DEGRADABILITY OF BAMBOO FIBRE REINFORCED POLYESTER COMPOSITES

A dissertation submitted by

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Doctor of Philosophy

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Abstract

Fibre reinforced polymer composites made up of synthetic fibres such as glass and carbon have shown outstanding performance in civil engineering load bearing applications. Development in replacing these fibres with natural fibres from plants has recently gained much attention due to the promotion of green-technology. However, the current applications of natural fibre/polymer composites in civil engineering are mostly concentrated on non-load bearing indoor components due to their vulnerability to environmental attack. Their ease to biodegrade becomes a main challenge in the widespread use of these types of materials. In this study, fibre treatment through alkaliisation and the application of commercial weather protection coating are suggested to enhance outdoor performance of natural fibre/polymer composite. Bamboo fibre reinforced polyester composites are selected for the current work due to their potential in civil applications. The study is divided into two stages: optimisation of sodium hydroxide (NaOH) treatment on bamboo fibre/polyester composite and the degradability of bamboo fibre/polyester composite. The degradation study involves material exposure to heat, moisture and the combination of both heat and moisture to provide hygrothermal effect.

The test samples comprised of untreated fibre/polyester composite, treated fibre/polyester composite, coated fibre/polyester composite and neat polyester. All composite samples were fabricated using vacuum bagging process on randomly oriented bamboo fibres. To study the optimum fibre treatment using NaOH, bamboo fibres were treated with 0, 4, 6 and 8 wt. % NaOH. Through tensile testing of both fibre and composite, as well as interfacial shear strength study, it was revealed that alkali treatment results in improvement in strength of fibres and fibre/matrix adhesion up to 6 wt. % NaOH concentration due to the decrease in microfibril angle and rougher fibre surface for better interlocking with neat polyester. At higher NaOH concentrations, fibrils were found damaged causing deterioration in these properties. Thus, the optimum concentration of NaOH for bamboo fibre treatment is considered to be at 6%, with 181% and 22% of improvement in fibre tensile strength and interfacial shear strength, respectively. The coating product selected is an acrylic-based weather protection coat, commercially available for outdoor use and it is applied on the optimised NaOH treated composite. The study has shown that the coating provided improved mechanical properties of the composite up to 15.5% for tensile strength and 5.5% for stiffness at room temperature as well as added durability against heat and moisture below 80⁰C. Generally, the thermal degradation study involves the use of thermo gravimetric analysis (TGA), dynamic mechanical analysis (DMA) and thermo-mechanical test. From the TGA, it was found that alkali treated fibres decomposed at lower temperatures than the untreated fibres due to the reduction in thermal stability of the cellulosic component of the fibres. For the composites, the decomposition temperature decreased by approximately 7.7% with the addition of the thermally less stable bamboo fibres in the neat polyester, but an approximately 90% increase in charring was observed. The glass transition temperature (T_g) for the composites is approximately 120⁰C obtained through DMA. The visco-elastic properties of the composites were found to be better than neat polyester above T_g as the bamboo fibres restrict the molecular movements of the softened resin. Similar findings were observed through the thermo-mechanical test, which was conducted at 40, 80 and 120⁰C. As the exposure temperature approaches T_g, the strength of the composites, although reduced, becomes better than neat
polyester, with 331% higher for treated composite due to the presence of fibres which provide restriction to molecular movements of the resin. In comparison with the tensile behaviour of the composites at room temperature, the strength of the composites were found to improve up to 23% at 80⁰C, which through scanning electron microscopy (SEM) observations, attributed this to better fibre/matrix adhesion. With the immersion of samples in water, the changes in physical and mechanical properties were observed. Without the addition of fibres into the neat polyester, the resin sample showed better resistance to moisture, with less than 1% of moisture absorption observed in 60 days. The voids observed on alkali treated fibres have influenced the increment on moisture absorption of individual bamboo fibres. However, with better interlocking with neat polyester, the moisture gain and absorption rate of the composites were found to decrease with NaOH treatment, whereby 6% NaOH treated composite achieved 60% less moisture gain than untreated composite. The thickness swelling of the untreated composites showed comparable result with treated composites but a notable improvement was observed with the application of the coating layer, providing 40% additional barrier against swelling. However, the strength of moisture degraded treated and untreated composites were comparable at 22 MPa, both approximately 2% higher than dry samples. This is due to the plasticising effect by free water molecules which was advantageous to the strength of cellulose fibres and also to the increased in interfacial shear strength by fibre swelling which filled the voids at the fibre/matrix interface. With the influence of both moisture and thermal exposure, the Tg was found to decrease which was attributed to the hydrolytic depolymerisation of neat polyester whereby the entanglement between the ester links were cleaved by chemical reaction with water, reducing its Tg from 112⁰C to 103⁰C. The rate of absorption and swelling were higher in hygrothermal condition for all samples while the strength experienced a 13.6% reduction compared to immersion at room temperature. Through SEM, this was explained by the presence of microcracks on the resin and deterioration of fibre/matrix adhesion. NaOH treatment and coating layer did not play a major role on the moisture absorption and swelling behaviour of the composites in hygrothermal condition.

From this study, it can be concluded that alkali treatment of fibres has the potential to improve the resistance of bamboo fibre/polyester composites against the effects of heat and moisture, depending on how the degradation parameters alter the condition of the fibre/matrix interface. The presence of a good coating system may help increase the durability of the composite but it must be designed specifically for a certain exposure condition to ensure its effectiveness.
Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this thesis are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature of Candidate
Date

Endorsement

Signature of Principal Supervisor
Date

Signature of Associate Supervisor
Date
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To my husband, Hizam Shah, whose help and support throughout this project had lightened my burden and worries, and without him, all this might not be possible. A special thanks to him. Last but not least, I would like to thank my beloved parents and sons, whose love and encouragement had enabled me to complete this work. To those whom I failed to mention but have been a great part of this endeavour, thank you very much.
List of Publications

**Journals**


Azwa, Z. N., Yousif, B. F., Manalo, A. C., & Karunasena, W. (*In progress*). Physical and mechanical characteristics of bamboo fibre/polyester composites subjected to moisture and hygrothermal conditions.

**Refereed Conference Proceedings**


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<th>Description</th>
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<tbody>
<tr>
<td>$Al(OH)_3$</td>
<td>Aluminium hydroxide</td>
</tr>
<tr>
<td>AO</td>
<td>Antioxidants</td>
</tr>
<tr>
<td>APP</td>
<td>Ammonium polyphosphate</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BPC-0</td>
<td>0% $NaOH$ treated bamboo fibre/polyester composite</td>
</tr>
<tr>
<td>BPC-4</td>
<td>4% $NaOH$ treated bamboo fibre/polyester composite</td>
</tr>
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<td>BPC-6</td>
<td>6% $NaOH$ treated bamboo fibre/polyester composite</td>
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<tr>
<td>BPC-6C</td>
<td>Coated BPC-6</td>
</tr>
<tr>
<td>BPC-8</td>
<td>8% $NaOH$ treated bamboo fibre/polyester composite</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>DAP</td>
<td>Diammonium phosphate</td>
</tr>
<tr>
<td>DMA</td>
<td>Dynamic mechanical analysis</td>
</tr>
<tr>
<td>DTA</td>
<td>Differential thermal analysis</td>
</tr>
<tr>
<td>DTG</td>
<td>Derivative thermo gravimetric</td>
</tr>
<tr>
<td>FR</td>
<td>Fire retardant</td>
</tr>
<tr>
<td>FRC</td>
<td>Fibre reinforced cement</td>
</tr>
<tr>
<td>FRP</td>
<td>Fibre reinforced polymer</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier transform infrared</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>Water</td>
</tr>
<tr>
<td>HALS</td>
<td>Hindered amine light stabilizers</td>
</tr>
<tr>
<td>HDPE</td>
<td>High-density polyethylene</td>
</tr>
<tr>
<td>HIPS</td>
<td>High impact polystyrene</td>
</tr>
<tr>
<td>HRR</td>
<td>Heat release rate</td>
</tr>
<tr>
<td>IFSS</td>
<td>Interfacial shear strength</td>
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<tr>
<td>KOH</td>
<td>Potassium hydroxide</td>
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<tr>
<td>KSR</td>
<td>Swelling rate parameter</td>
</tr>
<tr>
<td>LDI</td>
<td>Lysine-based diisocyanate</td>
</tr>
<tr>
<td>LLDPE</td>
<td>Linear low density polyethylene</td>
</tr>
<tr>
<td>LLG</td>
<td>Limited life geotextiles</td>
</tr>
<tr>
<td>LOI</td>
<td>Limited oxygen index</td>
</tr>
<tr>
<td>MAPE</td>
<td>Maleic anhydride</td>
</tr>
<tr>
<td>MAPP</td>
<td>Maleic anhydride polypropylene</td>
</tr>
<tr>
<td>$Mg(OH)_2$</td>
<td>Magnesium hydroxide</td>
</tr>
<tr>
<td>MLR</td>
<td>Mass loss rate</td>
</tr>
<tr>
<td>MPS</td>
<td>Methacryloxyethyltrimethoxy silane</td>
</tr>
<tr>
<td>MST</td>
<td>Moisture saturation time</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal solid waste</td>
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<tr>
<td>NaOH</td>
<td>Sodium hydroxide</td>
</tr>
<tr>
<td>NP</td>
<td>Neat polyester</td>
</tr>
<tr>
<td>PBS</td>
<td>Poly-butylene succinate</td>
</tr>
<tr>
<td>PCL</td>
<td>Polycaprolactone</td>
</tr>
<tr>
<td>PE</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
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<tr>
<td><strong>PHB</strong></td>
<td>Poly-hydroxybutyrate</td>
</tr>
<tr>
<td><strong>PLA</strong></td>
<td>Poly-lactic acid</td>
</tr>
<tr>
<td><strong>PP</strong></td>
<td>Polypropylene</td>
</tr>
<tr>
<td><strong>PVC</strong></td>
<td>Polyvinyl chloride</td>
</tr>
<tr>
<td><strong>RH</strong></td>
<td>Relative humidity</td>
</tr>
<tr>
<td><strong>rHDPE</strong></td>
<td>Recycled high density polyethylene</td>
</tr>
<tr>
<td><strong>RT</strong></td>
<td>Room temperature</td>
</tr>
<tr>
<td><strong>SEA</strong></td>
<td>Specific extinction area</td>
</tr>
<tr>
<td><strong>SEM</strong></td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td><strong>SFFT</strong></td>
<td>Single fibre fragmentation test</td>
</tr>
<tr>
<td><strong>SFTT</strong></td>
<td>Single fibre tensile test</td>
</tr>
<tr>
<td><strong>T_d</strong></td>
<td>Decomposition temperature</td>
</tr>
<tr>
<td><strong>T_g</strong></td>
<td>Glass transition temperature</td>
</tr>
<tr>
<td><strong>TGA</strong></td>
<td>Thermo gravimetric analysis</td>
</tr>
<tr>
<td><strong>THR</strong></td>
<td>Total heat released</td>
</tr>
<tr>
<td><strong>TS</strong></td>
<td>Thickness swelling</td>
</tr>
<tr>
<td><strong>TTI</strong></td>
<td>Time to ignition</td>
</tr>
<tr>
<td><strong>UPE</strong></td>
<td>Unsaturated polyester</td>
</tr>
<tr>
<td><strong>US</strong></td>
<td>United States</td>
</tr>
<tr>
<td><strong>UV</strong></td>
<td>Ultraviolet</td>
</tr>
<tr>
<td><strong>UVA</strong></td>
<td>Ultraviolet light absorber</td>
</tr>
<tr>
<td><strong>VTS</strong></td>
<td>Vinyltrimethoxy silane</td>
</tr>
<tr>
<td><strong>WF</strong></td>
<td>Wood fibre</td>
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<tr>
<td><strong>WPC</strong></td>
<td>Wood/polymer composites</td>
</tr>
<tr>
<td><strong>Wt</strong></td>
<td>Weight</td>
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<td><strong>XPS</strong></td>
<td>X-ray photoelectron spectroscopy</td>
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