat was supplied by Zul Sdn Bhd, Malaysia. The bamboo mat was procured from Shijiangzhuang Bi Yang Technology Co. Ltd, Hebei, China. D.E.R * 331 epoxy resin (reaction product of epichlorohydrin and bisphenol A) and the epoxy hardener Jointmine 905-3S (modified cycloaliphatic amine) were used in this study. Silicon spray was used as a releasing agent. The epoxy resin, commercial curing agent, and silicon spray were obtained from Tazdiq Engineering Sdn. Bhd., Selangor, Malaysia. Figure 1 shows the woven kenaf mat and bamboo mat. The properties of epoxy hardener Jointmine 905-3S and epoxy resin are shown in Tables 1 and 2, respectively.

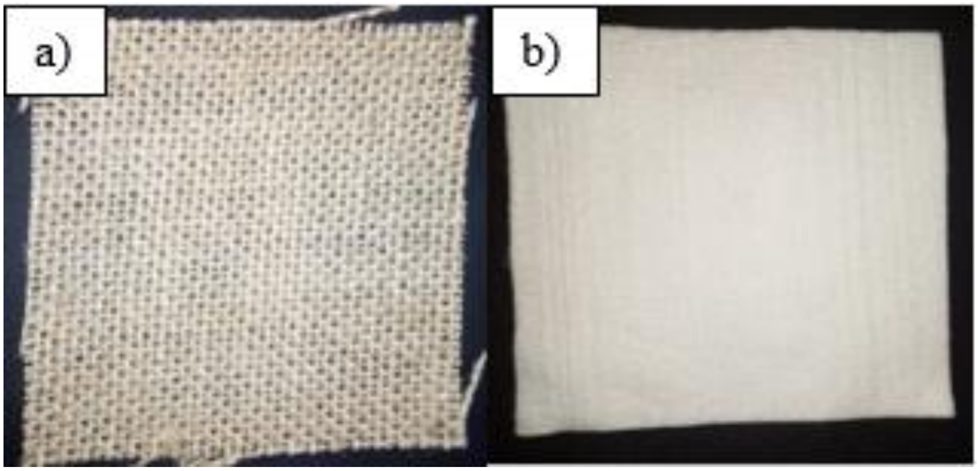

Fig. 1. a) Woven kenaf mat and b) bamboo mat

Table 1. Typical Properties for Hardeners

Property	Value
Amine value (mg KOH/g)	300 ± 20
Viscosity (BH type @25ºC, cPs)	200 ~ 400
Color (Gardner)	<2
Equivalent Wt (H)	95
Pot life (100 g @25°C)	75 min
Hardness (Shore D)	85
Thin film set time (@25°C)	5 h

Table 2. Typical Properties for Epoxy Resin

Property	Value
Epoxide Equivalent Weight (g/eq)	182 – 192
Epoxide Percentage (%)	22.4 – 23.6
Epoxide Group Content (mmol/kg)	5200 – 5500
Color (Platinum Cobalt)	75 Max.
Viscosity @ 25°C (mPa•s)	11000 – 14000
Hydrolyzable Chloride Content (ppm)	500 Max.
Water Content (ppm)	700 Max.
Density @ 25°C (g/mL)	1.16
Epichlorohydrin Content (ppm)	5 Max.
Shelf Life (Months)	24

Fabrication of composites

The hand lay-up method was used to fabricate the bamboo mat, kenaf mat, and hybrid kenaf/bamboo. The bamboo mat and woven kenaf were cut according to mould size, 300 mm × 300 mm, and put in the oven at 60 °C for 24 h to remove moisture. The epoxy and hardener were mixed with a 2:1 ratio and stirred with wooden stick at room temperature for 2 to 4 min. The mould was sprayed with a thin layer of silicon spray, which acts as a releasing agent. Hybrid composites of kenaf and bamboo were prepared with different weight ratios of 70:30, 50:50, and 30:70, with total fiber loading at 40% by weight. A thin layer of epoxy was poured into the mould followed by the bamboo and woven kenaf mats. Epoxy was applied on every layer of the mats. The mould was transfer into a hot press with a temperature of 110 °C for 10 min, then transferred into a cold press for 5 min before it was demoulded. A single woven kenaf mat and bamboo mat were prepared as reference. Figure 2 shows the prepared samples.

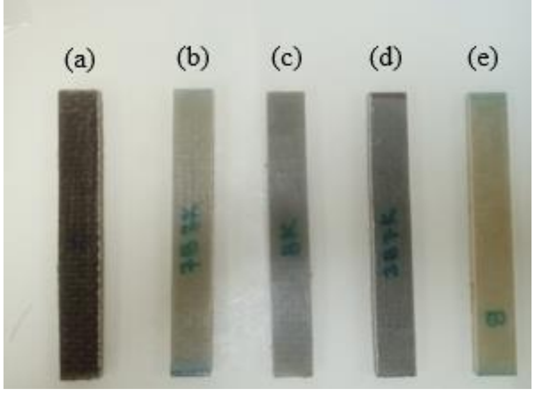

Fig. 2. a) Kenaf (K), b) B 70: K 30 (7B3K), c) B 50: K 50 (BK) d) B 30: K 70 (3B7K), e) Bamboo (B)

Characterization

Density

The density of the composites was measured using the ASTM D 1895-96 (2003) standard. The density of the samples was calculated by using Eq. 1,

$$\text{Density (g / cm}^3\text{)} = m / v \quad (1)$$

where *m* is the weight of composite sample, and *v* is the sample volume.

Water absorption

The test specimen for water absorption (with dimensions of 20 mm x 20 mm x 5 mm) was prepared and tested according to ASTM D 570-98 (2010). The initial weight of the test specimen (W_d) was measured and recorded before immersion in distilled water. The weight of test specimen (W_n) was measured and recorded every 24 h for a week. Water absorption of the composites were calculated using Eq. 2,

$$Water\ absorption(\%) = \frac{W_n - W_d}{W_d} x100 \quad (2)$$

where W_n is the weight of composites samples after immersion and W_d is the weight of the composite samples before immersion.

Thickness swelling

The test specimen for thickness swelling (with dimensions of 20 mm x 20 mm x 5 mm) was prepared and tested according to ASTM D 570-98 (2010). The initial thickness of the test specimen was measured and recorded before it was immersed in distilled water. The test specimen’s thickness was measured and recorded every 24 h for a week. Thickness swelling of the samples was calculated using Eq. 3,

$$Thickness\ Swelling\,(\%) = \frac{T_1 - T_0}{T_0} x100 \quad (3)$$

where T_1 is the thickness after soaking and T_0 is the thickness before soaking.

Flexural testing

The tensile test specimen had dimensions of 160 mm × 20 mm × 5 mm and was prepared and tested according to ASTM D790 (2015) using a 30 kN Bluehill INSTRON 5567 universal testing machine (Shakopee, USA). The support span was 16 times the specimen depth, and the testing speed was calculate using Eq. 4. The samples were put in a conditioning chamber for one day at 23 ± 3 °C and relative humidity of 50 ± 10%. In every sample, five replications were tested, and the average value was tabulated,

$$R = 0.01L^2 / 6d \quad (4)$$

where *R* is the rate of crosshead motion (mm/min), *L* is the support span (mm), and *d* is the depth of beam (mm).

Impact testing

Notched Izod impact test specimens (with dimensions of 70 mm × 15 mm × 6 mm) were prepared and tested according to standard ASTM D256 (2010) using Gotech GT-7045-MD (Taichung City, Taiwan). The notch angle was 45°, and the depth was 2.5 mm.

In every sample, five replications were tested, and the average value was tabulated.

Scanning electron microscopy (SEM)

The fracture surface morphology of the composite flexural sample was examined using an EM-30AX scanning electron microscope (SEM; COXEM, Daejeon, Korea) with an acceleration voltage of 20 kV. The samples were coated with a thin layer of gold prior to structure analysis.

RESULTS AND DISCUSSION

Density

The density of kenaf, bamboo, and kenaf/bamboo hybrid composites are shown in Table 3. Bamboo composites had a higher density compared to kenaf composites, which were 1.18 g/cm^3 and 1.08 g/cm^3, respectively. This is because the density of bamboo fiber is higher than kenaf fiber. The density of hybrid composites increased as the bamboo weight ratio increased. Hybrid composites with the highest bamboo weight ratio (7B3K) showed the highest density compared to BK and 3B7K. Even though BK had a higher bamboo ratio compared to 3B7K, it was demonstrated that BK had lower density than 3B7K. The lower density of BK compared to 3B7K might be due to the void formation in the composites. The void formation was due to the incomplete wetting of fibers by the resin (Abdul Khalil *et al.* 2007a). In another study it was shown that hybridization of low-density material with high density material will lead to increased density of the hybrid composites (Mohd Nurazzi *et al.* 2017).

Table 3. Density of Composites

Type of Composites	Density (g/cm^3)
Kenaf (K)	1.0750
B 30: K 70 (3B7K)	1.1475
B 50:K 50 (BK)	1.1450
B 70: K 30 (7B3K)	1.1525
Bamboo (B)	1.1825

Water Absorption

Figure 3 shows the water absorption rate of kenaf, bamboo, and kenaf/bamboo hybrid composites over the span of a week. The rate of water absorption decreased as time of immersion increased. Usually water absorption of composites is influenced by factors such as fiber loading, voids, viscosity of matrix, temperature, and humidity (Jawaid *et al.* 2010). Kenaf-reinforced epoxy composites have higher water absorption compared to the bamboo reinforced epoxy composites. Water absorption of kenaf and bamboo after a week were 0.12% and 0.05%, respectively. The higher percentage of water absorption was due to several factors such as void content, fiber hydrophilicity, and the type of matrix. Water is absorbed into the available voids and cracks of the composite through capillary action, and the presence of high hemicellulose content, which is hydrophilic in nature, leads to water absorption (Kushwaha and Kumar 2010; Abdul Khalil *et al.* 2011). The hemicellulose content of kenaf (17.8%) is higher than bamboo (11.1%) (Ahmad Safwan *et al.* 2018), making kenaf more hydrophilic than bamboo. The use of bamboo together with kenaf reduced the water absorption of the composite. As the bamboo weight ratio increased, the water absorption of the hybrid composite decreased. Of the three hybrid composites, 7B3K showed the lowest water absorption after a week at 0.07%. Hybrid composites, BK and 3B7K did not show much different in water absorption behaviours, as their value was only 0.10%. This might be due the higher void formation in BK compared with 3B7K, which promoted more water absorption. Kenaf/bamboo hybrid composites exhibited lower water absorption as compared to kenaf composites.

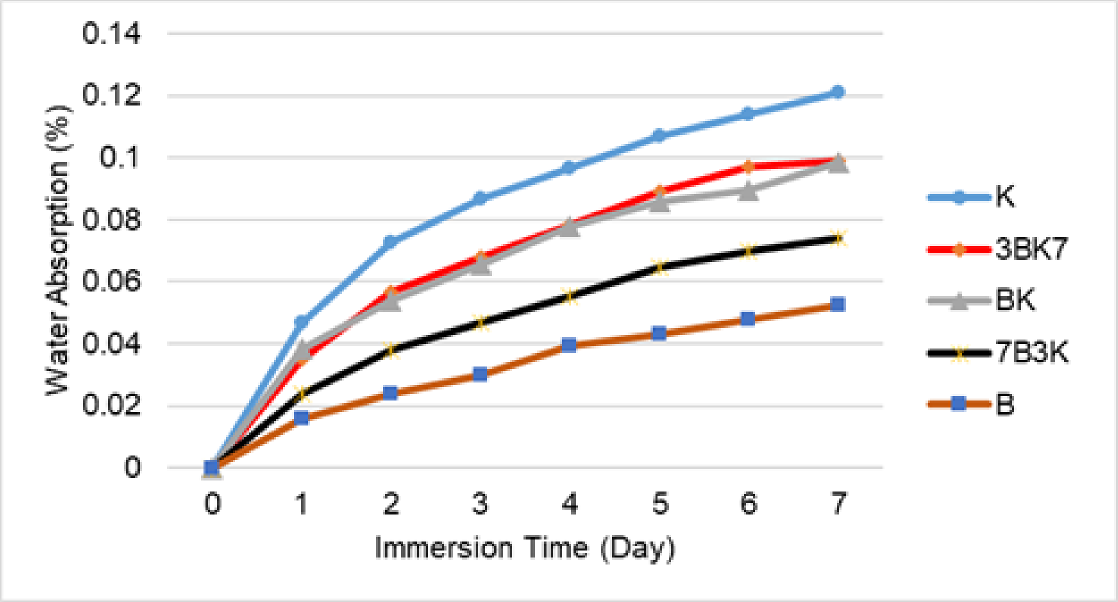

Fig. 3. Water absorption for bamboo, kenaf, and kenaf bamboo hybrid composites

Thickness Swelling

The thickness swelling results for kenaf, bamboo, and kenaf/bamboo hybrid composites are shown in Fig. 4. Thickness swelling of the composites increased as immersion time was increased. Water was absorbed by the fibers until the cell wall was saturated with water, and beyond this point, no more thickness swelling occurred. The presence of polar groups, such as hydroxyl and oxygen groups, in lignocellulosic fiber attracts water molecules through hydrogen bonding, leading to moisture build-up in the cell wall and fiber–matrix interface (Abdul Khalil *et al.* 2007a). The results showed that the thickness swelling of kenaf composites was higher than bamboo composites. The finding was in accordance with the water absorption results. The highest thickness swelling among hybrid composites was shown by BK, which was 5.43%, and followed by 3B7K, with thickness swelling of 5.38%. This indicates that there was not much difference in the thickness swelling of BK and 3B7K. Therefore, the thickness swelling of hybrid composites decreased as bamboo loading increased. This is because bamboo fiber absorbed less water than kenaf fiber. The decrease in thickness swelling is due to the less hydrophilic nature of one of the materials used (Jawaid *et al.* 2012).

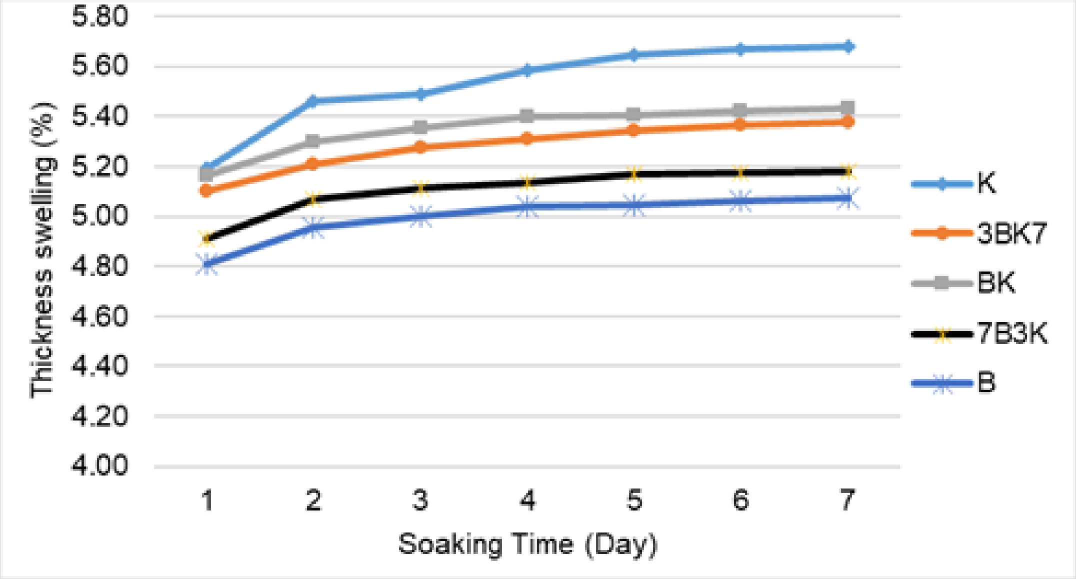

Fig. 4. Thickness swelling for bamboo, kenaf, and kenaf bamboo hybrid composites

Flexural Properties

Flexural strength and modulus of kenaf, bamboo, and kenaf/bamboo hybrid composites with different ratios are depicted in Fig 5. Comparison of bamboo and kenaf composites illustrated that the flexural strength of the bamboo composites (116.4 MPa) was higher than the kenaf composites (90.9 MPa). Studies on hybrid kenaf/coir and bamboo/coir composites have shown that bamboo/coir hybrid composites had higher flexural strength compared to kenaf/coir (Yusoff *et al.* 2016). This indicates that bamboo has better flexural strength than kenaf. Additionally, the higher flexural strength and modulus of bamboo composite were due to the good fiber and matrix interfacial bonding (Abdul Khalil *et al.* 2007b; Da Silva *et al.* 2012). Hybrid composites typically had higher flexural strength and modulus compared with kenaf composites, but lower than bamboo composites.

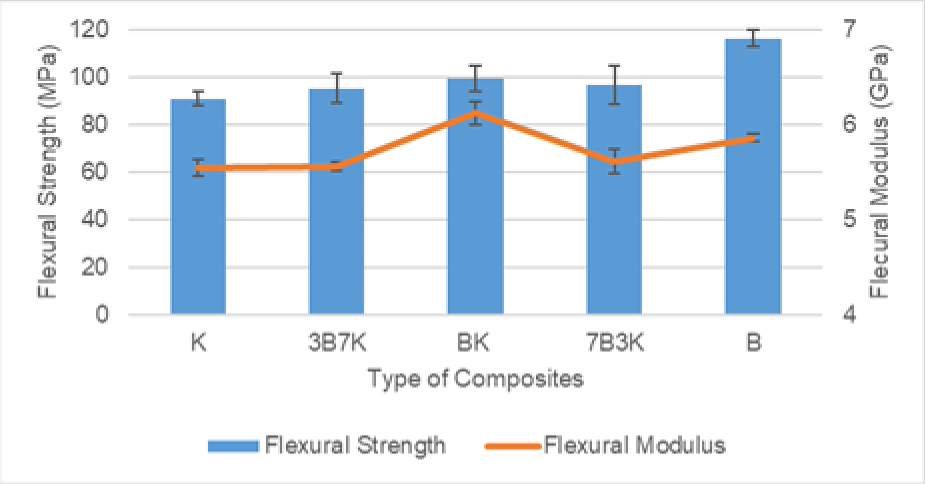

Fig 5. Flexural strength and modulus of kenaf, bamboo, and kenaf bamboo hybrid composite with different ratios

The flexural strength of 7K3B, BK, and 3K7B demonstrated improvement of 4.8%, 9.4%, and 6.3%, respectively, compared with kenaf composites. The flexural modulus of 7K3B, BK, and 3K7B increased 1.2%, 10.5%, and 0.3% respectively.

Even though 3K7B had the highest bamboo ratio, it had lower flexural strength and modulus compared with BK. This might be due to the failure of kenaf fiber in 3K7B, resulting in lower flexural strength and modulus. Among these three combinations, hybrid composites with a ratio 50:50 kenaf to bamboo had the highest flexural strength and modulus, which were 99.4 MPa and 6.12 GPa respectively. Boopalan *et al.* (2013), Hanan *et al.* (2018), and Zainudin *et al.* (2014) reported that low flexural properties of a fiber can be improved by combining it with another fiber possessing better flexural properties. Additionally, they found that a hybrid composite with a ratio of 50:50 exhibited the best flexural properties.

Tables 4 and 5 show an ANOVA analysis on the flexural strength and flexural modulus of the composites. Variance of flexural strength and modulus was divided into two components: a between-group component (BG) and a within-group component (WG). The F-ratio is a ratio for BG estimate to WG estimate and, for the flexural strength data, the F-ratio was 15.5. For the flexural modulus analysis, the F-ratio was 35.4. The P-value obtained from this analysis was less than 0.05. There was a statistically significant difference between mean flexural strength and flexural modulus from one level of composites to another at a 95% confidence level.

Table 4. ANOVA Test for Flexural Strength

Source	SS	Df	MS	F-ratio	P-value
BG	1937.99	4	484.50	15.47	0.00
WG	626.26	20	31.31		

* BG, between group; WG, within group; SS, sum of square; Df, degree of freedom; MS, mean square; F, F-test for ANOVA; Number of observations=25; Number of samples=5.

Table 5. ANOVA Test for Flexural Modulus

Source	SS	Df	MS	F-ratio	P-value
BG	1252033.22	4	313008.30	35.38	0.00
WG	176921.78	20	8846.09		

* BG, between group; WG, within group; SS, sum of square; Df, degree of freedom; MS, mean square; F, F-test for ANOVA; Number of observations=25; Number of samples=5.

Scanning Electron Microscopy (SEM)

Figure 6 shows the SEM images of flexural fracture surfaces for bamboo, kenaf, and hybrid composites. Fiber breakage, pull-out, air bubbles, and matrix cracking were observed. Figure 6(a) shows the flexural fracture surface of bamboo composites, where fiber breakage and pull-out are clear. Fiber breakage indicates that the interfacial bonding of fibre and matrix is adequate. Additionally, flexural fractures of kenaf composite are depicted in Fig. 6(b). There are voids in the composite that affect its flexural properties and density. The presence of voids decreases the mechanical properties and density of the composite as well (Jawaid *et al.* 2010; Saba *et al.* 2016). In addition, fiber breakage and fiber pull-out are shown in Fig. 6(a).

Fibers in the horizontal direction showed fiber breakage while those in vertical direction exhibited fiber pull-out. The results show that fiber orientation contributed to interfacial bonding of fiber and matrix. Interfacial bonding of fiber and matrix was strong in the horizontal direction but poor in the vertical direction.

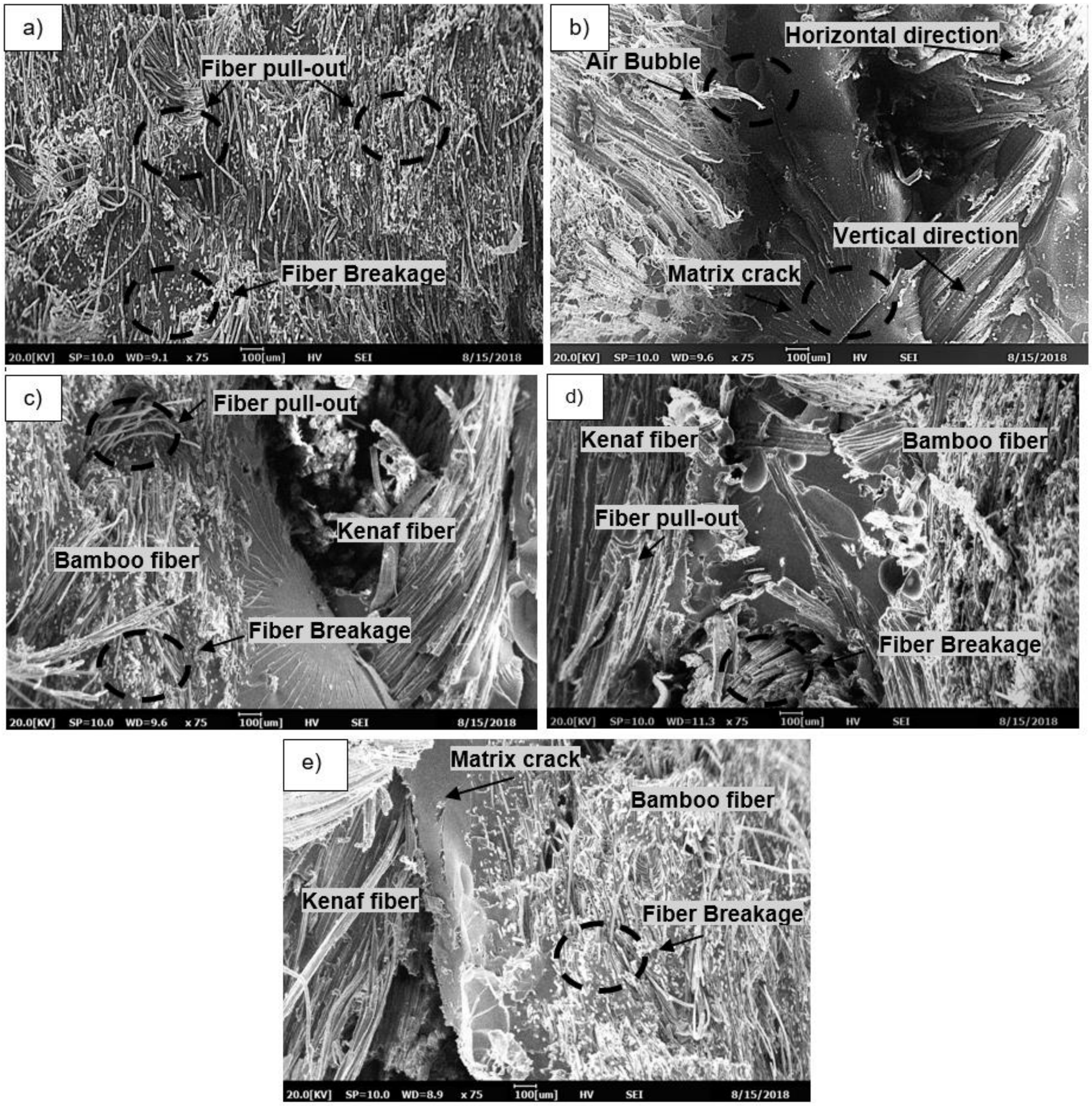

Fig. 6. SEM micrographs flexural fracture surface of composites (a) B; (b) K; (c) 3B7K; (d) BK; and (e) 7B3K

Figures 6 (c) and (d) show the flexural fracture of hybrid composites. The hybrid composites contained two layers of fiber, kenaf and bamboo. Fiber pull-out, breakage, and air bubbles were observed in all images for hybrid composites. There was less fiber pull-out in BK, which indicates that interfacial bonding between fiber and matrix was slightly stronger than in the other two hybrid composites, leading to higher flexural properties in BK composites. Moreover, air bubbles were observed in BK. Air bubbles contributed to BK having a slightly lower density than 3B7K.

Impact Properties

The ability of composite material to absorb and dissipate energy in the form of creating new surfaces under shock or sudden blow is known as impact strength (Kumar and Kumar 2012). Figure 7 shows the impact strength of kenaf, bamboo, and kenaf/bamboo hybrid composites with different ratios. Kenaf composites had better impact strength (40.6 J/m) than bamboo composites (37.8 J/m). The geometry construction of the kenaf mat provides it with superior impact strength compared with the bamboo composite. Impact properties of composite material are influenced by interfacial bonding, fiber and matrix properties, the construction and geometry of the composites, and test conditions (Wambua *et al.* 2003; Biswas *et al.* 2011). In study conducted by Khan *et al.* (2016) it was found that composites made from woven jute fabric had better impact strength compare to non-woven jute fabric.

Ratim *et al.* (2012) studied the effect of woven and non-woven fiber on mechanical properties of polyester composite reinforced with kenaf. The findings showed that composite reinforced with woven kenaf had higher impact strength compared to composite reinforced non-woven kenaf. The use of kenaf fiber together with bamboo fiber improved the impact strength compared to bamboo composites alone. The 3B7K and 7B3K composites showed slight improvements in impact strength of approximately 4.32% and 3.49%, respectively. Hybrid composites with ratio 50:50 showed a positive synergistic effect, which gave the highest impact strength compared to other composites. Boopalan *et al.* 2013 studied jute/banana reinforced epoxy hybrid composites. Different ratios of jute and banana were used (jute:banana; 0:100, 25:75. 50:50, 75:25, and 100:0). Based on the experiment it was found that jute/banana reinforced epoxy hybrid composites with ratio 50:50 had the highest impact strength and went beyond the impact strength of pure jute and banana composites. Another study conducted by Zainudin *et al.* (2014) investigated the effect hybridization of empty fruit bunch (EFB) with coir. It was found that optimum impact strength was with a 50:50 ratio of the two fiber types.

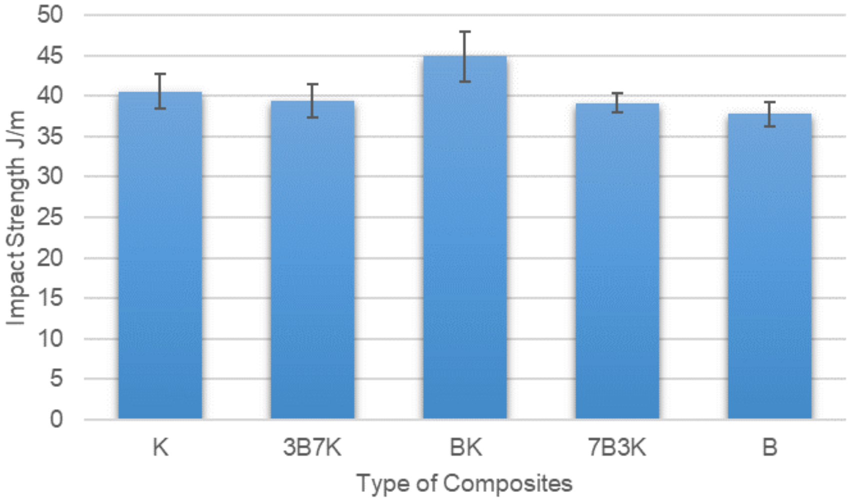

Fig. 7. Impact strength of kenaf, bamboo, and kenaf bamboo hybrid composites

Table 6 shows an ANOVA analysis on the impact strength of the composites. Variance of impact strength was divided into two components: a between-group component (BG) and a within-group component (WG). The F-ratio is a ratio for BG estimate to WG estimate, and in this case the F-ratio was 8.35. The P-value obtained from this analysis was less than 0.05. The results indicate that there was a statistically significant difference between the mean impact strength from one level of composites to another at a 95% confidence level.

Table 6. ANOVA Test for Impact Strength

Source	SS	Df	MS	F-ratio	P-value
BG	146.59	4	36.65	8.35	0.00
WG	87.74	20	4.39		

* BG, between group; WG, within group; SS, sum of square; Df, degree of freedom; MS, mean square; F, F-test for ANOVA; Number of observations=25; Number of samples=5.

CONCLUSIONS

1. The hybrid composites density increased as the bamboo weight ratio increased, since bamboo has a higher density compared to kenaf. The 7B3K hybrid composites had the highest density compared to the two other ratios of hybrid composites.
2. Water absorption for hybrid composites decreased as the bamboo weight ratio increased. Accordingly, 3B7K and BK had the highest water absorption.
3. The use of bamboo together with kenaf reduced the thickness swelling of hybrid composites compared to kenaf composites.
4. Hybrid kenaf/bamboo with a 50:50 ratio showed the highest flexural strength and modulus compared to other hybrid composites.
5. Morphological analysis by SEM showed that there was fiber pull-out, fiber breakage, matric cracking, and air bubbles in the composites. Based on the analysis, hybrid composites with a 50:50 ratio had better interfacial adhesion compared to the other two ratios.
6. The impact strength of hybrid kenaf/bamboo seemed to improve beyond the impact strength of pure kenaf and bamboo composite, which was 44.8 J/m.
7. Based on the analysis, hybrid kenaf/bamboo composites with a ratio of 50:50 showed the best overall performance.

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REFERENCES CITED

Abdul Khalil, H. P. S., Hanida, S., Kang, C. W., and Fuaad, N. A. N. (2007a). "Agro-hybrid composite: The effects on mechanical and physical properties of oil palm fiber (efb)/glass hybrid reinforced polyester composites," *Journal of Reinforced Plastics and Composites* 26(2), 203-218. DOI: 10.1177/0731684407070027

Abdul Khalil, H. P. S., Issam, A. M., Ahmad Shakri, M. T., Suriani, R., and Awang, A. Y. (2007b). "Conventional agro-composites from chemically modified fibres," *Industrial Crops and Products* 26(3), 315-323. DOI: 10.1016/j.indcrop.2007.03.010

Abdul Khalil, H. P. S., Jawaid, M., and Bakar, A. A. (2011). "Woven hybrid composites: Water absorption and thickness swelling behaviours," *BioResources* 6(2), 1043-1052. DOI: 10.15376/biores.6.2.1043-1052

Ahmad Safwan, I., Jawaid, M., Sultan, M. T. H., and Azman, H. (2018). "Preliminary study on tensile and impact properties of kenaf/bamboo fiber reinforced epoxy composites," *Journal of Renewable Materials* 6(5), 529-535. DOI: 10.7569/JRM.2018.634103

Asim, M., Jawaid, M., Abdan, K., Ishak, M. R., and Alothman, O. Y. (2017). "Effect of hybridization on the mechanical properties of pineapple leaf fiber/kenaf phenolic hybrid composites," *Journal of Renewable Materials* 6(1), 38-46. doi:10.7569/jrm.2017.634148

ASTM D1895-96 (2003). "Standard test method for apparent density, bulk factor, and pourability of plastic materials," ASTM International, West Conshohocken, USA.

ASTM D256 (2010). "Standard test method for determining the izod pendulum impact resistance of plastics," ASTM International, West Conshohocken, USA.

ASTM D570-98 (2010). "Standard test method for water absorption of plastics," ASTM International, West Conshohocken, USA.

ASTM D790 (2015). "Standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials," ASTM International, West Conshohocken, USA.

Biswas, S., Kindo, S., and Patnaik, A. (2011). "Effect of fiber length on mechanical behavior of coir fiber reinforced epoxy composites," *Fibers and Polymers* 12(1), 73-78. DOI: 10.1007/s12221-011-0073-9

Boopalan, M., Niranjanaa, M., and Umapathy, M. J. (2013). "Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites," *Composites Part B: Engineering* 51, 54-57. DOI: 10.1016/j.compositesb.2013.02.033

Da Silva, L. V., Júnior, J. H. S. A., Angrizani, C. C., and Amico, S. C. (2012). "Short beam strength of curaua, sisal, glass and hybrid composites," *Journal of Reinforced Plastics and Composites* 32(3), 197-206. DOI: 10.1177/0731684412467561

El-Shekeil, Y. A., Sapuan, S. M., Abdan, K., and Zainudin, E. S. (2012). "Influence of fiber content on the mechanical and thermal properties of kenaf fiber reinforced thermoplastic polyurethane composites," *Materials & Design* 40, 299-303. DOI: 10.1016/j.matdes.2012.04.003

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

Hanan, F., Jawaid, M., and Md Tahir, P. (2018). "Mechanical performance of oil palm/kenaf fiber-reinforced epoxy-based bilayer hybrid composites," *Journal of Natural Fibers* DOI: 10.1080/15440478.2018.1477083

Holbery, J., and Houston, D. (2006). "Natural-fiber-reinforced polymer composites in automotive applications," *Journal of Minerals, Metals and Material Society* 58(11), 80-86. DOI: 10.1007/s11837-006-0234-2

Hubbe, M. A. (2017). "Hybrid filler (cellulose/noncellulose) reinforced nanocomposites," in: *Handbook of Nanocellulose and Cellulose Nanocomposites*, Vol. 1, H. Kargarzadeh, I. Ahmad, S. Thomas, and A. Dufresne (eds.), Wiley-VCH, Ch. 8, pp. 273-299.

Jawaid, M., Abdul Khalil, H. P. S., Hassan, A., and Abdallah, E. (2012). "Bi-layer hybrid biocomposites: Chemical resistant and physical properties," *BioResources* 7(2), 2344-2355. DOI: 10.15376/biores.7.2.2344-2355

Jawaid, M., Abdul Khalil, H. P. S., Noorunnisa Khanam, P., and Abu Bakar, A. (2010). "Hybrid composites made from oil palm empty fruit bunches/jute fibres: Water absorption, thickness swelling and density behaviours," *Journal of Polymers and the Environment* 19(1), 106-109. DOI: 10.1007/s10924-010-0203-2

Khan, G. M. A., Terano, M., Gafur, M. A., and Alam, M. S. (2016). "Studies on the mechanical properties of woven jute fabric reinforced poly(l-lactic acid) composites," *Journal of King Saud University - Engineering Sciences* 28(1), 69-74. DOI: 10.1016/j.jksues.2013.12.002

Krishna, K. V., and Kanny, K. (2016). "The effect of treatment on kenaf fiber using green approach and their reinforced epoxy composites," *Composites Part B: Engineering* 104, 111-117. DOI: 10.1016/j.compositesb.2016.08.010

Kumar, V., and Kumar, R. (2012). "Improved mechanical and thermal properties of bamboo-epoxy nanocomposites," *Polymer Composites*, 33(3), 362-370. DOI: 10.1002/pc.22155

Kushwaha, P. K., and Kumar, R. (2010). "The studies on performance of epoxy and polyester-based composites reinforced with bamboo and glass fibers," *Journal of Reinforced Plastics and Composites* 29(13), 1952-1962. DOI: 10.1177/0731684409342006

Mahjoub, R., Yatim, J. M., Mohd Sam, A. R., and Raftari, M. (2014). "Characteristics of continuous unidirectional kenaf fiber reinforced epoxy composites," *Materials & Design* 64, 640-649. DOI: 10.1016/j.matdes.2014.08.010

Maleque, M. A., Afdzaluddin, A., and Iqbal, M. (2012). "Flexural and impact properties of kenaf-glass hybrid composite," *Advanced Materials Research* 576, 471-474. DOI: 10.4028/www.scientific.net/AMR.576.471

Mohd Nurazzi, N., Abdan, K., Salit, M. S., and Mohamed, R. (2017). "Physical, mechanical and thermal properties of sugar palm yarn fibre loading on reinforced unsaturated polyester composite," *Journal of Physical Science* 28(3), 115-136. DOI: 10.21315/jps2017.28.3.8

Okubo, K., Fujii, T., and Yamamoto, Y. (2004). "Development of bamboo-based polymer composites and their mechanical properties," *Composites Part A: Applied Science and Manufacturing* 35(3), 377-383. DOI: 10.1016/j.compositesa.2003.09.017

Paridah, M. T., Basher, A. B., SaifulAzry, S., and Ahmed, Z. (2011). "Retting process of some bast plant fibres and its effect on fibre quality: A review," *BioResources* 6(4), 5260-5281. DOI: 10.15376/biores.6.4.5260-5281

Pickering, K. L., Efendy, M. G. A., and Le, T. M. (2016). "A review of recent developments in natural fibre composites and their mechanical performance," *Composites Part A: Applied Science and Manufacturing* 83, 98-112. DOI: 10.1016/j.compositesa.2015.08.038

Rana, S., and Fangueiro, R. (2016). *Fibrous and Textile Materials for Composite Applications*, Springer Singapore.

Ratim, S., Bonnia, N. N., and Surip, S. N. (2012). "The effect of woven and non-woven fiber structure on mechanical properties polyester composite reinforced kenaf," *AIP Conference Proceedings* 1455(1), 131-135. DOI: 10.1063/1.4732481

Ratna Prasad, A. V., and Mohana Rao, K. (2011). "Mechanical properties of natural fibre reinforced polyester composites: Jowar, sisal and bamboo," *Materials & Design* 32(8), 4658-4663. DOI: 10.1016/j.matdes.2011.03.015

Rawi, N. F. M., Jayaraman, K., and Bhattacharyya, D. (2013). "A performance study on composites made from bamboo fabric and poly(lactic acid)," *Journal of Reinforced Plastics and Composites* 32(20), 1513-1525. DOI: 10.1177/0731684413498296

Saba, N., Paridah, M. T., Abdan, K., and Ibrahim, N. A. (2016). "Effect of oil palm nano filler on mechanical and morphological properties of kenaf reinforced epoxy composites," *Construction and Building Materials* 123, 15-26. DOI: 10.1016/j.conbuildmat.2016.06.131

Sanjay, M. R., Madhu, P., Jawaid, M., Senthamaraikannan, P., Senthil, S., and Pradeep, S. (2018). "Characterization and properties of natural fiber polymer composites: A comprehensive review," *Journal of Cleaner Production* 172, 566-581. DOI: 10.1016/j.jclepro.2017.10.101

Tara Sen, H. N., and Reddy, J. (2011). "Application of sisal, bamboo, coir and jute natural composites in structural upgradation," *International Journal of Innovation, Management and Technology* 2(3), 186-191. DOI: 10.7763/IJIMT.2011.V2.129

Tiwari, A., and Srivastava, R. B. (2012). *Biotechnology in Biopolymers Developments, Applications & Challenging Areas*, Smithers Rapra Technology Ltd.

Vaghasia, B., and Rachchh, N. (2018). "Evaluation of physical and mechanical properties of woven bamboo glass polyester hybrid composite material," *Materials Today: Proceedings* 5(2), 7930-7936. DOI:10.1016/j.matpr.2017.11.475

Wambua, P., Ivens, J., and Verpoest, I. (2003). "Natural fibres: Can they replace glass in fibre reinforced plastics?" *Composites Science and Technology* 63(9), 1259-1264. DOI: 10.1016/S0266-3538(03)00096-4

Yusoff, R. B., Takagi, H., and Nakagaito, A. N. (2016). "Tensile and flexural properties of polylactic acid-based hybrid green composites reinforced by kenaf, bamboo and coir fibers," *Industrial Crops and Products* 94, 562-573. DOI: 10.1016/j.indcrop.2016.09.017

Zainudin, E. S., Yan, L. H., Haniffah, W. H., Jawaid, M., and Alothman, O. Y. (2014). "Effect of coir fiber loading on mechanical and morphological properties of oil palm fibers reinforced polypropylene composites," *Polymer Composites* 35(7), 1418-1425. DOI: 10.1002/pc.22794

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