CHARACTERIZATION OF HIGH-STRENGTH CROSS-PLY "GREEN" COMPOSITES

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ABSTRACT

Plant fibers, such as hemp, sisal, kenaf, and jute, are renewable and sustainable resources and are considered to be a good candidate for cost-effective alternatives to glass fibers. Unidirectional and cross ply "green" composites, which consist of Manila hemp fibers and a starch-based resin, were fabricated by hot-pressing method. Tensile and flexural tests for the cross ply "green" composites were performed to examine their mechanical properties as a function of fiber content. The flexural strength increased with increasing the fiber content. However, the tensile strength increased with the fiber content until 50 mass pct and remained constant thereafter. It is concluded that this peculiar dependence on the fiber content is due to the decrease in fiber strength caused by fiber damages introduced during hot-pressing.

1. INTRODUCTION

Plastic materials are indispensable to our life, and therefore they are massively used in wide fields such as packages, stationery, electronic products, sports goods, and storage tanks. The great majority of plastic products, however, are disposed into landfills after usage. Needless to say, this process is the easiest way and has high environmental loads. In order to reduce the environmental loads derived from the disposing of used plastic products, much more attention has been placed on biodegradable plastics in recent years. This relatively new plastic can be perfectly resolved into water and carbon dioxide by the action of the microorganism, as it is disposed of in underground or seawater, and moreover there is no emission of the toxic gas in combusting[1]. Recently, the biodegradable plastics has been applied to the commercial products such as ball-point pens, toothbrush, garbage bags, fishing lines, stringing of tennis racket, wrapping paper, etc.

Since the biodegradable plastics has relatively lower strength than conventional plastics such as polypropylene and polyethylene, the application of biodegradable plastics has been restricted to only low-strength products. Over the past few years a considerable number of studies have been made on "green" composites, which are composed of biodegradable matrix resin and biodegradable reinforcements such as natural fibers. Until now, the research on a wide variety of "green" composites, which were reinforced by several natural fibers of bamboo[2-6], ramie[7,8], pineapple[9,10], hemp[11-13], flax[14], kenaf[15,16], silk[17], and jute[18-21] have been carried out. As we gave an outline of former research on "green" composites, all of them had a fiber volume fraction less than 40 pct, and thus there is few "green" composite material with a higher tensile strength than 100 MPa.

The aim of this study is thus to develop high strength "green" composites, which have excellent mechanical properties comparable to those of glass fiber reinforced plastics (GFRP). High strength Manila hemp fibers were used as reinforcement for starch-based "green" composites, and both unidirectional composites and cross ply composites were fabricated under various process conditions.

2. EXPERIMENTAL PROCEDURES

2.1 Materials

In order to produce "green" composites with high volume fraction of fibers, a new starch-based emulsion-type biodegradable resin (Miyoshi Oil & Fat Co., Ltd.; CP-300) was used. In this emulsion-type resin, fine biodegradable resin particles of approximately 6 μm in diameter are suspended in water-based solution. Resin content is approximately 40 mass pct. Basic properties of this resin are listed in Table 1.

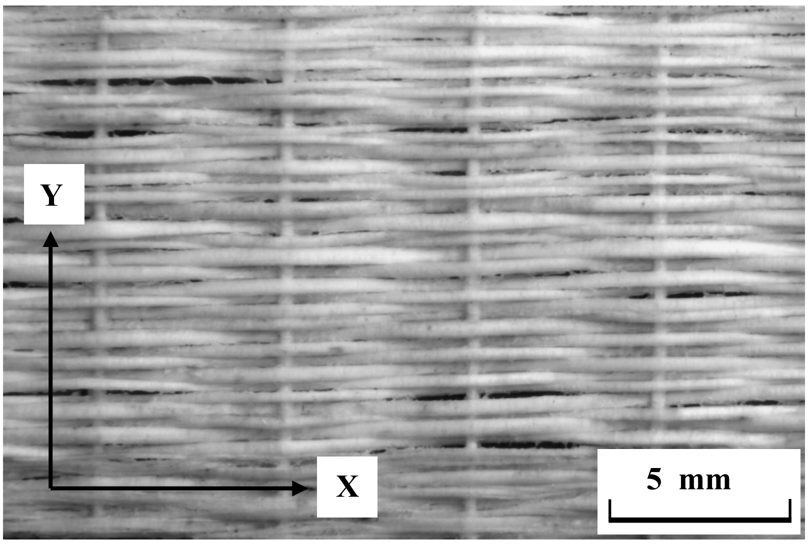
Manila hemp fibers were provided by Mr. Yoichiro Fujimori. In this paper, fiber bundles of about 200 μm in diameter were used. In addition, the surface treatment of fibers was not carried out.

"**Table 1.** Properties of biodegradable resin used as matrix."

Density (g/cm^3)	1.18
Water absorption (%)	2
Tensile strength (MPa)	12.2
Tensile elongation (%)	550
Young's modulus (MPa)	431

2.2 Fabrication of natural fiber reinforced prepreg sheets

Hemp fabrics of 100 mm square were knitted by using a weaving machine. The emulsion-type biodegradable resin was applied on the surface of these hemp fabrics. Manila hemp fiber-reinforced prepreg sheets were obtained by drying the fabrics with resin at 105°C for 7.2 ks in an oven. The photograph of the prepreg sheet is shown in Fig. 1. From this figure, it can be seen that the fibers parallel to the x-direction are aligned closely, but the fibers parallel to the y-direction are aligned at intervals of about 5 mm.



"**Fig. 1.** Photograph of a Manila hemp fiber-reinforced prepreg sheet."

2.3 Laminating method

Both 0° ply prepreg sheets and 90° ply prepreg sheets were stacked alternately to get a cross ply condition. The number of prepreg sheets used for the stacking was increased with increasing the fiber content in order to get the same specimen thickness. In the case of 0° ply laminates, the only 0° ply prepreg sheets were stacked regularly, and 90° ply laminates were also produced in the same manner.

2.4 Molding method

Cross ply "green" composite laminates were produced by the hot-pressing using an electric flexible heater and a hand operated pressing machine. The prepreg sheets stacked were placed in a metallic mold, and then the mold was heated to 130°C by a flexible heater wound around the mold. Next the mold was held at 130°C for 0.3 ks, and finally specimens were hot-pressed at 10 MPa and 130°C for 0.6 ks.

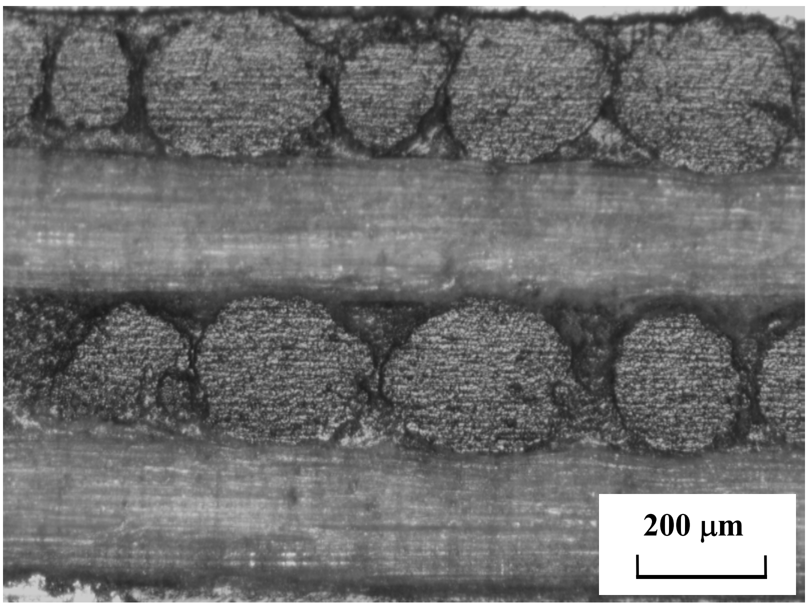
2.5 Mechanical testing

Three points flexural tests and tensile tests were carried out by using an Instron testing machine (Type 5567). The width and length of the flexural specimen are 15 mm and 100 mm, respectively. Those of the tensile specimen are 10 mm and 100 mm, respectively. The thickness of these specimens is approximately 1.5 mm. Flexural tests were performed at a crosshead speed of 1 mm/min and a span length of 50 mm. Tensile tests were performed at a strain rate of 6.67×10^{-4} s^{-1} and a gauge length of 30mm.

3. RESULTS & DISCUSSION

3.1 Microstructure of cross ply "green" composites

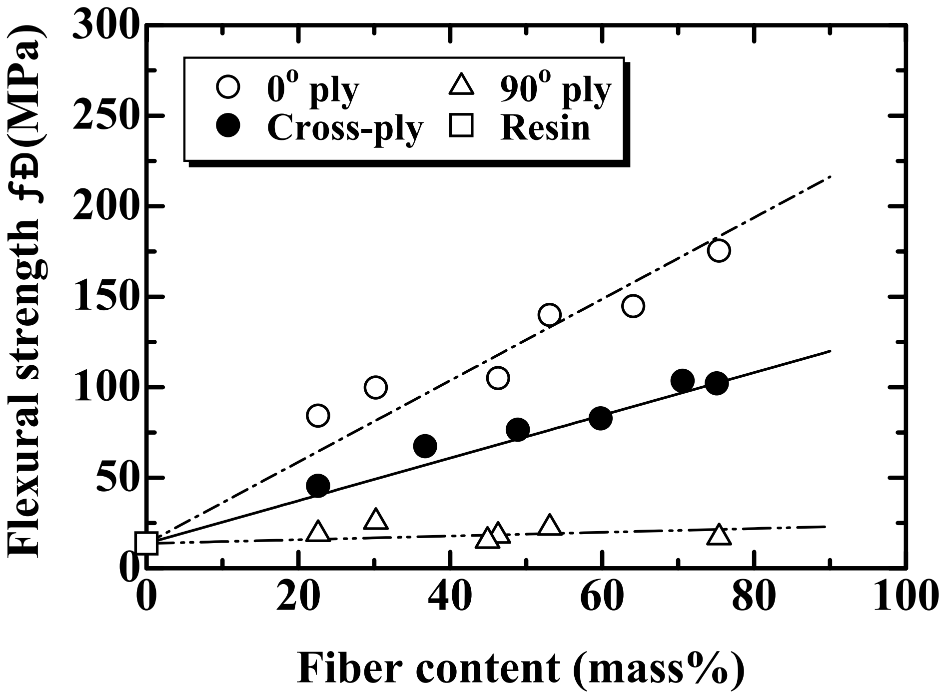
The transverse section of cross ply "green" composite with 59 mass pct of fibers is shown in Fig. 2. From this figure, all fibers were aligned regularly in bi-directions, and there is no void and no fiber contact that cause a strength decrease of composites. The typical density of this cross ply "green" composite material is 1.09 g/cm^3, therefore it is expected that this cross ply "green" composite material can be used as a lightweight structural material such as carbon fiber reinforced plastics (CFRP).



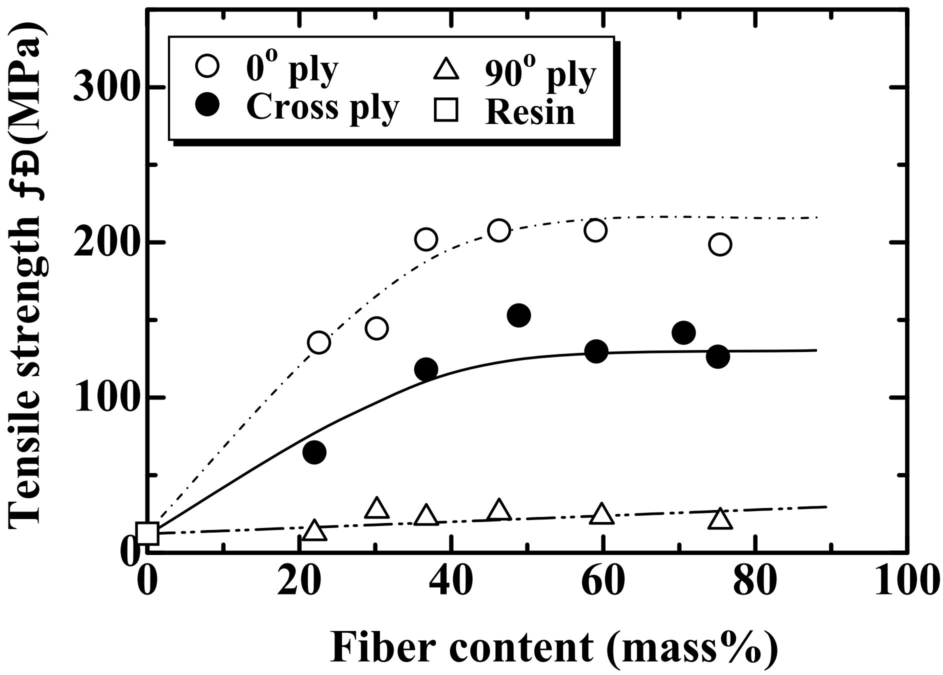
"**Fig. 2.** Optical micrograph of transverse section of cross ply "green" composites with 59 mass pct of fibers."

3.2 Mechanical properties of cross ply "green" composites

Figure 3 shows the relationship between flexural strength and fiber content, and Fig. 4 shows the relationship between tensile strength and fiber content. The cross ply "green" composites have maximum flexural strength of 104 MPa and maximum tensile strength of 153 MPa, respectively. From these figures, flexural strength increases with increasing the fiber content,



"**Fig.3.** Relationship between flexural strength and fiber content."



"**Fig.4.** Relationship between tensile strength and fiber content."

and flexural strength is higher than 100 MPa in the case of the samples with fiber mass fraction higher than 70 pct. On the other hand, tensile strength reached 150 MPa at 50 mass pct of fibers, but remain constant thereafter.

Now, we consider a model cross ply composite material that is applied a unidirectional external force along the fiber direction of 0° ply sheet. We can represent the longitudinal stresses generated in the 0° ply and in the 90° ply as σ_0 and σ_{90}, respectively. The external force carried by the cross ply composite is shared between 0° ply and 90° ply. Thus we obtain the following equilibrium equation: [22]

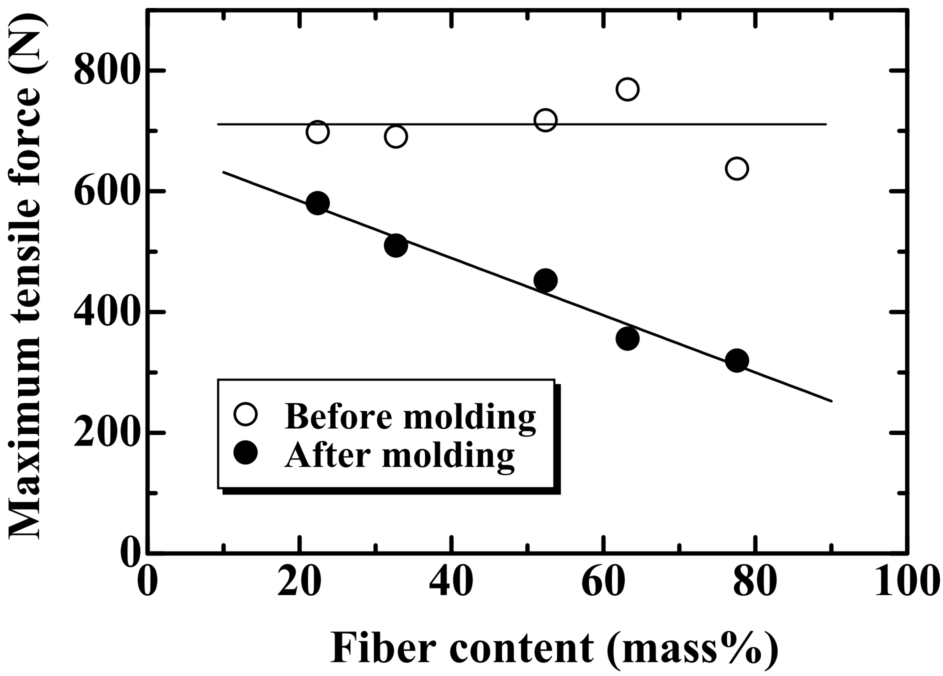
$$\sigma_c\,(a + b)\,w = \sigma_0\,a\,w + \sigma_{90}\,b\,w, \qquad (1)$$

where σ_c is a stress over entire composite, w is the width of composites, and symbols a and b are the thickness of 0° ply and 90° ply, respectively. Since the cross ply composite used in this research was laminated as a=b, we have

$$\sigma_c = \sigma_0 / 2 + \sigma_{90} / 2. \qquad (2)$$

The solid lines in Figs. 3 and 4 represent the theoretical strength value calculated from Eq. (2), and the strength obtained from Eq. (2) shows a good agreement with experimental result. It can be seen that flexural and tensile strength properties of cross ply laminates significantly depend on the strength of 0° ply laminates. As can be seen from fracture behavior of tensile specimen, the fibers parallel to loading direction were subject to getting damage by the fibers that intersected perpendicularly with the fibers parallel to loading direction. It was found that such fiber damage controls the fracture characteristics of whole composite material.

To confirm the presence of fiber damage after hot-pressing, maximum tensile force of 0°ply sheets with different fiber content before and after molding were also examined in details (Fig. 5). Before molding, maximum tensile forces were almost constant, however after



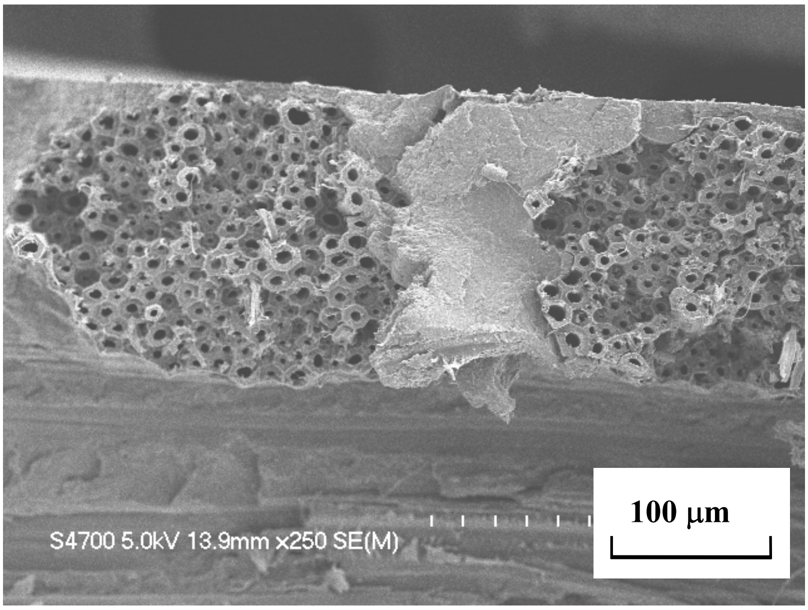
"**Fig.5.** Relationship between maximum tensile force of 0° ply sheet and fiber content."

molding, the maximum tensile forces decreased with increasing fiber content. These results indicate that the decrease in fiber strength is caused by hot-pressing. Therefore this fiber content dependence as shown in Fig. 5 is due to the fiber damage introduced during hot-pressing, thus it is necessary to examine further suitable molding conditions.

On the other hand, as shown in Fig. 3 there exists a proportional relationship between the flexural strength and the fiber content, and this dependence differs from that of the tensile strength. No fiber fracture was observed in all the flexural tests. Namely, this result indicates that the tensile stress generated at the outer surface of the flexural specimen did not reach the fiber failure stress. Consequently, flexural strength shows linear correlation with fiber content.

3.3 Fracture behavior of cross ply "green" composites

The photograph of the fracture surface of cross ply composites after tensile testing is shown in Fig. 6. There is neither crack between fibers and resin, nor pull-out fiber at the fracture surface. From these results, we can be considered that the interfacial bonding between the fibers and the matrix resin is chemically high, since both fibers and resin are hydrophilic.



"**Fig.6.** Fracture surface of cross ply "green" composites."

4. CONCLUSIONS

This research was performed to examine the mechanical properties of cross ply "green" composites that were made from an emulsion-type starch-based biodegradable resin as matrix and woven Manila hemp fibers as the reinforcement. The results obtained are summarized as follows:

(1) High strength cross ply "green" composites with high volume fraction of fibers were fabricated using the emulsion-type biodegradable resin and woven Manila hemp fibers.

(2) The cross ply "green" composites have flexural and tensile strength of 104 MPa and 153 MPa, respectively.

(3) The flexural strength increased with increasing the fiber content. However, the tensile strength increased with the fiber content until 50 mass pct and remained constant thereafter. This fiber content dependence is due to the decrease in fiber strength caused by fiber damage introduced during hot-pressing.

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