Effect of Fiber Orientation on Mechanical Properties of Kenaf-Reinforced Polymer Composite

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The increase of environmental awareness has led to interest in the use of materials with eco-friendly attributes. In this study, a sandwich composite was developed from polyester and kenaf fiber with various orientation arrangements. Polyester/kenaf sandwich composite was fabricated through the combination of a hand lay-up process and cold compression. The tensile, flexural, and Izod impact tests of the sandwich composites were evaluated by using a universal tensile tester and an impact tester. The thermal stability of polyester/kenaf sandwich composite and plywood were investigated by using a thermogravimetric analyser. Results showed that the polyester/kenaf sandwich composite with kenaf fiber in anisotropy orientation achieved the highest mechanical properties. The kenaf fiber in anisotropic orientation could absorb the impact energy and allow the sandwich composite to withstand greater impact forces compared to composite with fiber in perpendicular or isotropic orientations. The polyester/kenaf sandwich composite also showed higher thermal stability compared to a conventional plywood sheet. Thus, the fabrication of polyester/kenaf sandwich composite with kenaf fiber in an anisotropic orientation design has great potential to replace plywood sheets for beam construction applications.

Keywords: Kenaf fiber; Polyester; Tensile; Thermal stability; Impact strength

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INTRODUCTION

The increases in environmental and health concerns, cost awareness, more sustainable methods of manufacturing, and increased awareness of energy consumption are the factors that provide an impetus to drive the growth of new materials and products based on natural fibers (Fowler *et al.* 2006; Yu *et al*. 2006; Bakar *et al.* 2014). Nowadays, kenaf fibers are being applied in various products including bagging, carpet backing, packaging materials, papers, and fencing. In addition, their use is being extended to structural, automotive, plastic, and food packaging industries too. This natural-based fiber is widely used as reinforcing medium for thermoplastic resins such as polyethylene (Chen and Porter 1994), polypropylene (Sanadi *et al.* 1995), as well as thermosetting materials such as polyester (Aziz *et al.* 2005). Now, efforts have been taken to increase the usage of biobased fiber components in sandwich composites. Kenaf sandwiches with plastic composite are a potential substitute to replace wood-based products for use as building materials in construction industry. A comparison between various insulating materials including stone, paper, glass, and kenaf fiber has been reported (Ardente *et al*. 2008). The result shows that kenaf fibers experience less impact if various disposal scenarios are adopted in life cycle impacts (Ardente *et al*. 2008). Automotive manufacturing has adopted traditional material such as glass fibers and manufactured foams because of the issue of non-biodegradability (Davoodi *et al*. 2010). The use of kenaf fiber can provide lower density than the traditional materials and has resulted in lightweight and eco-friendly automotive interiors. Not only that, it has been shown that the cellulosic-based non-woven fiber has better sound absorption and noise level reduction (Parikh *et al.* 2006). This sandwich layer composite is a very efficient structural design with the benefit of being lower in cost. The previous work by Parikh (2002) had reported that the composite containing kenaf fiber showed lower strength and hardness compared to glass fiber reinforced plastic. However, the composite with kenaf reinforcement offers the advantages of being biodegradable and more economical (Parikh 2002).

The main objective of this study is to reduce the existing dependence on synthetic products or energy intensive materials for numerous composite applications. In this study, a sandwich composite base on polyester and kenaf fibers has been designed as an alternative material to replace the conventional plywood sheets in a beam construction system. This research will present the mechanical properties and thermal stability analysis of polyester/kenaf sandwich composites. Tested result parameters including tensile, flexural, and impact strength were compared and recorded based on different fiber orientation. Factors favoring this development include low cost, user-friendliness, availability, and productivity.

EXPERIMENTAL

Materials

Unsaturated polyester resin and methyl ethyl ketone peroxide (MEKP) were supplied from Mostrong Industries Sdn Bhd. Methyl ethyl ketone peroxide was used as a catalyst in this study. The mechanical properties of polyester resin are given in Table 1. A random mat of kenaf fiber with the density of 1.4 g/cm^3 was supplied by a local company named Innovative Pultrusion Sdn Bhd. The Young modulus and tensile strength of unidirectional kenaf fiber is about 2 to 4 GPa and 18 MPa, respectively. The kenaf fiber matt has the size of 500 mm x 2000 mm x 4 mm and was delivered without any surface treatment.

Table 1. Mechanical Properties of Polyester Resin

Properties	Value
Density (g/cm^3)	1.2 to 1.5
Young modulus (GPa)	1.5 to 3.5
Tensile strength (MPa)	5 to 12

Preparation of Polyester/ Kenaf Sandwich Composite

First, a surface treatment process known as mercerization was employed on kenaf fiber in order to enhance the interfacial adhesion of fiber-matrix. During the mercerization process, kenaf fiber was soaked in NaOH solution (6 wt %) for 12 h and subsequently washed with distilled water and dried at room temperature for 24 h. The mercerized kenaf fiber was further dried in the oven at 95 ºC for 4 h to remove the excess moisture, which had been in equilibrium with the air humidity. The treated kenaf fiber was then kept in a plastic bag to prevent moisture exposure. Polyester was blended with 1.0 wt% of methyl ethyl ketone peroxide catalyst. The polyester solution was cast onto the polytetrafluoroetheylene (PTFE) coated pan. The polyester solution was left to cure under room temperature conditions into a sheet film. Lastly, the polyester sheets were removed from the molds for the lamination process.

A liberal coating of lay-up laminating resin was evenly brushed over the base polyester sheet and then the treated kenaf fiber was laid on top of it. Subsequently, the second layer of polyester sheet was coated and stacked on top of the kenaf fiber. The same process was repeated until the last layer of polyester sheet was stacked as shown in Fig. 1. The composites were prepared by sandwiching a layer of treated kenaf fiber in between two layers of polyester films. The final sandwich composite was prepared with 5 layers height. The polyester/kenaf sandwich composite contains 3 layer of polyester resins and 2 layers of kenaf fibers. The volume fraction weights of polyester and kenaf fiber layers were controlled to maintain composites with the ratio of 70:30. There were 3 different polyester/kenaf sandwich composite prepared, with the fiber arrangement in perpendicular, anisotropic, and isotropic orientations. Thereafter, a cold compression method (150 N loads) was applied to the polyester/kenaf sandwich composite for 2 h at room temperature. This process is important to release the bubbles between the bonding surfaces and to achieve homogeneity within the sandwich composite. After 2 h of cold compression, the sample was then removed from the mould and dried at 95 ºC for 12 h.

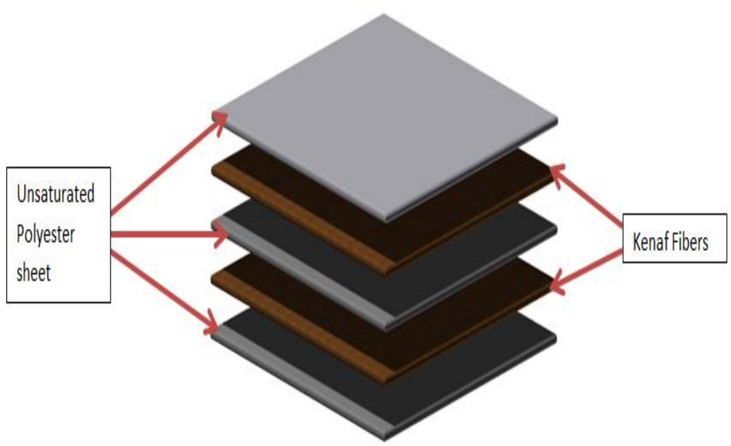

Fig. 1. Stacking sequence of kenaf fibers and polyester matrix

Characterization Study

The tensile, flexural, Izod impact tests of the sandwich composites were carried out according to ASTM D638-03, D790-90, and D256-04, respectively by using a universal tensile tester and an Izod impact tester. The tensile properties such as tensile stress, elongation to breakage, and modulus elasticity were performed by using the Universal tensile tester (Instron 4400). Every specimen was cut into size of 246 mm (L) X 29 mm (W) X 12.7 mm (T) with gauge length of 30 mm and tested according to D638-03 type III specimen. Yield stress, elongation at break, and modulus elasticity were recorded. The data obtained represent an average of 5 specimens. The Izod impact resistance test was conducted in compliance to ASTM D256-04 by using an Izod pendulum type impact machine *(*PST-300-N) with standard pendulum type hammers. The facture energy was calculated by dividing the experimentally determined breaking energy by the thickness of the specimen. The maximum pendulum energy is determined by the weight attached to the pendulum. Every specimen was cut into size of 63.5 mm X 12.7 mm X 12.7 mm. The milled notch of the specimen was done by a milling machine with constant feed and cutter speed throughout the notching operation. The energy loss at no load of the machine is recorded at 1.62698J. Five individual determinations of impact resistance were made on each sample and an average of five samples was taken for the final result. Impact strength of specimen is determined by using the formula,

$$Impact\ strength = \frac{E}{w \times t} \tag{1}$$

where $E = E_r - E_o$, E_r is the energy loss read at the scale, and E_o is the energy loss at no load.

The flexural test was performed by using the Universal testing machine according to the 3-point bending method (ASTM D790-03). The dimensions of the specimens were 127 mm (L) x 12.7 mm (W) x 3.2 mm (T). The distance between the spans was 100 mm, and the strain rate was 5 mm/min. Thermal stabilities of polyester, polyester/kenaf composite, and plywood were carried out by using thermogravimetric analysis (TGA). Thermogravimetric analysis (TGA) was carried out by using Mettler TGA 851. The weight loss and temperature of weight change of the specimens were identified throughout the experiment, and descending TGA thermal curves were plotted.

RESULTS AND DISCUSSION

Tensile Properties

A typical stress-strain plot for the different fiber orientations of polyester/kenaf sandwich composite and pure polyester resin is shown in Fig. 2. The curve shows linear deformation behaviour with the stress rising to a maximum value before fracture occurred. The stress strain curve was plotted during the test for the determination of the ultimate tensile strength and elastic modulus. The tensile strength and elongation at break for different fiber orientations of polyester/kenaf sandwich composite and pure polyester are plotted in Figs. 3 and 4.

Figure 3 indicates that the incorporation of kenaf fiber increased the tensile strength of polyester/fiber composites. However, the elongation at break of the polyester was reduced with the introduction of kenaf samples in all the stacking orientations, as shown in Fig. 3. An anisotropic specimen showed the lowest elongation at break, which was recorded at 2.81%, while an isotropic specimen was recorded at 3.32%, and a perpendicular specimen was recorded at 3.71%. This result indicates that the polyester effectively transferred the tensile force to the kenaf fiber. The reinforcement of kenaf fiber eventually absorbed the tensile force.

The tensile strength of composite with fibers in anisotropic arrangement achieved the highest tensile strength. It was 55% higher than the composite sample with fiber arrangement in perpendicular directions. On the other hand, the composite with kenaf fiber in isotropic arrangement gave a tensile strength 49% lower than fiber in an anisotropic arrangement.

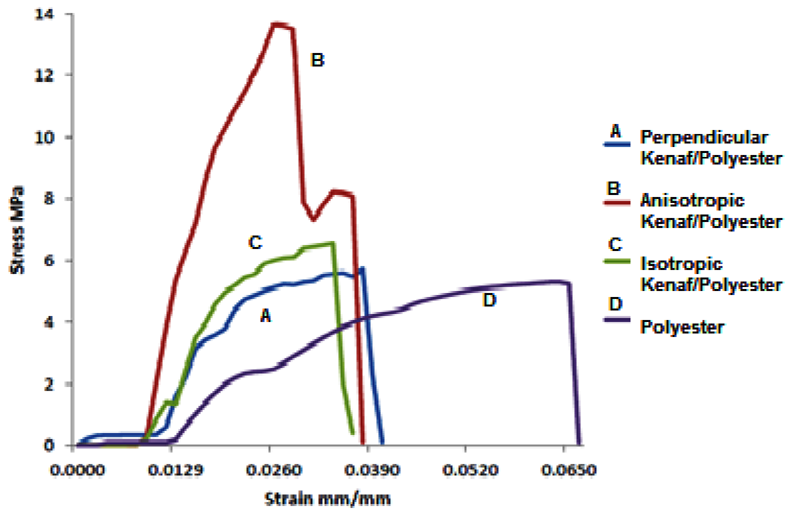

Fig. 2. Stress strain curve of different fiber orientation of Kenaf/polyester sandwich composite

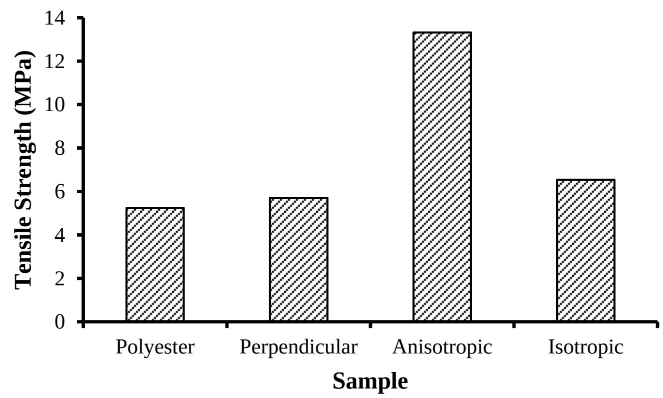

Fig. 3. Tensile strength of polyester and polyester/kenaf sandwich composite

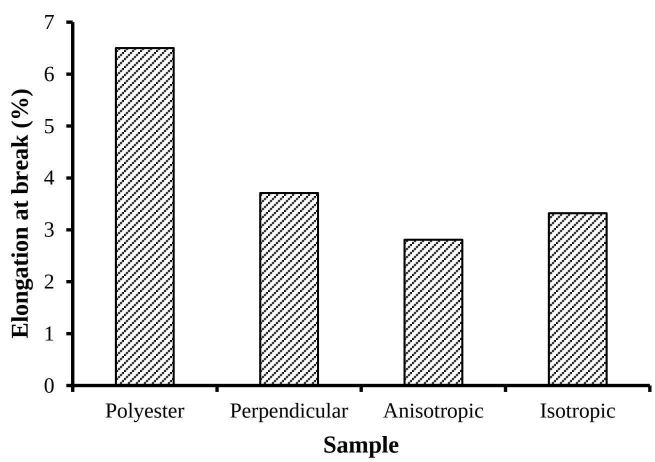

Fig. 4. Elongation at break of polyester and polyester/kenaf sandwich composite

This result indicates that the tensile strength was reduced with the increase of fiber orientation angle. The increase of fiber contents in loaded direction would increase the strength efficiency. However, the strength efficiency was decreased when the loaded fiber was in perpendicular direction. A similar observation has been reported by Nishino and co-workers (2003), who indicated that a large mechanical anisotropy will result in high mechanical performance.

Young's Modulus

The Young's modulus, *E*, of the polyester/kenaf sandwich composite and neat polyester was calculated from the slope of the stress-strain curve as shown in Fig. 2. Figure 5 shows results indicating that the arrangement of anisotropic fiber in a polyester/kenaf sandwich composite successfully improved the Young's modulus of polyester from 314 MPa to 650 MPa. The figure also illustrates that the fiber stacked in anisotropic arrangement was stiffer than other fiber orientations. Work by Campbell (2010) also reported that the materials will become stiffer when the fiber is aligned parallel to the direction of applied load. On the other hand, Bernasconi *et al.* (2007) reported that the Young modulus would decrease as the fiber orientation angle increases with a maximum at 0 degrees and minimum at 90 degrees.

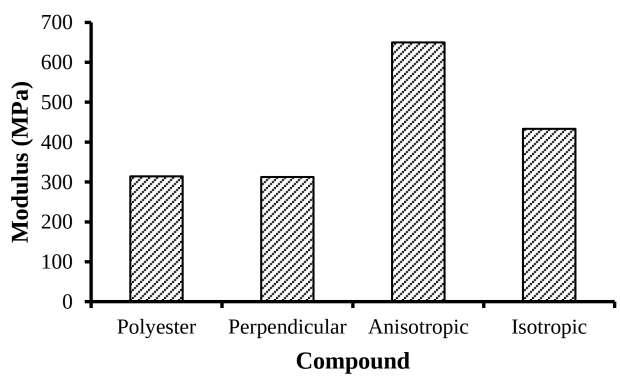

Fig. 5. Young modulus of polyester and polyester/kenaf sandwich composite

Impact Strength

The Izod impact test was used in this study to measure the impact strength of the resulting composite materials. The notch impact strength generally reflects the energy required to propagate an existing notch in the specimen. The fibers play an important role for the propagation of a crack through a matrix by increasing the volume which can allow the energy dissipation to take place (Amal 2012). The presence of fibers also led to the improvement in the number of potential energy absorbing mechanisms in the system (Sanadi *et al*. 1995). Figure 6 shows the impact strength of polyester and polyester/kenaf sandwich composites. Pure polyester exhibited the lowest value of impact strength, which was 1.42 kJ/m^2. The composite with an anisotropically oriented fiber arrangement achieved the highest Izod impact strength of 6.68 kJ/m^2. The impact strength of polyester/kenaf composite with anisotropic orientation was at least >50% higher than those composites with kenaf reinforcement stacked in perpendicular and isotropic orientation. It can be concluded that the fabrication of polyester/anisotropic kenaf sandwich composite could effectively transfer the stress from polyester matrix to kenaf fiber.

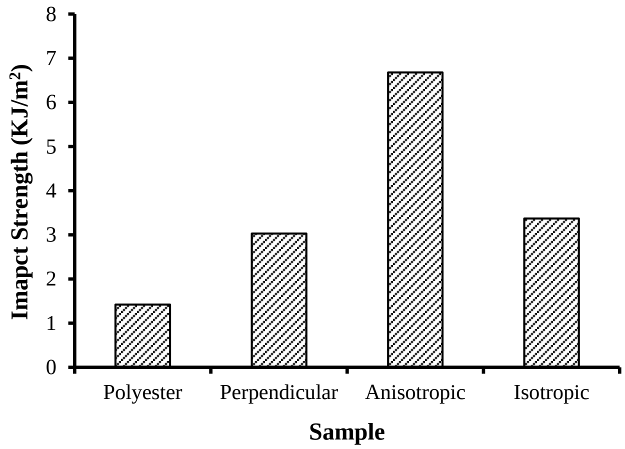

Fig. 6. Izod impact strength of polyester and polyester/kenaf sandwich composite

The interfacial bond strength between the polymer and fiber has high influence on the impact response of the sandwich composite. Failure mechanisms such as fiber/matrix debonding, fiber and/or matrix fracture, and fiber pull-out are able to account for the dissipation of the impact energy. All of these damage mechanisms were observed in the post-experiment specimens. Figure 7 shows the failure mechanisms of the polyester/kenaf sandwich composite with fiber oriented in a perpendicular direction. When the pendulum strikes on the specimen, the matrix will transfer the force to the fiber. This action has caused the fiber to split or peel along the interface of the polyester/fiber. As a result, the crack propagated easily along the fiber axial direction. The interfacial failure was observed along the fiber axial direction. In this case, the polyester was the main matrix to absorb energy.

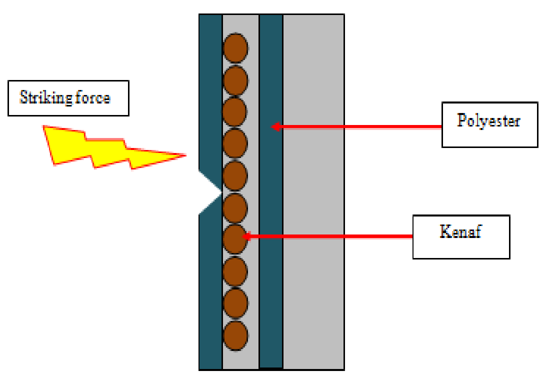

Fig. 7. Schematic diagram of perpendicular polyester/kenaf sandwich composite

Figure 8 shows a schematic diagram of polyester/anisotropy kenaf sandwich composite. When the pendulum strikes the specimen, the pendulum first will contact the fiber and then forces the bundle of fibers in anisotropic orientation to bend. As the fibers bend, subsequently fiber pull-out, fiber matrix debonding, and fiber breakage will be observed (Kim and Sham 2000). For composite with kenaf in anisotropic orientation, the crack tip normally propagate through the polymer matrix until it reaches the next layer of fibers and then is arrested there. When the fibers in the first layer are broken, a high shear stress will develop in the matrix between these two layers (Broutman and Rotem 1972). This shear stress will initiate cracks which could run to both sides parallel to the layers. The impact is continued and when the stress in the second layer is high enough, the fibers will be broken and again a crack will propagate up to the third layer and branch to the side (Broutman and Rotem 1972). Those cracks that run to the sides could delaminate the specimen and absorb the greatest amount of energy during the failure process. In summary, the mechanism for the sandwich composite with kenaf fiber in anisotropic orientation involves the steps such as the following: A strong fiber forms bridges over the cracks before the fiber breakage occurs, and the fiber breakage contributes to the absorbtion of higher energy, resulting in higher toughness (Marcus and Peter 2014). Thus, the fiber in anisotropic orientation helps to improve the toughness and impact resistance of the polyester/kenaf sandwich composite. In other words, the sandwich composite with kenaf fiber in anisotropic orientation can absorb more energy and experience more than one fracture mode before failure.

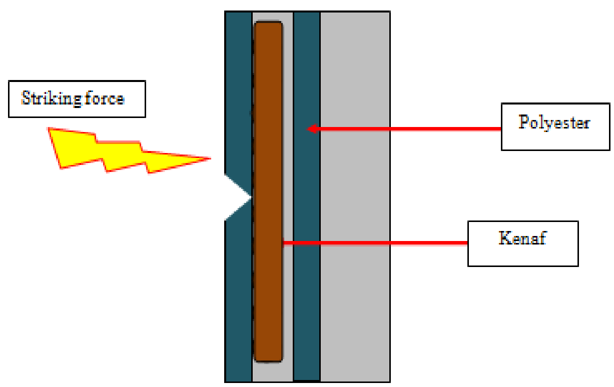

Fig. 8. Schematic diagram of anisotropy polyester/kenaf sandwich composite

A composite with fiber in isotropic orientation showed an intermediate failure mechanism in between composite with fiber in perpendicular and anisotropic orientation. When the pendulum strikes the specimen, less fiber pull out, and breakage were observed as compared to polyester/anisotropy kenaf composite. The presence of fibers arrested the crack propagation in the test specimen. Thus, the final failure was due to delamination between layers in the compression zone. In conclusion, the composite with fiber in isotropic orientation, which experiences more than one fracture mode, will have higher toughness and higher impact resistance than the sandwich composite with fiber in isotropic orientation.

Flexural Modulus

Figure 9 show that the incorporation of kenaf fiber in anisotropic and isotropic arrangements successfully improved the flexural modulus of the neat polyester from 24.6 MPa to 95.9 MPa and 43.8 MPa, respectively. However, the fabrication of a sandwich composite with kenaf fiber in perpendicular orientation reduced the flexural modulus significantly to 10.3 MPa. This result indicates that a crack had propagated easily along the axial direction when the fiber was arranged in perpendicular orientation. The separation between the fiber layer and polyester resulted in a significant drop in the flexural modulus of the polyester/fiber composite with kenaf fiber in a perpendicular orientation.

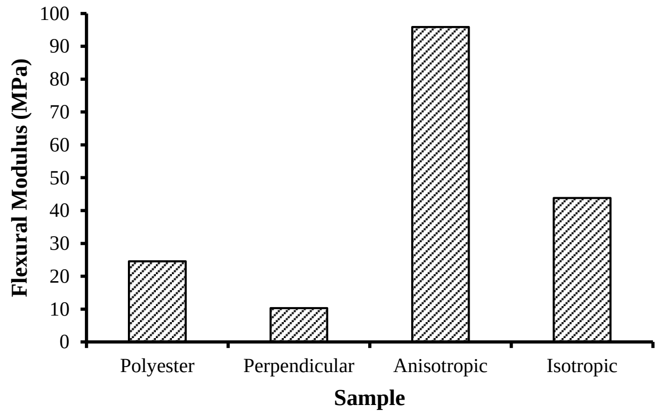

Fig. 9. Flexural modulus of polyester and polyester/kenaf sandwich composite

The polyester/kenaf sandwich composite with kenaf fiber in anisotropic orientation achieved the highest flexural modulus. This is because the flexural modulus decreases with the increasing of orientation angle (Shenoy and Melo 2007). Thus, the kenaf fiber in anisotropic orientation exhibits high bending resistance and manages to carry high tensile and compressive stress. However, kenaf fiber in a perpendicular arrangement does not carry much stresses since the crack can propagate easily along the fiber-matrix bonding, resulting in separation between matrix and fiber.

A similar result has been reported by Bernasconi *et al.* (2007), where the modulus was found to decrease as the fiber orientation angle increased with a maximum at 0 degree and minimum at 90 degree. The work by Manalo *et al.* (2010) also considered the flexural behavior and failure mechanism of the sandwich composite in both flatwise and edgewise directions.

Thermogravimetric Analysis

Thermal stability is important to evaluate the potential use of polyester/kenaf sandwich composite in a structural beam system. The structural beam must always maintain good mechanical properties and high structure rigidity. Thermal and photochemical degradation would jeopardize the mechanical properties of the structural beam (Chee *et al.* 2013). Thus, an intensive study on thermal stability property is important and useful during the designing stage of the composites. The thermogravimetry analysis (TGA) and differential thermogravimetry (DTG) analysis for polyester, polyester/kenaf sandwich composite, and plywood materials are shown in Figs. 10 and 11, respectively. Polyester was shown to possess the highest thermal stability among the materials. The decomposition of polyester occurred in two mass loss steps with the thermal degradation occurring at around 230 °C.

Plywood exhibited the lowest thermal stability, exhibiting thermal degradation at 120 °C. The upper use temperature of the polyester/fiber composite was at around 180 °C. The polyester/kenaf sandwich composite degraded at their intermediate temperature. So the sandwich composite carries the thermal properties of both kenaf fiber and polyester matrix material. The result indicates that the thermal stability of the kenaf-reinforced polyester composite is better than plywood. In other words, the used of polyester/kenaf sandwich composite for a structural system could enhance the thermal resistance and prolong the degradation against thermal and photochemical reaction.

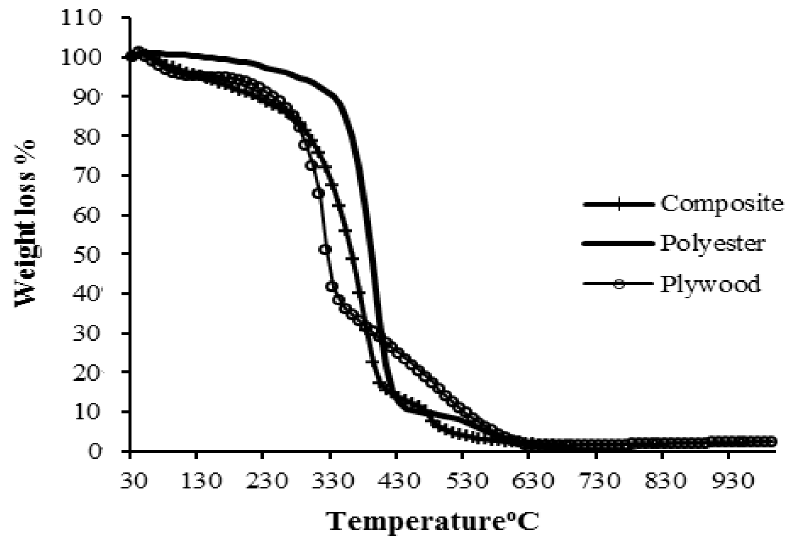

Fig. 10. Comparison TGA result of polyester, plywood, and polyester/kenaf sandwich composite

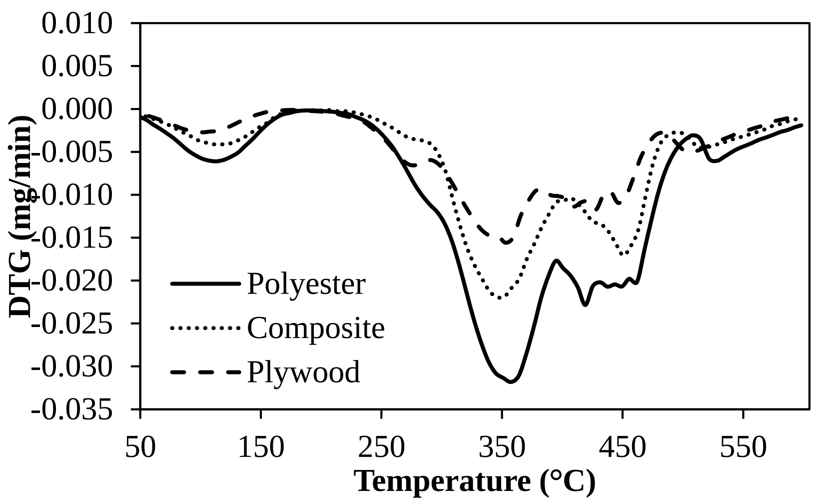

Fig. 11. Comparison DTG result of polyester, plywood, and polyester/kenaf sandwich composite

CONCLUSIONS

1. Fiber orientation plays a significant role to determine the mechanical properties of a sandwich composite for structural application. Polyester/kenaf sandwich composites with various fiber orientations were fabricated successfully by sandwiching a layer of treated kenaf fiber in between two layers of polyester sheets until 5 layers height by using hand lay-up and cold press processes. The volume fraction weights of polyester to kenaf fiber in the composite were controlled at 70:30.

2. The polyester/kenaf sandwich composite with kenaf fiber in anisotropic orientation design will form a strong bridge over the cracks, thus increasing the breakage resistance of the kenaf fiber.
3. Polyester/kenaf composite with kenaf fiber in anisotropic arrangement achieved the highest tensile, flexural, and impact properties. This was followed by a sandwich composite with kenaf fiber in isotropic and perpendicular orientations. It can be concluded that the strength of polyester/kenaf sandwich composite increases with the decreases of fiber orientation.
4. The polyester/kenaf sandwich composite also showed higher thermal stability and thermal resistant than plywood. Thus, the design of polyester/kenaf sandwich composite shows high potential to replace the existing use of plywood in beam construction systems.

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