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Effect of γ-irradiation on the short beam shear behavior of pultruded sisal-fiber/glass-fiber/polyester hybrid composites

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Pultrusion has been now accepted as an effective and versatile technique for the production of continuous fiber reinforced composites with constant profile cross-section. Fillers such as calcium carbonate, hollow glass microspheres, liquid rubber are quite often added to reduce materials cost and to improve impact resistance [1]. One possible class of filler for pultruded glass fiber reinforced plastics (GRP) is the natural cellulosic fibers. Cellulose-based natural fibers are used as reinforcing fillers in polymeric matrix composites [2] for their low cost and attractive specific properties. A comprehensive review on cellulosic natural fiber reinforced composites is given by Bledzki and Gassan [3].

The microstructures of sisal fibers are very different from those of synthetic fibers. A sisal fiber is not a single fiber but is made up of a bundle of tubular micro-fibers of diameter 4–12 μm. The cell wall of a tubular micro-fiber is 1–2 μm thick and has a composite structure of lignocellulosic material reinforced by helical micro-fibrillar bands of cellulose. The cell walls are in turn covered by a layer of bonding material that separates one micro-fiber from another [4, 5].

The major problem in using sisal fiber in polymer matrix composite is the poor interfacial bonding. The general approach to improve the interfacial bonding between sisal fiber and polymer matrix include mercerization, heat treatment and coupling agent coating [6–8]. In the mercerization process, some of the lignin phase will be dissolved away by the alkali solution, which will give a corresponding increase in the density of the treated sisal fibers [6]. For heat treated sisal fibers, the crystallinity of the cellulosic micro-fibers will be increased as determined from X-ray diffraction [6]. The objective of the present investigation is to determine the effect of γ-irradiation treatment on the short beam shear (SBS) behavior of a sisal-fiber/glass-fiber/polyester hybrid composite produced by pultrusion.

Pultrusion was carried out by using a small pultrusion machine (model HB/LJ-3, manufactured by Harbin FRP Institute) with 12 kN pulling force capacity. The pultruded profile has a near rectangular cross-section (with both ends semi-circular, see Fig. 1) with dimensions 15.3 × 4.3 mm. Two compositions of specimens were pultruded. In the first composition, both sisal fiber and glass fiber were used as reinforcements, and the resulting composite is called hybrid in this work. The matrix used was an unsaturated polyester containing 10 phr of $Al(OH)_3$ as filler and 1 phr of mold release agent. The volume fractions of glass fiber and sisal fiber are 37.2 and 11.0% respectively. In the second composition, only glass fiber was used as the reinforcement and with a fiber volume fraction of 54%. The matrix composition is the same as in the previous case. The resulting composite will be called GFRP.

The temperature settings in the pultrusion die are 120 °C close to the die entrance region, 150 °C at the mid-section and close to the exit of the die. The pulling velocity was fixed at 300 mm/min. A micrograph showing the cross-sectional details of the pultruded hybrid profile is shown in Fig. 1. It can be seen that the sisal fibers were located at the center of the pultruded profile and were surrounded by glass fiber reinforcements.

Some of the pultruded specimens were subjected to a γ-ray exposure of 154 mR (over 10 min) using a Cs-137 source (gamma energy = 0.662 MeV). The γ-irradiated and un-treated specimens were subjected to short beam shear (SBS) test (ASTM D2344) with length to thickness and span to thickness ratio equal to 7 and 5 respectively. The SBS tests were conducted using an Instron (model 4206) universal testing machine at a cross-head speed of 1.3 mm/min. Three specimens were tested for both γ-irradiated and un-treated conditions.

Force-displacement curves for the γ-irradiated and un-treated hybrid specimens are shown in Fig. 2.

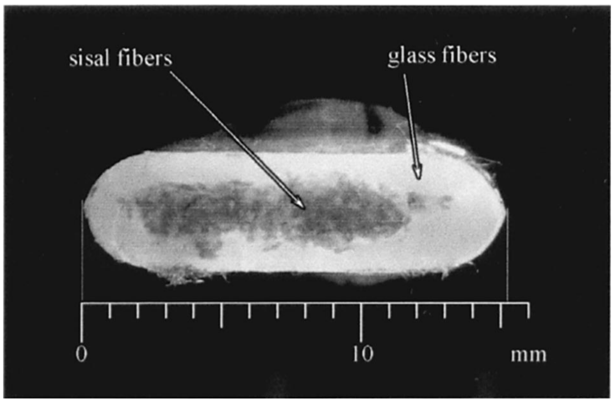

Figure 1 Micrograph showing the cross-section of a pultruded hybrid composite profile.

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TABLE I Short beam shear strength for γ-irradiated and un-treated specimens

	Short beam shear strength	
Specimen type and treatment condition	Mean (MPa)	Standard deviation (MPa)
γ-radiated hybrid	16.48	1.33
Un-treated hybrid	13.03	1.39
γ-radiated GFRP	27.17	0.82
Un-treated GFRP	27.44	1.35

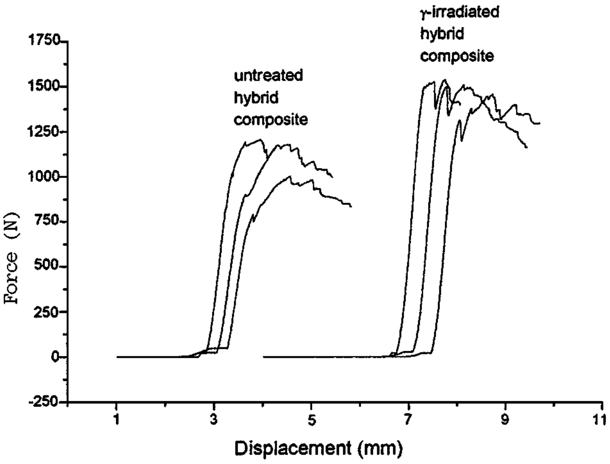

Figure 2 Force-displacement curves for the hybrid specimens measured from SBS testing (3 examples of each).

It is obvious that the γ-irradiated specimens failed at a higher loading than the un-treated specimens. The apparent shear strength was calculated using the formula:

$$\tau_{\max} = \frac{3}{2}\frac{P_{\mathrm{f}}}{wt} \tag{1}$$

where P_{f} is the load at failure, w and t are the width and thickness of the specimen respectively. The apparent shear strength for the γ-irradiated and un-treated specimens are summarized in Table I.

Apparently, γ-irradiation increased the SBS behavior of the hybrid composites. The increased SBS behavior may be due to modifications in the glass/polyester phase or the sisal/polyester phase. A comparison of the force-displacement curves for the γ-irradiated and un-treated GFRP samples obtained from the SBS experiments is shown in Fig. 3. It can be seen that the GFRP specimens were not affected by γ-irradiation. A summary of the short beam shear strength for the GFRP is shown in also shown in Table I. It can be concluded that the applied γ-irradiation treatment did not affect the glass/polyester phase.

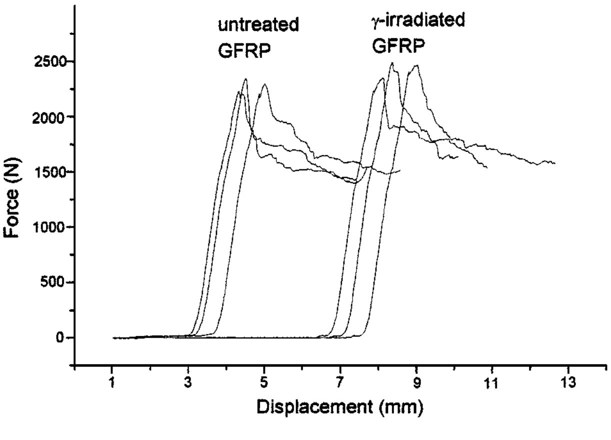

Figure 3 Force-displacement curves for the GFRP specimens measured from SBS testing.

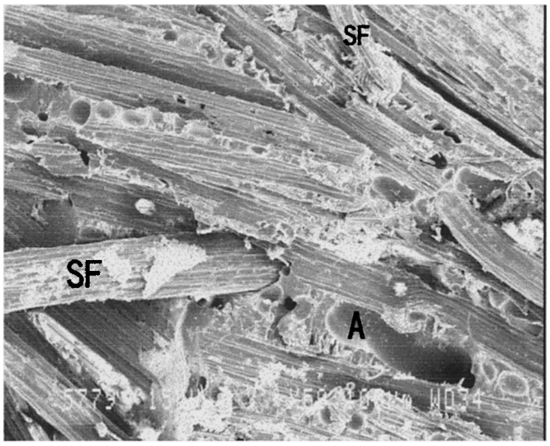

Figure 4 Shear fracture surface of an untreated hybrid specimen showing the sisal fiber rich region.

Fig. 4 shows the shear fracture surface of an untreated hybrid specimen. Some sisal fibers (labeled SF) can be seen. The slanted hole (labeled A) is thought to be the remnant from a pulled out sisal fiber. This indicates the weak bonding between sisal fiber and polyester matrix. A number of small holes can also be identified on the fracture surface. This indicates the poor wetting between sisal fiber and polyester matrix. On the other hand, good bonding was observed between glass fiber and polyester matrix on the same fracture specimen (Fig. 5).

The shear fractured surface for a γ-irradiated hybrid specimen is shown in Fig. 6. Some fibrillar features can be seen to be coming out from the diagonally aligned sisal fiber. These fibriller features cannot be found on the untreated hybrid samples. They are thought to be the helical cellulosic fibrils that have been drawn out

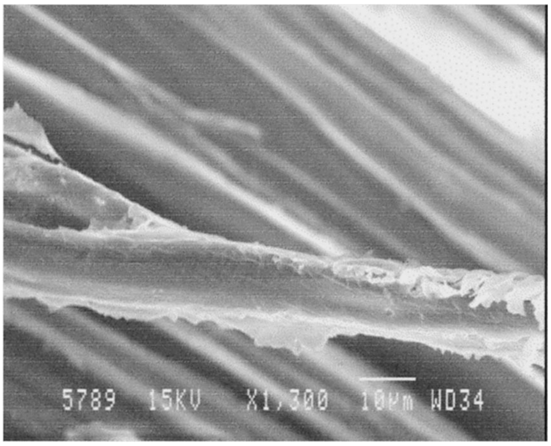

Figure 5 Strong bonding between glass fiber and polyester matrix.

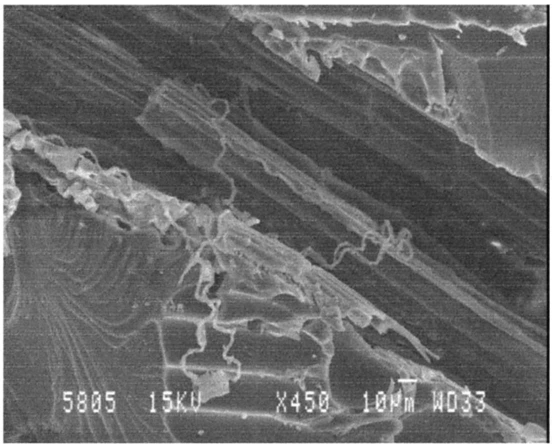

Figure 6 Shear fracture surface of a γ-irradiated hybrid specimen showing the sisal fiber rich region.

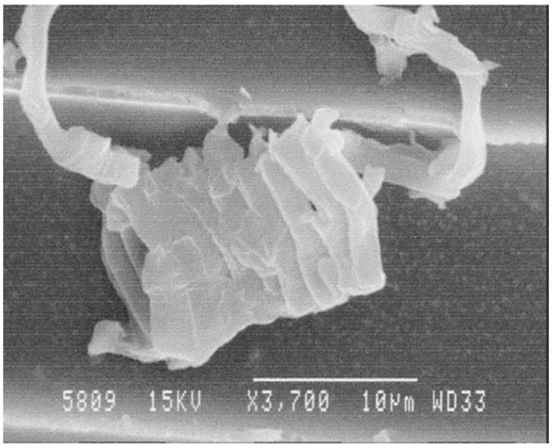

Figure 7 Attached segment of tubular micro-fiber. It can be clearly seen that the tubular micro-fiber is composed of a helical micro-fibril.

from the micro tubular fibers, as supported by the SEM micrograph shown in Fig. 7, where a segment of a helical cellulosic fibril in the form of a micro tubular fiber can be seen. This segment was sheared from the micro tubular fiber with helical cellulosic fibrils being drawn out from both ends. The stretching of the helical cellulosic fibrils and their debonding from the surrounding bonding materials consume a significant amount of energy during shear failure.

In summary, the lower short beam shear strength for the hybrid specimens in comparison to the GFRP specimens were due to the poor interfacial bonding between sisal fiber and matrix. γ-irradiation did not have any effect on the SBS behavior of the GFRP samples, while the effect on the hybrid specimens was more pronounced.

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