The effects of natural weathering exposure on the properties of pultruded natural fibre reinforced unsaturated polyester composites

M. H. Affzam, H. M. Akil, Z. A. Mohd Ishak & A. Abu Bakar
Universiti Sains Malaysia, Malaysia

Abstract

Due to the demand for green technology, the extensive use of fibre reinforced composites has built-up an interest in finding out new and reliable composites. The natural fibre reinforced composites produced by the pultrusion technique may eventually replace the conventional fibre composite production technique used today. Considering outdoor applications, experiments were performed to study the effects of weathering exposure on pultruded natural fibre reinforced composites. Kenaf fibre reinforced composites were produced using the pultrusion technique at 70% fibre loading. The composites were then subjected to natural aging, which involved exposing specimens to an outdoor natural environment for a period of time. After a few weeks, the specimen showed some degradation and discolouring. Subsequently, compression and flexural tests were performed with the aim of determining the mechanical properties after exposure. The decrease in the value of these properties was verified and discussed. The repeated process of sun-heating and the invasion of moisture from natural atmosphere such as rain and dew everyday had led to debonding and weakening over the fibre-matrix interfaces of the composite.

Keywords: fibres, polymer-matrix composites, weathering exposure, pultrusion.

1 Introduction

Historically, natural fibres were used as reinforcement in composites long ago by the ancient Egyptians. The first composite materials known were made with clay and natural bamboo straw to build walls in Egypt 3,000 years ago. However, starting in the 20th century, modern composites such as glass fibre reinforced
composites, simply called fibreglass, were used to make boats and aircrafts in the 1930s [1].

Since the 1970s, the development of new fibres such as boron, aramid and carbon has made the application of composites products widely spread. These high-tech synthetic fibres entered and dominated the composites market due to their superior mechanical and thermal properties [2]. Recently however, environmental legislation as well as consumer awareness of recyclability have opened a huge opportunity for natural fibres once again to appear as ideal reinforcement and thus as a replacement to those synthetic fibres. The emerging demand of green economy or technology over the last few years has shown how important it is to produce a new material with approximately the same properties as the materials commonly used today.

Currently, many types of natural fibres are available and are continuously being studied to be used as reinforcement in polymer composites; such fibre types include kenaf, jute, rice husk, ramie, sisal, coir, hemp, pineapple leaf fibre and many more. Compared to traditional glass fibre, a natural fibre has a lot of welcome advantages such as abundant availability of raw materials from renewable resources [3], low density, good specific strength and modulus, economical viability, reduced tool wear, enhanced energy recovery, reduced dermal and respiratory irritation and good biodegradability [4]. However, natural fibre reinforced composites exhibit some disadvantages including incompatibility between the hydrophilic natural fibres and hydrophobic thermoplastic and thermoset matrices requiring appropriate use of physical and chemical treatments to enhance the adhesion between fibre and the matrix [5].

Kenaf (Hibiscus cannabinus L.) has been used as a cordage crop to produce twine, rope and sackcloth [6], but recently, the development of this fibre as a reinforcement in polymer composite materials is attracting attention among researchers. Various techniques and treatments have been used to improve the mechanical and physical properties of these natural fibres. This lignocellulosic natural fibre can be produced in direct roving forms, which make it easier for the fibre to be used as raw material in the pultrusion technique. The latter principally produces a fibre-reinforced polymer composite with constant and continuous cross-section shapes [7].

The main concern of this study is to observe the effects of absorption of moisture to the pultruded kenaf fibre reinforced composites (KFRC) when exposed to natural weathering and, in particular, these effects on their mechanical and physical properties. Basically, all polymer composites tend to absorb moisture in humid atmosphere; this may lead to degradation of the fibre-matrix interface region creating poor stress transfer efficiencies and resulting in a reduction of mechanical and dimensional properties [8]. Moisture diffusion in polymeric composites is known to be governed by three different mechanisms. The first involves diffusion of water molecules inside the micro gaps between polymer chains. The second involves capillary transport into the gaps and flaws at the interfaces between fibre and the matrix. The third involves transport of micro cracks in the matrix arising from the swelling of fibres (particularly in the case of natural fibre composites) [9].
This paper focuses on the development and evaluation of a pultruded KFRC. Standard half an inch diameter rod samples of KFRC produced by the pultrusion technique have been used in this study. The samples were left exposed to natural weather over a certain period of time and, subsequently, tests were conducted to evaluate their mechanical and physical properties.

2 Experimental work

2.1 Materials

The kenaf fibre was in direct roving form and supplied by JUTEKO Bangladesh Pvt. Ltd, while the unsaturated polyester resin (Crystic P9901) for pultrusion grade was purchased from Rivertex Company, Malaysia. The applied unit for yarn count varies between the fibre types, but the standard unit is “tex” which is defined as mass per unit length (g/1000 m) of roving, tow, yarn or strand (ASTM D2260). Tex also specifies roving linear density [10]).

2.2 Preparation of pultruded composites

KFRC was prepared using the pultrusion technique. Unidirectional kenaf fibre strands were placed on a creel of bookcase-type shelves, which were equipped with roving guider to lead the strands to the resin bath. A roving guider was used to ensure the strands did not scrape across one another as this would generate considerable static and caused “fuzz-balls” to build up in the resin bath, raising its viscosity [11]. The continuous natural fibres were first impregnated with pultrusion grade unsaturated polyester (USP) resin in the resin impregnation tank. The pulling device worked as a pulling mechanism to pull the impregnated natural fibre through the heated steel die. The pulling device drew the stock through the die and determined the production speed [12]. The curing process was carried out in a heated die, which was precisely machined to impart the final shape. Finally, a cut-off mechanism was carried out to cut the continuous pultruded composites into the desired length. The average diameter of all composites rod was 12.7 mm and the fibre content used for all the samples in this study was 70% by weight. The processing parameters are given in table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pulling speed (mm/min)</th>
<th>Curing temperature range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KFRC</td>
<td>195–210</td>
<td>90–110</td>
</tr>
</tbody>
</table>
2.3 Material characterization

2.3.1 Water absorption investigation
Specimens produced by the pultrusion technique were cut into specific lengths and dried in an oven at 100°C for 24 hours to remove any moisture trapped inside. After measuring the dry weight of the specimens using an electronic balance accurate to $10^{-4}$ g, the specimens were left out to natural weathering exposure to study the behaviour of the composites towards moisture uptake. The weight change was monitored as a function of time until 4800 h (200 days). The moisture content, $M(t)$ absorbed by each specimen was calculated according to Tsai et al. [13]:

$$M(t) = 100 \left( \frac{w_t - w_0}{w_0} \right)$$

(1)

where $w_0$ is the dry weight and $w_t$ is the weight after being exposed to natural environment for several times.

The diffusion coefficient, $D$ is evaluated from the first term of eqn 5.25 found in the book *The Mathematics of Diffusion* [14], which is:

$$D = \pi a^2 \left( \frac{2}{M_{\infty}} \right)^2 \left( \frac{M_t}{\sqrt{t}} \right)^2$$

(2)

where $a$ is the radius of the specimen and $M_{\infty}$ is the saturation level of water absorption which is assumed as the maximum moisture content ($M_{mm}$) absorbed by the specimen. The $D$ value is calculated using the moisture content, $M_t$, within a certain time range, $t$, which is applied only at the initial stages of diffusion. The time was chosen at a very early stage of the moisture process, so that the weight change can still be measured to vary linearly with the square root of time.

2.3.2 Flexural testing
Flexural tests were carried out using Instron 8802 according to the standard ASTM D4476-03. Specimens were cut into two parts so that the cross section of each part was smaller than a half-round section. The specimen length was 16 to 24 times its thickness or depth, with at least 20% of the support span to allow a minimum of 10% overhang at the supports. The crosshead speed for flexural testing was set at 5 mm/min. Three specimens for each condition were used to obtain a satisfactory result.

2.3.3 Compression testing
Compression tests were carried out using Instron 8802 in accordance to the standard ASTM D 695-02a. The diameter and length of the specimen were 12.7 mm and 25.4 mm, respectively. The crosshead speed for flexural testing was set at 1.5 mm/min. Three specimens for each condition were used to obtain a satisfactory result.
3 Results and discussion

3.1 Water absorption investigation

Moisture uptakes or water absorption behaviour is the main concern regarding structural composites in various outdoor applications. Every composite system has a unique behaviour with respect to moisture uptake characteristics which depends on several factors such as fibre content, fibre orientation, environmental temperature, exposed surface area, permeability of the fibre, void content and hydrophilicity of each individual component [15]. Fig. 1 shows the percentage of moisture content absorbed by three different tex of KFRC specimens within a 200 days exposure to natural weathering. The moisture content, $M$ (%) absorbed by each specimen was calculated using eqn (1).

![Figure 1: Moisture content absorbed after natural weathering exposure of KFRC.](image)

Fig. 1 shows the inconsistency of moisture content absorbed by KFRC from each day of data collection. The highest moisture content was taken on the 75\textsuperscript{th} day of exposure while the lowest was on day 150. This inconsistency occurred due to the changes of weather with different amount of UV from the sun and moisture from the atmosphere every day.

However, this inconsistency shows the trend between the three tex of KFRC. For every data taken, KFRC 1400 tex has the lowest moisture content followed by KFRC 2200 tex and the highest was KFRC 3300 tex. After 200 days, the data can be simplified (as shown in fig. 2).
Figure 2: Summary of moisture content absorbed during natural weathering exposure of KFRC.

From fig. 2, the minimum, maximum and average percentage of moisture content within 200 days of exposure can clearly be seen. The minimum and maximum moisture content uptakes were 1–4% and 14–17% of each tex, respectively. The average moisture content uptake for 200 days of exposure ranged between 6 and 9%.

The inconsistent results also came from the moisture diffusivity of KFRC for each tex. The diffusion coefficient \(D\) and maximum moisture content \(M_m\) for all tex of KFRC specimens was calculated using eqn (2) above and are summarized in table 2.

Table 2: Maximum moisture content and diffusivity of KFRC for different tex.

<table>
<thead>
<tr>
<th></th>
<th>1400 tex</th>
<th>2200 tex</th>
<th>3300 tex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum moisture content, (M_m) (%)</td>
<td>14.6143</td>
<td>16.0630</td>
<td>16.6576</td>
</tr>
<tr>
<td>Diffusion coefficient, (D) ((m^2/s))</td>
<td>(2.7535 \times 10^{-13})</td>
<td>(3.2820 \times 10^{-13})</td>
<td>(4.0865 \times 10^{-13})</td>
</tr>
</tbody>
</table>

From the summarized values of \(D\) and \(M_m\) as shown in table 2, it is clear that KFRC with 3300 tex has greater maximum moisture content and diffusion coefficient compared to 1400 and 2200 tex. This difference can be attributed to the exposed area of the fibre itself to the surroundings, which can make contact to the water molecules. The greater amount of fibre area exposed to the surrounding, the higher the tendency of absorbing water. However, the molecular and microstructure aspects such as polarity, the extent of crystallinity of polymers and the presence of residual hardeners or other water attracting species may also effect the moisture diffusion [16].
3.2 Flexural testing

The variation of flexural strength and flexural modulus of KFRC after being exposed for 200 days to natural weathering are summarized in figs. 3 and 4, respectively. Each value represents average data from three different tex of specimens and the flexural strength for polyester resin alone is 48 MPa [17].

![Figure 3: Flexural strength of KFRC after natural weathering exposure.](image)

From figs. 3 and 4, the flexural strength and flexural modulus for all tex of KFRC was decreased with increasing time of exposure to natural weathering. But still, the KFRC with 3300 tex has the highest value among all for each day of data taken. It is assumed that the stress transfer between fibre and matrix interface is less effective due to the presence of moisture. Besides, moisture also causes the formation of hydrogen bonding between the cellulose fibre and water molecules [16].

![Figure 4: Flexural modulus of KFRC after natural weathering exposure.](image)
3.3 Compression testing

Figs. 5 and 6 represent, respectively, the compressive strength and compressive modulus of KFRC after exposure for 200 days to natural weathering. Each value represents average data from three different tex of specimens.

Figure 5: Compression strength of KFRC after natural weathering exposure.

Figure 6: Compression modulus of KFRC after natural weathering exposure.

As shown in fig. 5, the compression strength was decreased with increasing exposure time. This result was similar to that for the flexural properties as discussed earlier. The compression strength for 3300 tex of KFRC showed reduction from 63 MPa to 31 MPa after 200 days of exposure. After 200 days of exposure, the compression strength for all different tex of KFRC seems to have
almost the same value range from 29 to 31 MPa. However, in fig. 6, inconsistent data was collected on the compression modulus in different tex of KFRC. The compressive modulus increased at the middle stage and finally drops at the end of exposure.

Both observations on flexural and compressive strength indicated that the moisture content can attack the fibre-matrix interface and significantly reduce the strength of the composites. Aside from the effect from moisture, micro cracks are also sources of failure with respect to strength properties. Rapid changes of weather everyday caused the micro cracks to develop on the surface and within the volume of the composites [16].

4 Conclusions

KFRC has been successfully produced using the pultrusion method. From this study, a few conclusions can be drawn. Firstly, the natural weathering exposure study showed that KFRC could still be degraded throughout a period of time by several factors such as moisture and temperature changes. Prolonged exposure of KFRC to natural weathering may interfere with the fibre matrix interface and cause degradation which significantly reduces the composite’s flexural and compression properties.

Acknowledgements

The authors are grateful to the School of Materials and Mineral Resources Engineering and Institute of Postgraduate Studies of Universiti Sains Malaysia (USM-814023 and 8640013) and the Construction Industry Development Board of Malaysia (CIDB) for their assistance and contribution that has resulted in this article.

References


Madsen, B., Properties of Plant Fiber Yarn Polymer Composites: An Experimental Study. Technical University of Denmark, Department of Civil Engineering, Sektionen for Bygningsmaterialer og Geoteknik, 2004.


