Tensile and impact behaviour of rice straw-polyester composites

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Rice straw fibres have been extracted and incorporated in polyester resin matrix to prepare rice straw reinforced polyester composites and the tensile and impact properties of the resultant composites studied. The rice straw fibres have a tensile strength of ~ 69.72 MPa and Young’s modulus of ~ 2427 MPa. The composites have been formulated up to fibre volume of about 40%, resulting in a mean tensile strength of 46 MPa which is greater than that of plain polyester (31.5 MPa). The tensile modulus of composite is found to be 1045 MPa which is about 1.66 times to that of plain polyester. The specific tensile modulus is nearly 2.17 times to that of polyester resin. The work of fracture measured in impact at a fibre volume of 46% is found to be 284 J/m. Therefore, the straw-based composites have potential to be used as core material for structural board products.

Keywords: Impact strength, Natural fibre composite, Polyester, Rice straw, Tensile modulus, Tensile strength

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1 Introduction

In many parts of the world, apart from agricultural uses, different parts of the plants and fruits of many crops have been found to be viable sources of raw materials for industrial purposes. The use of natural fibres in polymer matrices is highly beneficial because the strength and toughness of the resulting composites are greater than those of the un-reinforced plastics. Moreover, the incentive for partially or completely replacing synthetic fibres such as nylon, glass and carbon arises from low density, high strength and high modulus of natural fibres. In addition, cellulose-based natural fibres are cheap, abundant, renewable and bio-degradable compared to synthetic fibres, which are expensive and non-renewable.

Recently, cellulosic products and wastes such as wood flour, wood chips and pulp have been used as fillers in polymers, primarily for cost effectiveness and high volume applications. ∆ Several researchers in different parts of the world have reported the study on the use of lignocellulosic natural fibres like sisal, coir, jute, bamboo and banana as reinforcing agents in thermostetting and thermoplastic polymers. Some studies were also carried out on the extraction and tensile properties of various natural fibres such as vakka and date in comparison to bamboo. Over the past decade, cellulose fillers of a fibrous nature have been of great importance, because the composites made from these fibres exhibit improved mechanical properties compared to those containing non-fibrous fillers. Annual crop fibres such as sugarcane bagasse, wheat straw and rice straw have been used as fibrous reinforcement in composites. The performance of these fibres depends on their cellulose content.

Even though many reports have been published on using various natural fibres, in view of the 136 million tones (India) and 572 million tones (world) of rice produced every year, the study on rice straw fibre for composites application is justified. In our earlier paper, the flexural properties of rice straw reinforced polyester composites have been reported.
Hence, the objective of the present paper is to investigate the tensile and impact properties of rice straw reinforced polyester composites. Unsaturated polyester resin has been chosen as the matrix material because it is relatively cheap, having lower shrinkage and can be moulded at room temperature. Accordingly, various percentage volumes of rice straw have been combined with an unsaturated polyester resin to produce rice straw reinforced polyester composites, and the extraction of rice straw fibres, testing of specimens and the resulting composite properties such as tensile strength, modulus and toughness were reported.

2 Materials and Methods

The general purpose polyester resin of the grade ECMALON 4411 was procured from Ecmass Resins (Pvt) Ltd., Hyderabad, India. It is an unsaturated polyester resin having viscosity of 500-600 cps (Brookfield viscometer) and specific gravity of 1258 kg/m$^3$ at 25$^\circ$C. Its acid number (mg KOH/g) is 22 and monomer content is 35%.

2.1 Extraction and Preparation of Straw Fibre

The rice straw variety MTU 2077, which is widely cultivated in the local area, was used for the study. The method of extraction and preparation of straw fibre which is used for the fabrication of specimens have been reported earlier. The quality and properties of these natural fibres depend upon the soil conditions, season and climatic conditions of the crop during which it is harvested in addition to the variety of rice straw.

2.2 Properties of Straw Fibres

2.2.1 Determination of Modulus and Strength

Straight, flaw free length of uncrushed and rolled fibres was selected and the values of fibre tensile strength and Young’s modulus were determined in accordance with the standard test method ASTM D3379-75. Both the uncrushed and crushed fibres were gripped with hard board tabs glued to the fibre ends with epoxy resin. Tests were performed at a crosshead speed of 0.2 mm/min and strain was measured with an extensometer. In the calculation of the stress, the cross-sectional area of the fibres was obtained from the mass, length and density of the fibres. The mass of the rice straw fibres was measured using a weighing machine having a least count of 0.00001 g and the length using digital vernier calipers with a least count of 0.01 mm. The density of the fibres was obtained using picnometric method. The average Young’s modulus and strength of uncrushed and crushed fibres are derived from the close to linear stress-strain characteristics (Table 1). It is observed that the fibre failure is discontinuous and consistent.

2.2.2 Calculation of Volume Fraction and Density of Fibre

The density and volume fraction of fibre in a cured polyester resin matrix were calculated by the method which enables the rule of mixtures analysis of measured composite properties. The method involves measuring the density ($\rho_C$) of the composite of mass $M_C$ at a given mass fraction ($M_F$) of resin. The picnometric procedure was adopted for measuring the density of the composite. Volume fraction ($V_F$), and the density ($\rho_F$) of the straw fibre were calculated using the relationships given in our earlier paper.

The density of fibre was also measured taking a known weight of fibre separately using picnometric method. Both the methods produced approximately similar results.

2.3 Fabrication and Testing of Composites

2.3.1 Fabrication

The specimens were prepared by hand lay up method in the form of a rectangular strip to confirm to the required dimensions. The mould was prepared on a smooth ceramic tile by fixing a rubber shoe sole to the tile with a thin coating of polyvinyl alcohol. Rolled flat straw containing fibres of required length (160mm for tensile testing and 63.5 mm for impact testing) was accurately weighed and moulded with a mixer of unsaturated polyester resin, catalyst and accelerator (1.5% each by volume of resin). The method of orientation of fibres in the mould, the pressure applied over it and the period of curing were also studied.

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>No. of samples tested</th>
<th>Avg. tensile strength MPa</th>
<th>Avg. Young’s modulus MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncrushed</td>
<td>10</td>
<td>74.60</td>
<td>3323</td>
</tr>
<tr>
<td>Crushed</td>
<td>10</td>
<td>69.72</td>
<td>2427</td>
</tr>
</tbody>
</table>

2.3.2 Tensile Testing

A two ton capacity electronic tensometer (METM 2000 ER-1), model supplied by M/s Mikrotech, Pune, was used for tensile testing of the composite specimens. Tensile test specimens were made in accordance with ASTM D 638M to measure the tensile properties. The samples were 160 mm long, 12.5 mm...
wide and 3 mm thick. Overlapping aluminium tabs were glued to the ends of the specimen with epoxy resin filling the space at the tab overlap to prevent compression of the sample at the grip. The samples were tested at a crosshead speed of 0.5 mm/min and the strain was measured with an extensometer.

2.3.3 Impact Testing
Izod impact test specimens were prepared in accordance with ASTM D 256M to measure the impact strength. The specimens were 63.5 mm long, 12.7 mm deep, and 10 mm wide. A sharp file with included angle of 45° was drawn across the centre of the saw cut at 90° to the sample axis to obtain a consistent starter crack. The samples were fractured in a plastic impact testing machine (capacity-21.68 J), supplied by M/s International Equipments, Mumbai, and the impact toughness was calculated from the energy absorbed and the sample width.

3 Results and Discussion
3.1 Tensile Tests
The results of tensile tests for various percentage volumes of rice straw fibre composites are given in Table 2. The stress increases linearly as a function of percentage strain for the composite at highest volume of fibre (40%). The mean tensile strength versus percentage volume of fibre in the composites is shown in Fig. 1. It is observed that the mean tensile strength of rice straw composites is nearly same up to a straw volume of 10.6%. But it increases gradually up to 46 MPa, which is 46% more than that of pure polyester, with the increase in volume of straw fibre to 40% in the composite. As the volume of straw increases, the increase in tensile strength of the composite is expected since the fibre has a higher strength compared to the unreinforced polyester matrix material.

In-plane shear and compressive stresses acting on rice straw composite samples tested in three-point bending are absent in the composite tested in pure tension. As a result, with the increase in percentage volume of fibre there is no initial fall in the value of the tensile modulus but after that it increases steadily, as shown in Fig. 2. A rule of mixtures relationship for tensile modulus is given by the following relationship:

\[ E_C = E_F V_F + E_R (1 - V_F) \]  ... (1)

where \( E_C \) is the modulus of the composite; \( E_F \), the modulus of fibre; \( V_F \), the volume fraction of fibre; and \( E_R \), the modulus of pure polyester matrix material. This relationship is unlikely to predict the composite modulus due to the random orientation of the straw fibres. The equation represents an upper limit of the

<table>
<thead>
<tr>
<th>Volume of fibre ((V_F)_%)</th>
<th>Density of composite (\text{kg/m}^3)</th>
<th>Mean tensile strength (\text{MPa})</th>
<th>Mean tensile modulus (\text{MPa})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1258</td>
<td>31.50</td>
<td>630</td>
</tr>
<tr>
<td>10.6</td>
<td>1186</td>
<td>31.87</td>
<td>817</td>
</tr>
<tr>
<td>21.2</td>
<td>1123</td>
<td>34.68</td>
<td>913</td>
</tr>
<tr>
<td>26.0</td>
<td>1107</td>
<td>37.00</td>
<td>949</td>
</tr>
<tr>
<td>30.8</td>
<td>1066</td>
<td>40.85</td>
<td>973</td>
</tr>
<tr>
<td>34.5</td>
<td>1011</td>
<td>42.85</td>
<td>996</td>
</tr>
<tr>
<td>40.0</td>
<td>956</td>
<td>46.00</td>
<td>1045</td>
</tr>
</tbody>
</table>
modulus that cannot be exceeded and assumes that the fibre and matrix undergo the same strain and are stressed along a unidirectional fibre axis. A lower limit of modulus is predicted by the following equation:

\[ E_C = \left[ \frac{V_F}{E_F} + \left( \frac{1-V_F}{E_R} \right) \right]^{-1} \] … (2)

This assumes that the composite is stressed perpendicular to the straw fibre axis and the stresses in the fibre and matrix are the same. The tensile modulus results shown in Fig. 2 are found to fall between the two extremes of Eqs (1) and (2), which might be expected from the orientation of fibres.

The specific tensile strength and modulus results (Fig. 1) follow the same trend approximately as that of mean tensile strength and modulus (Figs 1a & 2) respectively. The specific properties are calculated as the ratio of the respective strength/modulus in MPa to the mass density in kg/m³ of the composite. The tensile failure surface of the specimens (Fig. 3a) shows the evidence of pull out of straw fibres. These results also suggest that suitable surface modification of rice straw fibres before incorporation in the matrix would improve the tensile properties of the composites further.

3.2 Impact Tests

The results of pendulum impact tests are shown in Fig. 4. As the percentage volume of rice straw increases, the value of impact strength increases and at \( V_F = 46\% \), the composite has a work of fracture of 284 J/m. The impact strength of rice straw composite is 18 times to that of pure polyester resin considered in the present work, 10 times more than that of wheat straw-polyester composites and 38% more than the toughness of soft woods.\(^{16}\) Hence, the rice straw composite can be placed in the category of tough engineering materials. In impact, at high percentage volumes of fibre the rice straw fibres are capable of arresting and diverting the progress of propagating cracks from an edge of the notch, thus blunting the crack by delamination (Fig.3b).
4 Conclusions

The results have demonstrated that a useful composite material can be manufactured from the rice straw and polyester resin. The rice straw fibres considerably improve the tensile strength, stiffness and toughness to a great extent of the resin alone, and reduce its density with the increase in percentage volume of fibre in the composite. As the rice straw acts as a cost reducing agent the composite can be regarded as a successful engineering material in its own right, particularly as a lightweight building material.

In order to exploit the rice straw as reinforcement, it is important that the cost of processing the raw fibre prior to incorporation with resin should be minimized. Future work will investigate the performance of other low cost resin systems like thermoplastics and biodegradable matrices such as starch and cellulose acetate reinforced with rice straw.

References