Unidirectional Kenaf Fiber Reinforced Plastic Composite: Strength and Fracture Toughness

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ABSTRACT

This paper reported the investigation made on the properties of the Kenaf Fiber Reinforced Plastic (KFRP) composites manufactured using two types of resins (epoxy and polyester) namely physical and mechanical properties (tensile strength, flexural strength and fracture toughness). Prior to that, the tensile strength of kenaf bast fiber before and after treated and also the interfacial shear strength of the kenaf fiber bundles to resin interface in a droplet micro-bond test using as received fiber bundles were evaluated. The KFRP composites manufactured using epoxy resin has better performance than KFRP composites manufactured using polyester resin.

Keywords: Kenaf fiber reinforced plastic, Epoxy resin, Polyester resin, Mechanical properties, and Fracture toughness

Introduction

Composites containing unidirectional fibers are amongst the simplest form of composite materials and can have tensile strengths up to 3 GPa [1] along the fiber axis. Fibers that currently dominate the composite material industry are aramid fibers with E=120 GPa, carbon fibers with E=220-700 GPa and glass fibers with E=70-80 GPa [1]. These materials have been widely used in making...
composites used in the aerospace, automotive, leisure, sporting and construction industries. Of these, glass fibers are the most used due to their low cost and good mechanical properties [2]. However these materials are prohibitively expensive in their use for other general purposes and applications. Nowadays natural fibers like cotton, coir, sisal, jute and other natural fibers have attracted the attention of scientists and technologists for applications in packaging, low-cost housing and other structures. It has been found that the natural fiber composites possess required mechanical strength, good thermal and acoustic insulating properties but it varies from one type of natural fibers to another.

The emergence of lignocellulosic fibers as a viable replacement for glass fiber in reinforcing polymeric matrices has attracted the interest of researchers over the past few decades. Studies on natural fiber composites include those on sisal fibre [3,4], hemp [5,6,7], banana [8], pineapple [9], kenaf [6,7,10,11], flax [12], jute [13] and oil palm [14,15]. These fibers are known to deliver similar performance to glass fibers and can be 25-30% stronger than glass fibers for the same weight [16]. The elastic moduli for natural fibers are comparable to those of E-glass, with flax having potentially the highest value compared to the other fibers [16]. Their efforts to introduce the natural fibers composites are because of the following reasons; these fibers, despite their low strength can lead to composites with specific strengths because of their low density, natural fibers are abundantly available renewable resources, dried natural fibers are nontoxic and eco-friendly and biodegradable and are quite cheap and scientific data of the structure and properties of the fibers are readily available.

The choice of fiber for plastics applications depend on the availability of the fiber in the region and also on the ultimate composite properties needed for the specific application. Therefore this study investigated the properties of fiber reinforced plastic (FRP) composite using kenaf fiber. Kenaf is plantation crops grown in Malaysia which has the potential to be used in the manufacturing of fiber reinforced plastic. Kenaf filaments are extracted from bast of the plant *Hisbiscus cannabinus*. These filaments consist of discrete individual fibers, generally which are themselves composites of predominantly cellulose, lignin and hemicelluloses. Filament and individual fiber properties can vary depending on the source, age, separating techniques and history of fibers.

This paper reports the investigation made on the mechanical properties of the fiber reinforced plastic composite using kenaf bast fibers. The limited fracture toughness of natural fiber reinforced plastic composite at high strain rates can preclude their use in some applications. To understand and ultimately improve the fracture performance of these composites, tone must understand the fracture toughness properties of the composite. Therefore this study also investigated the fracture toughness properties of the composite.
Experimental Procedures

Materials
The natural fiber reinforced plastic composites were manufactured using kenaf bast fiber and an epoxy resin system. Kenaf fiber is a natural fiber extracted from *Hibiscus cannabinus* L.) and sourced from MARDI, Serdang Selangor Malaysia. Initially, the kenaf trunks taken from MARDI’s plantation were processed to undergo fiber extraction. The part of kenaf that has been used for fiber extraction is the bast. The kenaf trunks were soaked in water tank for 24 hours for debarking processes. The trunks were removed from the tank and then loosely placed on the canvas for drying. The outer skin will debark by itself and sometimes need to be torn manually from the trunk. The fiber was left to dry for a week and ready to be used.

Polyester resin was prepared by mixing two components, i.e. 100 ml unsaturated polyester resin in monomer and 50 ml catalyst, thoroughly at room temperature and allowing the mixture to stand for about 3 minutes, until the colour changed from pale pink to pale yellow. Epoxy resin was prepared by mixing 100 g of Asasin 8505 resin with 50 g of Asahard 8505 hardener thoroughly at room temperature. The resin was placed in a vacuum oven to remove any bubbles formed during the mixing process.

Physical properties and chemical composition of kenaf fiber
Preliminary measurements such as bulk density of the fibers, diameter, fiber morphology study and chemical analysis of the fibers were studied. Natural fibers come in varying sizes and textures to the extent that it becomes very difficult to determine a proper estimate for their dimensions. Different methods have been used to obtain approximate values for the diameters of such fibers. Eichorn and Young [17] measured the diameter of hemp fibers using a calibrated FEG-SEM at an excitation voltage of 2 keV. An assumption was made by the authors that the fibers had a circular cross section. Devi et al. [18] used a stereo microscope to obtain diameters of pineapple fibers based on a similar assumption of circular cross-section. The authors took six readings along the fiber length and the average was used as the diameter due to the variability of the fiber cross-section. Mwaikambo and Ansell [5] used SEM and image analysis techniques to obtain the diameters of sisal fiber bundles, assuming they had circular cross-sections.

In this work, the diameter of the kenaf fiber was obtained with an optical microscope with a graticule and confirms using scanning electron microscopy (SEM). For the microscopy method, the diameter of the fiber is obtained as an average of three measurements taken along the length of the fiber. Kenaf fiber bundles have variations over their cross sectional area, a characteristic of fibers derived from plant tissue. The average measurement is used as an approximation
for the apparent diameter of the fiber, assuming it is cylindrical, and the cross-sectional area of the fiber. The authors chose this method so that the outcomes of this study can be compared with other studies using the same method even though study conducted by Thomason et al. [19] demonstrated that by using the apparent diameter has led to huge errors for technical fibers.

The apparent bulk density of the as received kenaf fiber bundles was determined using the Archimedes principle.

**Tensile strength of kenaf fiber**

For any structural material the strength must be confirmed in order to satisfy the requirements of application. In nature, most of the natural fibers exhibit better tensile strength than flexural strength. Here, the tensile strength of kenaf fiber was determined and compared with the other well-known natural fibers.

The following section describes the brief procedure for determining the kenaf fiber tensile strength.

The kenaf fiber bundles were cut to lengths of approximately 70 mm weighed and finally mounted on manila-card coupons using epoxy resin as shown in Figure 1.

![Figure 1: Mounting Card of Fiber Test Piece](image)

The tensile test was conducted according to ASTM D885 (1995) using an Instron 1122 with a crosshead speed of 1mm/min. Twenty specimens were used. The ends of the manila-card coupons were gripped by hydraulic clamps to align the fiber with the machine axis. The sides of the hole on the coupon were cut with a pair of scissors to allow load transfer to the fiber during tensile testing. The tensile strength of the kenaf fiber bundle is determined using the cross-sectional area obtained from the apparent diameter of the fiber obtained from optical microscopy as shown in Equation 1.
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\[ \sigma = \frac{4F_{\text{max}}}{\pi d^2} \]  \hspace{1cm} (1)

Where \( d \) is the apparent diameter of the fibre obtained from optical microscopy.

**Interfacial shear strength measured by micro-bond pull-out**

The microbond test is a variation of the pull out test that was pioneered by Miller et al. [20] at the Textile Research Institute and has been used by various researchers [21, 22, 23, 24, 25]. A cured droplet is sheared from a fiber and the stress required to cause debonding at the fiber/matrix interface is measured. This measured stress is then used to interpret the interfacial properties between the fiber and resin matrix.

During the microbond pull-out test, the interfacial bonding between fiber and resin provides the resistance to the pull-out force as shown in the schematic representation of a fiber being pulled out of a resin droplet in Figure 2.

![Figure 2: Resin Droplet on the Fiber](image)

The tensile force required to pull out the fiber is given by \( P \). Given the circumference \( C = 2\pi r \) and area \( A = \pi r^2 \), the surface area of the embedded fiber is given by

\[ S = \pi r = \frac{P}{S} \]  \hspace{1cm} (2)

Where \( l_e \) is the embedded length of the droplet. The shear stress is given by:

\[ \tau = \frac{P}{S} \]  \hspace{1cm} (3)
Thus,

\[ \tau = \frac{P}{\ell_p \sqrt{4 \pi A}} \]  

In the test set-up, a droplet of polyester and epoxy resin was placed on the fiber mounted on a test coupon using an oiler (normally used for delivering precise amounts of oil drops). Surface tension allowed the droplet to wet the fiber bundle such that it surrounded the fiber bundle. The maximum dimension of the drops and embedded length of the fiber, \( \ell_p \), were measured using an optical microscope with a graticule. In addition, the apparent diameter of the fiber was measured at regions close to the drop and this measurement taken as an approximation of the fiber diameter. The droplet was left in the conditioning chamber for 48 hours before testing. Droplets were de-bonded with an Instron 1122 test machine at a crosshead displacement of 1 mm/min.

Specimen Preparation and Test Methods

KFRP composite manufacture

The composites were manufactured using unidirectional kenaf fiber bundles with polyester and epoxy resins as the matrix materials. Fibers were laid up in a lossy mould that allowed excess resin to flow out when pressure was applied in a heated press. This method is very common in the production of composites using thermosetting resins. The kenaf fiber composites were manufactured using a single compartment lossy stainless steel mould allowing discrete specimens to be produced with dimensions of 250 mm long by 20 mm wide by approximately 3 mm thick. The mould was cleaned using a soft scraper prior to use to clean off any residue left on the mould surface. A release agent, Frekote 700-NC was applied to all surfaces exposed to the resin to make the process of releasing the composites easier, and prevent damage to the mould. The kenaf fiber bundles were cut to a length slightly shorter than the length of the mould so that they did not bend when introduced into the mould. To enable good penetration of resin, the fibers were divided into several bundles approximately equal weight (Figure 3a) for each sample.

The fibers were introduced one at a time into the mould with a layer of resin being applied in between layers of fiber bundles (Figure 3b). No resin was introduced at the bottom of the first fiber bundle and the top of the last fiber bundle. The top section of the mould was inserted into the slots containing the fibers and resin and the mould was placed between the preheated platens on the press machine. To allow wetting of the fibers without substantial loss of resin the mould was allowed to rest between the platens for about 5 minutes before applying any pressure. When the resin began to feel tacky, the full pressure of 60 bars was applied for the required time depending on resin used. The curing regime for each resin was followed to produce the final test specimens.
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Tensile test
The tensile test is conducted to determine the tensile strength and tensile modulus of materials. The static tensile strengths of the different composites were measured using BS EN ISO 527-5 (1997) using straight edge specimens. The composites were fitted with 1.6 mm thick aluminium end tabs to minimize damage to the outer fibers and matrix as mentioned earlier. Good bonding surfaces were created by sanding the composite surface and shot blasting the aluminium end tabs. A high shear strength epoxy-based resin was used to prevent failure between the end taps and the composites during loading.

Flexural test
Flexural strength was determined using a three-point bend test, carried out accordance to ASTM D 790 (1996) on a test machine at a crosshead speed of 1mm/min. Specimens with a span to depth ratio of 16:1 were used. A total of ten specimens were used in determining the flexural properties of the kenaf fiber composites.

Fracture toughness test
Fracture toughness is an indication of the amount of stress required to propagate a pre-existing flaw. If a material has a large value of fracture toughness it will probably undergo ductile fracture. Brittle fracture is the characteristic of materials with a low fracture toughness value. In this study, the fracture toughness test was conducted accordance to ASTM D 5045 standard using single edge notched bend test (SENB). The SENB specimens were machined from the composite sheet with the fibers parallel to the beam axis and their configuration is shown in Figure 4.
First a notch of depth 4 mm that is equivalent to the thickness of the sheet was made using milling machine, a sharp initial crack tip was produced by tapping/sliding a fresh razor blade at the centre of the tip of the notch. The initial crack length was prepared between 0.45 and 0.55 mm. These variations in initial crack length are to see the effect of different pre-crack length on the fracture toughness. The pre-crack length \( a \), was measured using an optical microscope with a 4x objective lens. 5 specimens for each pre-crack length were prepared.

![Figure 4: Schematic Diagram of SENB Specimen](image)

Where: \( a \) is the pre crack length, \( x \) is the initial crack, \( B \) is the specimen thickness and \( W \) is the specimen width.

A three-point load bending test method was applied to all test specimens using an Instron 1122 Universal Testing Instrument equipped with a 500 kgf load cell. The load was applied with a crosshead speed of 10mm/min.

The fracture toughness properties are calculated as follows;

The critical stress intensity factor,

\[
K_{ic} = \frac{6YP}{BW^{1/2}}
\]  \hspace{2cm} (5)

Where,

\[
y = 1.93 \left( \frac{a}{W} \right)^{3/2} - 3.07 \left( \frac{a}{W} \right)^{5/2} + 14.53 \left( \frac{a}{W} \right)^{7/2} - 25.11 \left( \frac{a}{W} \right)^{9/2} + 25.80 \left( \frac{a}{W} \right)^{11/2}
\]

\( a \) is the pre crack length, \( P \) is the maximum load, \( B \) is the specimen thickness and \( W \) is the specimen width.
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The critical strain energy release rate, \( G_{IC} \), was calculated using the following formula:

\[
G_{IC} = \frac{K_{Ic}^2}{E}
\]  

(6)

Where \( E \) is the Young’s modulus.

Results and Discussion

Physical and mechanical properties of kenaf bast fiber

The physical and mechanical properties and chemical composition of kenaf bast fiber are shown in Table 1.

Table 1: Properties of Kenaf Fiber

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.75 g/cm³</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>400 – 550 MPa</td>
</tr>
<tr>
<td>Hollocellulose</td>
<td>80.94</td>
</tr>
<tr>
<td>Lignin</td>
<td>15.13</td>
</tr>
<tr>
<td>Alpha-cellulose</td>
<td>72.68</td>
</tr>
</tbody>
</table>

In this study the density and tensile strength of kenaf bast fiber was found to be 0.75 g/cm³ and 400-550 MPa respectively which is considered high when compared with other natural fiber such as sisal (1.33 g/cm³, 280-568 MPa) and jute (1.46g/cm³, 250-350 MPa) [26]. Fibers that currently dominate the composite material industry are aramid fibers with tensile strength of 3600 MPa, carbon fibers 3000 MPa and glass fibers 2000-4750 MPa [1]. Of these, glass fibers are the most widely used due to their low cost and good mechanical properties [2].

The diameter of the fiber was found to be in the range of 4.5 μm to 12 μm (see Figure 5).

A composite such as E-glass fiber reinforced plastic has fibers of approximately 15 μm in diameter [27]. In contrast, a sisal fiber bundle composite has fiber bundles with diameters ranging from 100-200 μm.

Interfacial shear strength

Twenty samples were used to determine the interfacial shear strength between kenaf bast fiber and polyester resin as well as between kenaf bast fiber and epoxy resin. Some of the fibers failed in tension, which could be a result of either weak...
parts on the fiber surface or a large contact area between drop and fiber. These values were not included in the computation of the interfacial shear strength. The values of the inter-facial shear stress (IFSS) were computed using Equation 4 is presented in Table 2.

Table 2: Interfacial Shear Strengths for Polyester and Epoxy Resin Droplets on Kenaf Fiber Bundles

<table>
<thead>
<tr>
<th>Type of resin</th>
<th>Mean IFSS (MPa)</th>
<th>Maximum Value (MPa)</th>
<th>Minimum Value (MPa)</th>
<th>Median (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>7.2±2.78</td>
<td>12.6</td>
<td>5.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Epoxy</td>
<td>15.3±5.18</td>
<td>25.0</td>
<td>11.7</td>
<td>18.5</td>
</tr>
</tbody>
</table>

The interfacial shear stress at fiber fracture for the epoxy resin droplets are about two times greater than those for polyester resin droplets. This reinforces the fact that epoxy resins bond strongly to natural fibers such as kenaf. Observations of the epoxy and polyester resin droplets under the SEM were made on untested droplets on fibers are shown in Figure 6.

The high IFSS value for epoxy resin droplets is confirmed by the appearance of the droplet as shown in Figure 6(a) where the contact angle is low. The droplet of the polyester resin on the fiber, Figure 6(b), has higher contact angle compared to epoxy resin droplet. It can also be observed that there is less spreading of resin along the fiber, beyond the meniscus on the droplet, for the polyester droplet as compared to the epoxy one.
Mechanical properties of KFRP composites

The KFRP composites prepared using epoxy and polyester resins were tested in tensile and bending. Ten samples of each composite were tested and the results are presented in Table 3.

Table 3: Tensile and Bending Strength of KFRP Composites

<table>
<thead>
<tr>
<th>Resin type</th>
<th>Tensile</th>
<th>Flexural</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean strength (MPa)</td>
<td>Young’s modulus (GPa)</td>
</tr>
<tr>
<td>Polyester</td>
<td>125.4±1.56</td>
<td>12.0</td>
</tr>
<tr>
<td>Epoxy</td>
<td>154.1±3.25</td>
<td>13.6</td>
</tr>
</tbody>
</table>

From Table 3, it can be seen that the tensile and flexural strength of epoxy KFRP composite is 22.9% and 28.6% higher than polyester KFRP composites respectively due to the good bonding between the kenaf fiber and epoxy resin.

Figure 7(a) shows the failed bending specimens from epoxy KFRP composite. Failure of the fibers in bending mode causes tensile and compressive stresses across the fibers due to in-phase buckling as shown in Figure 7(b).

It can be seen that the epoxy KFRP composites suffered extensive fiber buckling leading to formation of an un-fractured single kink zone as seen in Figure 7(b). A similar type of failure has been seen in carbon fiber composites [28]. The frictional force resulting from the movement of fibers within the composite makes it behave like a ductile material, hence the higher flexural
As seen in Table 4, it can be seen that epoxy KFRP composite has higher $K_{IC}$ and $G_{IC}$ (1.8 MPam$^{1/2}$ and 0.53 kJm$^{-2}$) than polyester KFRP composite (1.6 MPam$^{1/2}$ and 0.47 kJm$^{-2}$). Therefore epoxy KFRP requires higher energy strength. A similar observation was made by Pisanova et al. [21] on sisal-polyester composites.

**Fracture toughness properties of KFRP composites**

The fracture behavior of a unidirectional fiber-reinforced composite beam in the presence of a notch perpendicular to the fibers were conducted as described in Section 2.2.4 in order to measure the work of fracture and the results are presented in Table 4 which includes the critical strain energy release rate ($G_{IC}$) and critical-stress-intensity factor ($K_{IC}$).

The strain energy release rate ($G_{IC}$) provides a measure of the critical energy required to extend a mode I crack over a unit area. The critical local concentration of stresses at the crack tip in relation to the applied stress is measured by the critical-stress-intensity factor ($K_{IC}$). The work of Griffith [29] and Irwin [30], states that fracture occurs when there is sufficient energy for crack propagation.

**Table 4: SENB Fracture Toughness Properties of the KFRP Composites with Different Pre-Crack Length**

<table>
<thead>
<tr>
<th>KFRP composites</th>
<th>Maximum Load, $P_{max}$ (N)</th>
<th>$K_{IC}$ (MPam$^{1/2}$)</th>
<th>$G_{IC}$ (kJm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>157.40</td>
<td>1.8</td>
<td>0.53</td>
</tr>
<tr>
<td>Polyester</td>
<td>133.00</td>
<td>1.6</td>
<td>0.47</td>
</tr>
</tbody>
</table>

As seen in Table 4, it can be seen that epoxy KFRP composite has higher $K_{IC}$ and $G_{IC}$ (1.8 MPam$^{1/2}$ and 0.53 kJm$^{-2}$) than polyester KFRP composite (1.6 MPam$^{1/2}$ and 0.47 kJm$^{-2}$). Therefore epoxy KFRP requires higher energy...
to extend the crack due to better bonding between the epoxy and the fiber as mentioned earlier.

The fracture modes of the specimens that have failed are shown in Figure 9. According to the theory of fracture, when a force is applied to enable a crack to propagate the failure modes are categorized into three modes namely Mode I, Mode II and Mode III. In this study, the crack was initiated in Mode I (Figure 8) that is an opening mode which a tensile normal to the plane of the crack and the opening mode is perpendicular to the fibers (also see Figure 9a).

![Figure 8: Schematic Diagram of the Microstructure in the Central Region of the Notched Beam](image)

![Figure 9: Failed SENB Specimens for Epoxy KFRP Composites; (a) Crack Propagates in Zigzag Pattern and (b) Failure in the Fiber Bundle](image)
Figure 9(b) shows the cracks after the pre-crack length are in the zig-zag mode showing that the fibers tend to retard the cracks propagation and the area where there is more fibers concentration, the path of cracks propagation is very crude.

The fracture of highly stressed fibers ahead of the notch tip was followed by the fiber pull out and delamination (Figure 9c) which led to the relative matrix/fiber frictional sliding. This has led to an extremely non-linear problem in which marked snap-backs (e.g. the simultaneous reduction of the load) appear every time fibers break. Final fracture occurred by the propagation of a single crack perpendicular to the fibers, which began to grow through the matrix after the maximum load was attained in the test. The fracture surfaces provided evidence of fiber bridging and pullout in the crack wake (Figure 9 b and c). The debonding and pull-out of fibers causes them to rupture, revealing ultimate fibers as seen in Figure 9(c).

The energy absorption by the composites resulted from fiber breaking and pull-out from the matrix. The sharp crack and large defects make lower fracture strength of the specimen. One of the factors that cause high fracture strength is the good and strong bonding within kenaf fiber and adhesive as well as strong fiber and ductile adhesive. The fracture toughness of KFRC using epoxy resin is higher than KFRC using polyester can also due to good bond strength between kenaf fibre bundle and epoxy resin. The increased bond strength is evident from the extent of damage observed on the fibre surfaces of the composites (Figure 10a and b). Epoxy resin forms strong bonds with lignocellulosic fibres due to the formation of hydrogen bonds with hydroxyl groups on the fibre surface. A good manufacturing of the specimen also affects the result.

Figure 10: Surfaces Showing; (a) Pull-Out of Ultimate Fibres Coupled with Tearing of Fibre Cell Walls, and (b) Retention Resin at Failure Surfaces
Conclusions

The following conclusions can be drawn from this study.

1. The tensile strength of kenaf bast fiber is between 400-550 MPa which is higher than some natural fiber namely sisal and jute. Therefore kenaf fiber has the potential to be used as reinforcement in the polymer composite.

2. The interfacial shear stress at fiber fracture for the epoxy resin droplets are about two times greater than those for polyester resin droplets. This reinforces the fact that epoxy resins bond strongly to natural fibers such as kenaf.

3. The contact angle of droplet of epoxy resin on the kenaf fiber is low compared to polyester resin which enhances the good bonding between epoxy resin and kenaf fiber compared to polyester resin.

4. The tensile and flexural strength of epoxy KFRP composite is 22.9% and 28.6% higher than polyester KFRP composites respectively.

5. The epoxy KFRP composite has higher $K_{IC}$ and $G_{IC}$ (1.8 MPam$^{1/2}$ and 0.53 kJm$^{-2}$) than polyester KFRP composite (1.6 MPam$^{1/2}$ and 0.47 kJm$^{-2}$).

Acknowledgment

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