Influence of Water Uptake on the Mechanical Properties of Jute Fiber-Reinforced Polypropylene

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SYNOPSIS

Jute fiber-reinforced polypropylene composites have been produced and characterized in order to investigate the influence of water on their mechanical properties. Being hydrophilic, jute fibers absorb a high amount of water causing swelling of fibers. On the other hand, the thermal shrinkage of polypropylene melt leaves some gaps between jute fibers and matrix material. We investigated whether these gaps could be filled by the swelling of wetted fibers. The fillup of these gaps would result in a higher shear strength between fibers and matrix during fracture. Our results suggest that swelling of jute fibers in a composite material can have positive effects on mechanical properties. © 1994 John Wiley & Sons, Inc.

INTRODUCTION

There is a growing interest in the use of natural fibers such as jute, flax, and kenaf as reinforcing fibers in plastics. These types of natural fibers are able to satisfy economical as well as ecological interests. Their biodegradability can contribute to a healthy ecosystem while their low costs and high performance are able to fulfill the economic interests of industries. But some of the physical properties of these natural fibers are considered undesirable for their use as reinforcing fibers, especially for thermoplastic materials. One of those properties is their hydrophilic character. First, the hydrophilic lignocellulosic fibers don't adhere well to the hydrophobic thermoplastics used as matrix materials.[1-3] Second, the composite materials can take up a high amount of water[4,5] which generally causes a decrease in mechanical properties.[5,6]

In previous work,[5] we have reported that in a composite material with lignocellulosic fiber such as jute, water is absorbed mainly by the fibers. Because the thermoplastic matrix material is hydrophobic, its water absorption ability can be neglected.

The differences between the thermal expansions of jute fibers and thermoplastic matrix materials, means there will always be gaps between fibers and the matrix after the melt has been cooled to room temperature. On the other hand, water uptake causes an average increase of the diameters of jute fibers.[7]

We are interested in investigating whether the swelling of jute fibers in water can fill the gaps between fibers and polypropylene caused by the thermal shrinkage of polypropylene melt. The water absorption by the composites would increase the shear strength between jute fibers and polypropylene. Different types of mechanical tests have been applied in order to investigate these effects.

NOMENCLATURE

- σ tensile strength
- d diameter of fiber
- A cross-sectional area of fiber
- F load
- I length of specimen
- w width of specimen
- h thickness of specimen
- τ shear strength

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Subscripts

f fiber
sb short beam
sf single fiber
t tensile
c critical

EXPERIMENTAL

Materials

Polymer films of polypropylene, Novolen 1125 N (100 μm thickness), were kindly provided by BASF, Germany. Raw jute as well as jute yarn were supplied by Jute-Spinnerei und Weberei Bremen Aktiengesellschaft, Germany.

Composites Production

Laminates were produced by a film-stacking technique described previously.[5] The number of prepregs and the fiber direction were varied in order to achieve the desired thickness and a quasi-isotropic character.

Preparation and Treatment of the Specimens

Tensile Test

For tensile tests the specimens $(100*10*3)\,mm^3$ were cut from a $(90°/\pm45°/0°)_s$-laminate, produced with jute yarns/polypropylene. In order to investigate the influence of absorbed water on tensile strengths, the specimens were immersed in water at room temperature (21 ± 0.5)°C. After 14 days, the samples were removed, wiped with tissue paper, and subjected to tensile tests.

Short Beam Shear Test

Specimens $(56*5*5)\,mm^3$ were cut from unidirectionally produced laminates. At a distance of about 20 mm from one end, a groove of 1 mm width and 1 mm depth was cut around each specimen. The specimens were vertically immersed in water (see Fig. 1) so that the water level was up to half of the groove. With this experimental setup the water would be diffused mainly by the inner jute fibers of the specimens, because the outer fibers were not in direct contact with water. After 14 days of immersion, the specimens were cut at the groove and tested according to ASTM D 2344-84. At least five specimens were tested in order to obtain an average value.

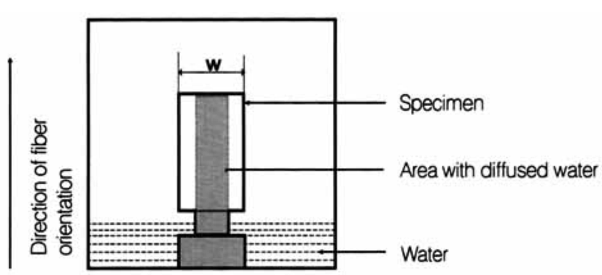

Figure 1 Water treatment of specimen for short beam tests (schematic presentation).

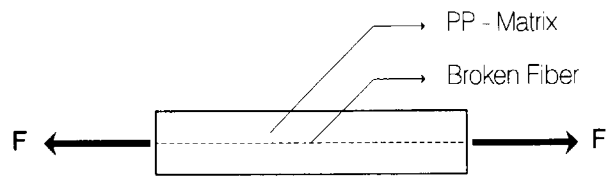

Figure 2 Specimen for single fiber composite tests (schematic presentation).

Single Fiber Composite Test

Individual jute fiber strands were sandwiched between two polypropylene films in a hot press. The press temperature and time were 215°C and 15 min, respectively. Each test specimen was 60 mm in length, 4 mm in width, and 4 mm in thickness. Details of sample preparation has been described elsewhere.[8]

The specimens were immersed fully in water for 14 days. After immersion, specimens were removed, wiped with tissue paper and tensile tests were conducted until addition of further load resulted in no further fiber fracture. A schematic view of a specimen of the single fiber composite test after tensile loading is shown in Figure 2.

CHARACTERIZATION OF COMPOSITES

Water Uptake and Swelling of Specimens

The specimens were from a $(90°/\pm45°/0°)_s$-laminate. The dimensions of specimen and the tests were carried out according to ASTM D 570-81. Two types of specimens were investigated. One type was cut so that the longer dimension was parallel to the fiber direction of the outer layers of the laminate, and the other type transverse. They will be referred to as longitudinal and transverse, respectively, in this paper.

Mechanical Tests

An Instron, Model 1122, was used to study the mechanical properties such as tensile and shear

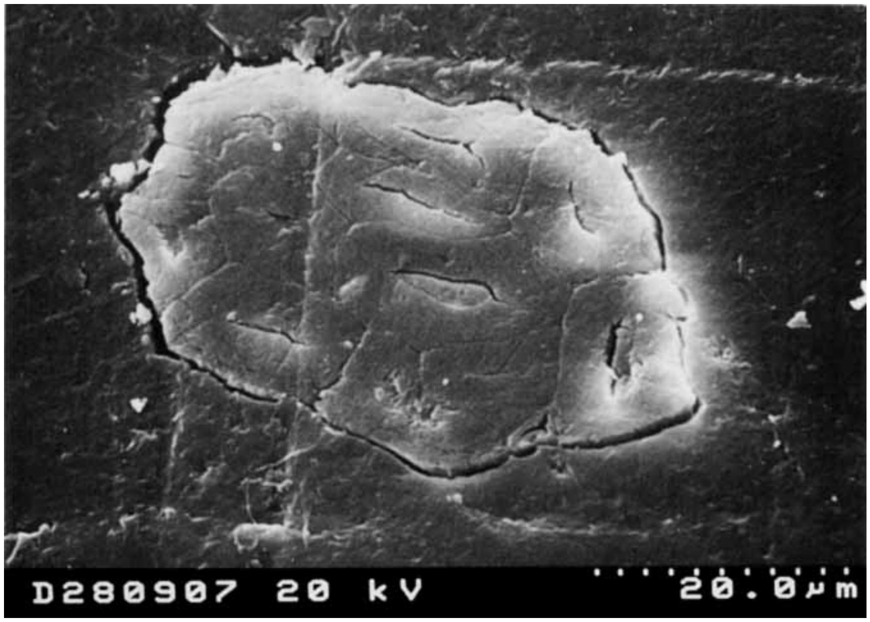

Figure 3 Cross-section of an embedded jute fiber strand in polypropylene (by electron microscopy).

strengths. For short beam shear tests special equipment was installed to modify the Instron.

The tensile and short beam shear tests were carried out according to ASTM D 638-90 and ASTM D 2344-84, respectively. No formal standardized test method was used for the experiments of single fiber composite tests. The stretch velocity, however, was 5 mm/min. All of the experiments were carried out under room temperature (21 ± 0.5°C).

The following equations were used for the calculation of different kinds of mechanical tests used in this work:

Tensile strength: $\sigma_t = F/A$

Shear strengths:

Short beam test: $\tau_{sb} = 0.75\ F/(w\ h)$

Single fiber composite test:

$\tau_{sf} = \sigma_f d/(2\ I_c)$

Tensile strength, σ_f, for the critical fiber length, I_c, was determined by Weibull statistics.[9]

RESULTS AND DISCUSSION

When a jute fiber strand is embedded in polypropylene matrix, the thermal shrinkage of the matrix results in a gap surrounding the fiber (see Fig. 3). The water treatment of single fiber composite specimens reveals an increase in shear strength (see Table I), which supports the hypothesis that the gap between fiber and matrix, caused by thermal shrinkage of polymer melt, has been filled by the swelled fiber. The value for single fiber composite specimens in Table I is an average of the values of 700 fiber fragments measured from the single fiber tensile tests. In Figure 3, the lumens of individual fibers are not clear. It is possible that during surface treatment (polishing) in presence of water the lumens are filled by small particles of broken fibers. Previously, we have reported that the average increase of diameters of jute fibers caused by swelling in water amounts to 3.6 μm,[7] which means an average increase of 6.58% of fiber diameter. This swelling is sufficient to fill a gap of up to 1.8 μm

Table I Influence of Water Uptake on Shear Strength

Samples	Share Strength [MPa]	Treatment
B1	21.3 ± 0.1	14 days standard conditioning
B2	19.2 ± 0.8	Water uptake by diffusion (see Fig. 1); 14 days
B3	25.5 ± 1.6	14 days standard conditioning
B4	32.7 ± 2.6	14 days in water

B1–B2: short-beam test.
B3–B4: single-fiber composite test.

width. The maximum width of a gap between an individual jute fiber and polypropylene was found to be only 700 nm.[8] This means the swelling of jute fibers cannot only fill the gap, but may even produce some radial pressure. As a result, we got a higher value of shear strengths of the wetted specimens tested by the single fiber composite method. Water absorption causes, mostly, an increase in tensile strength of many natural fibers such as jute,[7] cotton,[10] and flax.[11] The increased tensile strength of a jute fiber, embedded in polymer, can also cause an increase of shear strength, while complete swelling of the fiber is prohibited by the surrounding matrix polymer.

No increase in shear strength was found for the short beam shear test (see Table I) for specimens prepared with jute yarn/polypropylene. Despite the high compactness of fiber strands there will always be gaps between individual fiber strands of a yarn resulting in a large volume of voids. Figure 4a and b, shows a hypothetical arrangement of five individual jute fiber strands of a yarn, embedded in polypropylene, before and after water treatment. In Figure 4a, a high volume of voids within individual fiber strands as well as between fiber strands and matrix polypropylene has been shown schematically.

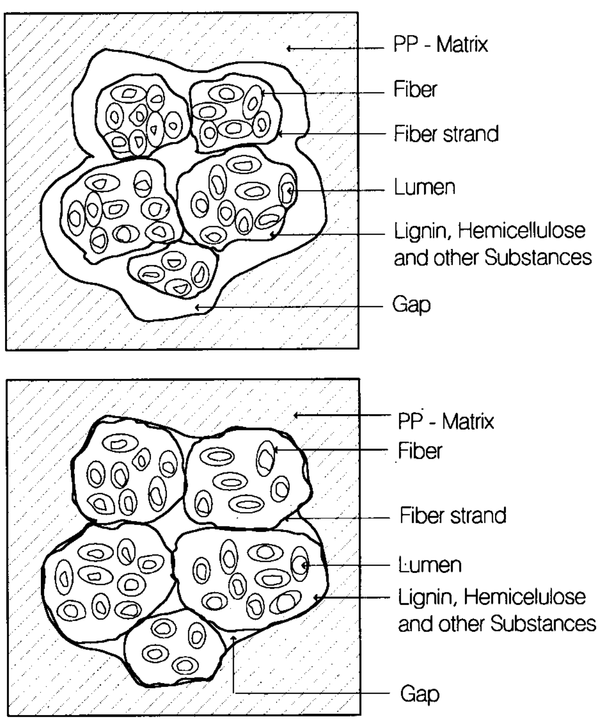

Figure 4 Cross-section of an embedded jute yarn in polypropylene (schematic presentation). (a) Before water absorption; (b) after water absorption.

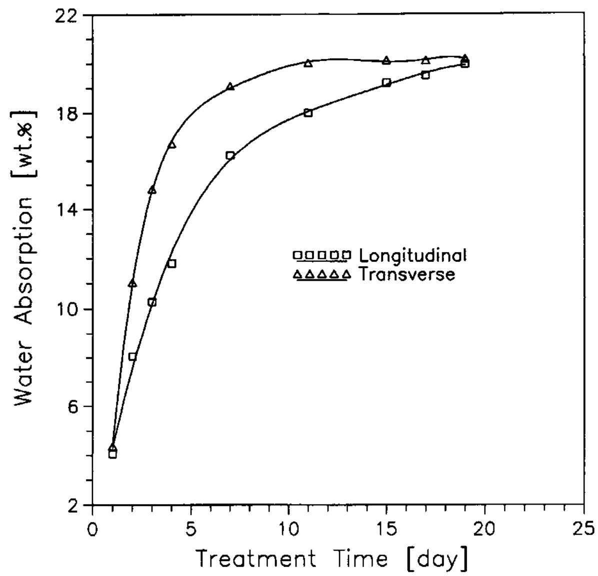

Figure 5 Water absorption dependence of jute fiber-reinforced polypropylene on treatment time: $(90°/\pm45°/0°)_s$-laminate.

Figure 4b shows that after water absorption, though almost all of gap between fiber strands and matrix have been filled, a relatively high volume of voids still remains between individual fiber strands. For a system such as jute yarn and polypropylene, it is difficult for the highly viscous polypropylene melt to enter into the spaces between fiber strands.[9] The swelling of individual fibers may not be able to fill all voids between fiber strands as well as between strands and polypropylene, because the swelling of individual fibers is limited by the neighboring fibers. The water absorption behavior of a quasi-isotropic, jute yarn-reinforced polypropylene, and its effect on tensile strength are shown in Figures 5 and 6.

At the initial stage (see Fig. 5) both types of specimens (longitudinal and transverse) absorb almost the same amount of water. As the immersion time increases, the specimens cut transversely to the fiber direction show more rapid diffusion compared to specimens parallel to the fiber direction. The fibers on the outer surfaces of the specimens of the transverse type are shorter, allowing water to enter through the cavity of the fibers more rapidly than for the specimens of the longitudinal type. However, the absolute water contents after the maximum time (19 days, in Fig. 5) do not differ from each other, because the fiber contents in both cases are the same (40 wt %) and will, therefore, equilibrate to the same water content.

The difference in water absorption rate between samples, cut longitudinally and transversely to the

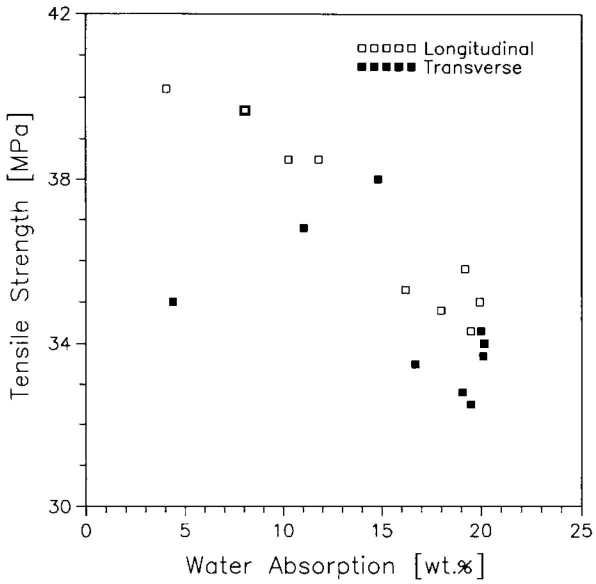

Figure 6 Dependence of tensile strength of jute fiber-reinforced polypropylene on water absorption: $(90°/\pm45°/0°)_s$-laminate.

outer layers of a $(90°/\pm45°/0°)_s$ composite, has a meaningful effect on the tensile strengths. There is a continuous decrease in tensile strength of longitudinal samples, because the main load-bearing layers, in this case the outer layers, are unprotected and can become very weak after water absorption. But in the case of transverse samples, up to a water absorption of about 14.5%, a linear increase in tensile strengths has been observed, which indicates a better load transfer by increased shearing between fibers and polypropylene. Unfortunately, the better load-transferring mechanism has not been found for further water absorption, because the fibers of the outer layers are unable to withstand the further radial pressure caused by the swelling of inner layers.

CONCLUSIONS

Most of the water in jute fiber-reinforced polypropylene composite is absorbed by the fiber itself. Although the rate of water absorption depends on the fiber orientation in the composite, the absolute water contents after the maximum absorption time will remain the same.

The thermal shrinkage of polypropylene melt causes gaps between fibers and polypropylene. The swelling, caused by water absorption, of an individual fiber embedded in polypropylene is able to fill this gap and to increase the shear strength. In the case of jute yarn, the swelling of individual fibers cannot increase the shear strengths, because all of the voids cannot be filled. If the individual fibers are embedded in matrix polymer, water uptake by the composite will not be as harmful to the mechanical properties of the specimens.

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