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Processing and Mechanical Properties of Long Maize Fiber Reinforced Composites with Recycled Polypropylene Matrix

Mohammed Dauda and Masayuki Yoshiba
Graduate School of Engineering, Tokyo Metropolitan University,
Hachioji, Tokyo 192-0397, Japan

Fax: 81-426-77-2717, e-mail: mdsmatt@ecomp.metro-u.ac.jp, yoshiba@ecomp.metro-u.ac.jp

Maize fibers have been incorporated into the recycled polypropylene (PP) matrix to form the uniaxially reinforced composites containing up to 55% cross-sectional fiber area fraction, in order to develop the composites with mechanical performance competitive to those with virgin PP, by using the sophisticated processing methodology. Optimum manufacturing conditions were determined in both cases by varying the processing parameters such as the molding temperature and forming pressure. Composites with almost equivalent mechanical performance such as tensile strength and apparent elastic modulus were able to be produced using the recycled PP matrix as compared with those with virgin PP. Improved mechanical properties were found to be commonly pronounced in the composites molded at 175°C and formed under the pressure 10 MPa, above which the properties tend to deteriorate. Tensile strength was also found to increase with increase in the fiber cross-sectional area fraction essentially in accordance with the rule of mixture (ROM). Microstructural examination was conducted mainly at the fiber/matrix interface by scanning electron microscopy and the degradation factors for the composite manufacturing was discussed in some detail.

Key words: Materials recycling, Long natural maize fiber, Recycled polypropylene matrix, Composite material, Mechanical properties

1. INTRODUCTION

Current debate regarding resource conservation is forcing researchers to find viable technologies for the re-utilization of renewable resources, particularly from fibrous agricultural waste of tropical origin in creating new materials [(1)(2)]. The idea is to offer significant opportunities for the improved materials with enhanced support for the global sustainability by converting the wastes into high performance composite materials as proposed in the author's previous work [(1)].

A recent study on the long maize fibers and virgin polypropylene (PP) composites without adding the coupling agents has demonstrated the attainability of reasonable mechanical properties [(3)]. Similarly, the improved mechanical properties were reported also on the bagasse fiber – recycled PP composites [(4)]. It was revealed in both cases that the methodology of fiber extraction and sophisticated processing technique adopted in the studies had helped for obtaining the improved mechanical properties of the composites.

The aim of this study is therefore to evaluate the mechanical performance of the low cost and long maize fiber reinforced composites with recycled PP matrix in comparison to those with virgin PP matrix.

2. EXPERIMENTAL

2.1 Characteristics of maize fiber

Corn stalks, like many agricultural fiber sources, consist of a pithy core (parenchyma) with an outer layer of long fibers or cortex. The total maize stem contains about 50% fibers, 50% parenchyma cells and vessels, and only about 1% epidermis cells [(5)].

The basic constituents of maize are cellulose, mostly present in the fiber, hemicellulose and lignin which binds the fibers together. Cellulose and hemicellulose are present in the form of holocellulose amounting to about 40% of the total constituents [(6)].

2.2 Preparation of maize fiber and polypropylene for matrix

The maize stalks were procured during the summer 2001 from local source in Nagano prefecture, Japan. The recycled PP used is the plain type (MFI about 10g/10min, 0.9g/cm^3) which was generously supplied by a petrochemical wholesaler company. For comparison, the virgin PP used is J-2021 GR (MFI 22g/10min, 0.9g/cm^3), produced by Idemitsu Petrochemical Co. Ltd, Japan [(3)]. The methods for fiber extraction and preparation, together with polypropylene are explained in detail in the authors' previous work [(3)].

2.3 Composite forming

The details of the composite manufacturing facility and the methodology of composite forming have been explained in detail in the previous study [(3)]. Composite specimens of ASTM Code D 638 (type V) geometry were manufactured with fiber loading 17, 30 and 38 mass %, corresponding to the fiber cross-sectional area fractions 25, 39 and 55% respectively. The thermo-mechanical processing parameters adopted in this study are listed in **Table I.**

2.4 Tensile testing

The mechanical behavior of the fiber, virgin and recycled PP together with the composites was examined by the tensile testing. The details of the methods adopted

Table I Processing parameters for composite forming

Molding temperature (°C)	Forming pressure (MPa)	Fiber area fraction (%)
160, 175, 190	5 ~ 15	0 ~ 55

are presented in the previous study [3].

Tensile tests for the recycled PP and composites were conducted of at least more than 2 specimens under the same condition except for the crosshead speed of 1 mm/min and 0.3 mm/min, respectively, by using the 10 kN capacity universal testing machine that is connected to a computer for subsequent data treatment. Scanning electron microscopy (SEM) was conducted for examining the microstructural characteristics of the fiber and composites after gold sputting.

3. RESULTS AND DISCUSSION

3.1 Tensile properties of maize fiber and polypropylene

Like other natural fibers, the surface of maize is characterized by a general uneven morphology. The fibers diameter, when considered as perfectly spherical (solid outer diameter), was found to vary approximately from 65 to 210μm, which provides wide differences in the tensile strength between 81 and 211 MPa, in average 141 MPa, as denoted later. It was however observed that a linear relationship exists between the outer and the inner hole diameter. The outer diameter was found to be approximately twice the inner diameter, producing almost similar effect on the tensile strength [3].

Table II shows the mechanical properties of the maize fiber used in this study in comparison with other plant fibers [3][4][7][8].

3.2 Tensile properties of composites

The typical stress – strain curves of the composites are shown in **Fig. 1**. Composites manufactured with virgin PP are marked with subscript "v" for each fiber area fraction (A~C). In the case of composites manufactured with virgin PP, it was observed that after the initial linear region, the composites yield and the molecules slip past one another resulting in a higher strain rate as indicated by the curvatures of the curves, which are more pronounced in B and C, probably due to the increased stress bearing capacity with higher fiber contents [3]. However, the composites manufactured with recycled PP exhibited similar behavior except that about halfway after the initial linear region, the composites suddenly yields resulting in an extended deformation that produced higher strain rate as compared to their counterparts manufactured using the virgin PP. The strain rate as indicated by the curvature of the curves is more pronounced in A and C. This phenomenon may be attributed to the inability of the recycled PP matrix to provide the homogeneous and continued load transfer to the fibers through the interface beyond a certain limit, especially in C, which may be caused by rather lower viscosity of the recycled PP. On the other hand, the composite B traces almost same path of curve B_v, although with a relatively higher strain and lower strength. This may be due to the attainment of optimum fiber loading in the composite system, hence any combination beyond or below this should bring about an insufficient load trnsfer, as noted in C and A.

Table II Mechanical properties of maize and other natural fibers

Material/ Property	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)	Reference
Maize	256	7.5	2.5	3*
Bagasse	60	3.0	3.1	4
Jute	318	27.0	2.4	7
Wheat Straw	43	9.3	-	8

* Average value of 15 specimens

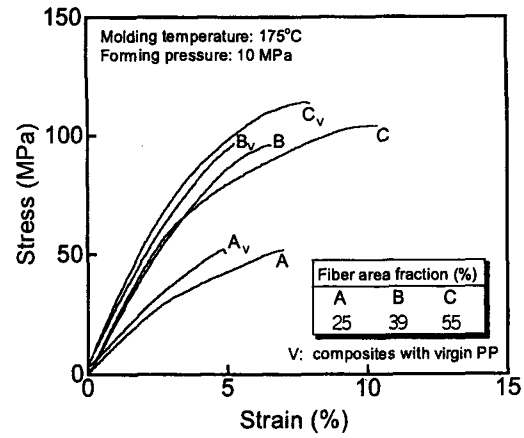

Fig. 1 Nominal stress-strain curves of composites with recycled PP matrix.

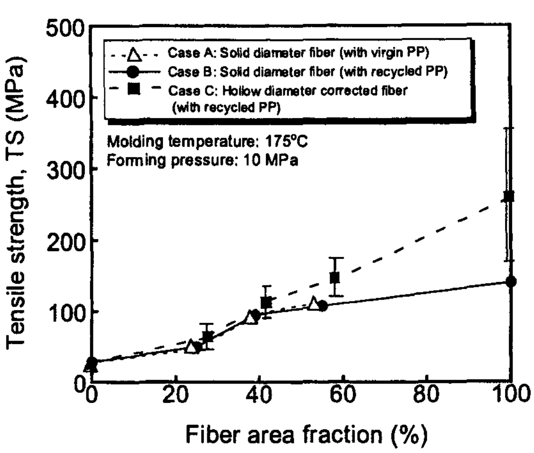

Fig. 2 Dependence of tensile strength on fiber area fraction.

Figure 2 shows the effect of fiber area fraction on the tensile strength of composites formed under 175°C – 10 MPa with pure and recycled PP, as well as maize fiber that has not been subjected to no any thermo-mechanical treatment, along with the data corrected by the hollow diameter consideration [3]. Surprisingly, both composites manufactured with virgin and recycled PP showed almost equivalent strength (between Case A and B) that tends to increase almost linearly with increase in the fiber area fraction, in accordance essentially with the rule of mixture (ROM). Pure fiber exhibits the highest strength but with large scatter band. The data scatter associated with the hollow diameter correction (Case C) depends strongly on the fiber area fraction. The higher the fiber area fraction, the more the disparity in fiber diameters due to the inherently non-uniform topography of the fiber surface [3]

In general, an average error of the data resulted from the tensile testing of the composites with virgin and recycled PP stood at 5.3% and 6% respectively, when more than 2 specimens were used under the same testing condition. While for only a few condition yielded a relatively large data scatter beyond 10%, then additional specimens were adopted for testing under the same condition; these data are then represented with scatter band in the figures. Apparent elastic modulus obtainable from the gradient of an initial linear stage of the stress-strain curve, may be used where necessary.

The overall effect of the fiber area fraction on the tensile properties of composites is summarized in **Fig. 3**. Afterthere, the nominal stress derived from the solid fiber diameter will be denoted. To enable the property comparison with composites manufactured with virgin PP, some results are highlighted for those with PP_v at only the optimum conditions in the figures. In the case of same forming pressure of 10 MPa, both composites manufactured by using virgin and recycled PP showed similar tendency, producing almost equivalent tensile strength and elastic modulus. An increase in the fiber area fraction resulted in the improvement in both tensile strength and elastic modulus, especially at 175 to 190°C molding temperatures for composites containing 39 and 55% fiber area fractions. Similar effect is noted at 175°C in the case of the composites with virgin PP [3]. When the same molding temperature of 175°C is considered, both the tensile strength and elastic modulus increase with increase in the fiber area fraction in both composite systems, especially under the forming pressure of 10 and 15MPa. However, two composite systems somewhat differ when an elongation is considered. For both composite systems, a remarkable increase in the elongation at break is noted for those with 55% fiber area fraction in the case of 10 and 15 MPa. This should be attributed to the improved interfacial adhesion between the fibers and PP matrices. However, the elongation in composites with the recycled PP is almost twice the ones with virgin PP, especially for the composite formed at 15 MPa. This may be related to the low melt flow index of the recycled PP, which requires higher pressure to attain a compaction for improving the adhesion at the interface. The increased elongation ensuing from the sensitivity of the recycled PP to foreign inclusion is under consideration.

The overall effect of the processing conditions on the mechanical properties of the strongest composites with 55% fiber area fraction is summarized in **Fig. 4**. In the same manner, both the composite systems produced nearly equivalent values with similar tendency at the reference conditions. Tensile strength can be improved effectively with increase in the forming pressure, particularly for the composites molded at 175 and 190°C, suggesting the possible sufficient temperature regime for manufacturing the property-enhanced composites. Conversely, a somewhat fall in the tensile strength is noted for the composite prepared under the combination of the 190°C molding temperature and 15 MPa forming pressure, probably due to an excessive fiber damage. On the other hand, an elastic modulus shows almost equivalent value regardless of the molding temperature, as already noted in the previous study [3].

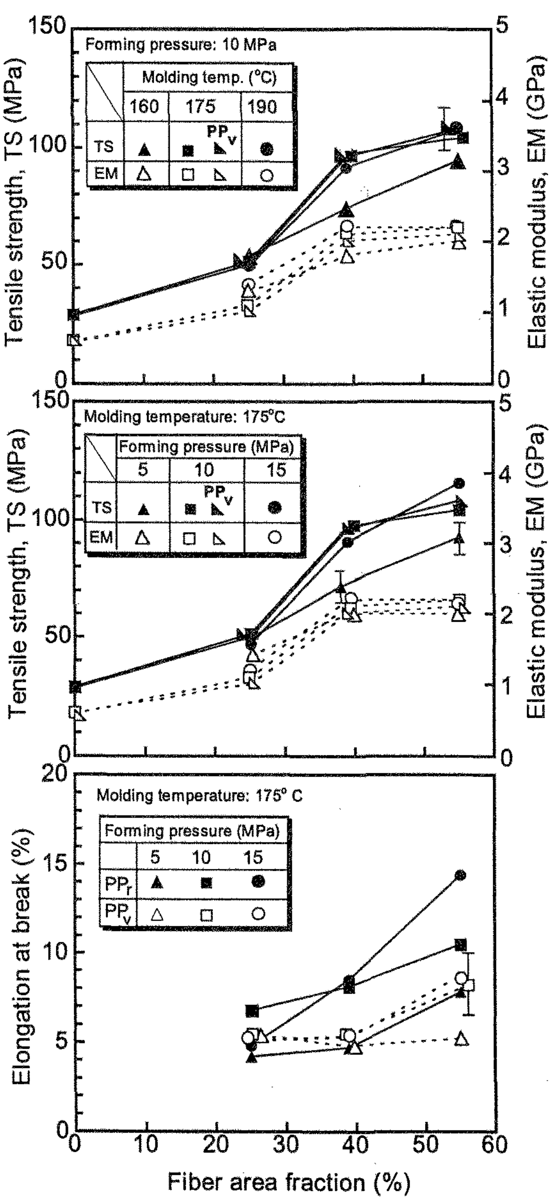

Fig. 3 Effect of fiber area fraction on tensile properties of composites with recycled PP matrix. PP_v and PP_r indicate composites manufactured with virgin PP and recycled PP, respectively.

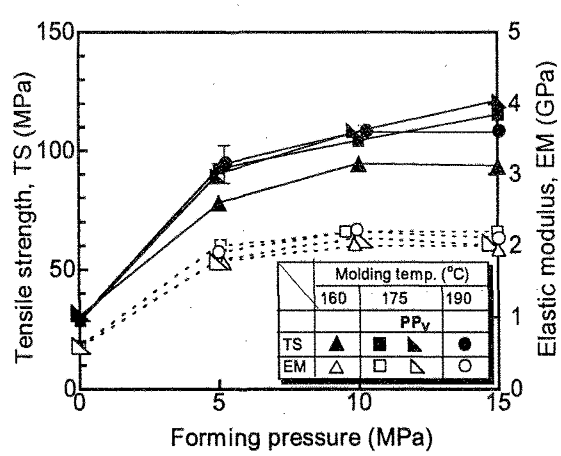

Fig. 4 Effect of forming pressure and molding temperature on strength and modulus of the composites with 55% fiber area fraction.

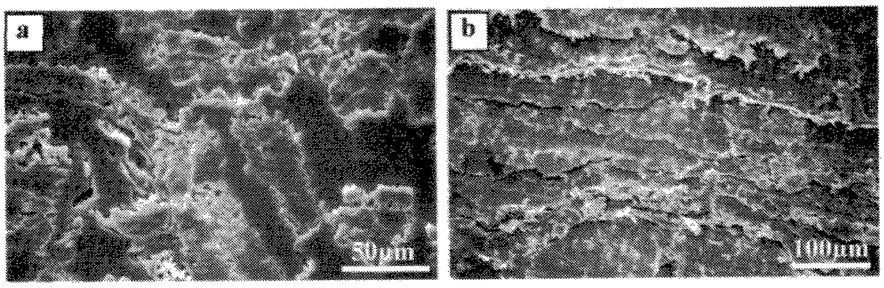

Fig. 5 SEM photographs of the cross-section of composite specimens (a) with virgin PP and (b) with recycled PP (55% fiber area fraction, molded at 175°C and formed under 10 MPa).

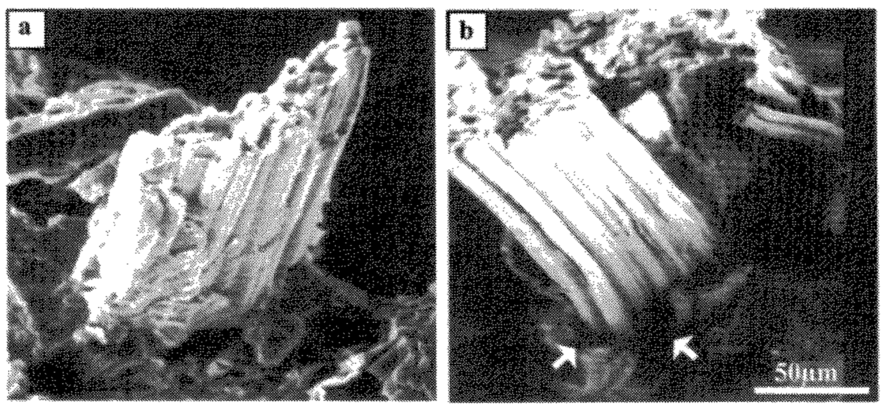

Fig. 6 Typical SEM photographs of the fracture surface for composite specimens containing 55% fiber area fraction, manufactured with (a) virgin PP and (b) recycled PP (molded at 175°C and formed under 10 MPa). Arrows indicate a gap between the interface.

3.3 Microstructural examination of composites

Microstructural examination using SEM technique was conducted at the interfaces in order to investigate the actual interactions between the maize fibers and PP matrices. The SEM photographs of the composites prepared with virgin and recycled PP were compared and representative photographs are shown in **Fig. 5.** The composite with recycled PP showed a rather rougher interface, indicating the effect of the altered flow characteristics of the recycled PP due to reprocessing. Otherwise, no result obtained showed any significant variation as compared to the composites with virgin PP. In the case of the composites prepared with the recycled PP, further investigation revealed some gaps at the base of protruding fiber that appeared to have been pulled out during the fracture process, as shown in **Fig. 6 (b).**

As a general note, the composites prepared outside the optimum conditions may result in any of the degradation scenarios. Molding at lower temperatures and forming pressures may result in an insufficient melting of PP and poor compaction of composites, respectively. However, molding at higher temperatures and forming pressures may bring about the enhanced thermal degradation of fibers and mechanical damage, respectively [3].

4. CONCLUSIONS

(1) Long maize fiber reinforced composites with recycled PP with reasonable mechanical properties have been successfully manufactured using the sophisticated composite processing technique, and the mechanical performance of the recycled PP based composites was proved almost equivalent to the ones manufactured by using virgin PP.

(2) The rather low melt flow index of the recycled PP may have been the cause for the higher strain rate obtained with these composites. The optimum conditions for manufacturing the high performance composite have been specified to be around 175°C molding temperature and 10 MPa forming pressure.

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