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Effect of Fiber Loading on the Mechanical Strength of NFR Hybrid Composites

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Ortho-type UP resin is reinforced with long abaca and short bagasse fibers to produce a novel type of natural fiber-reinforced (NFR) hybrid composite material that is environment-friendly, has a long service life, possesses the properties of both long and short FRP's, and has also acquired the advantages of utilizing two different types of natural fiber reinforcements. The abaca and bagasse fibers are treated in 5wt% NaOH(aq) solution at 80°C for 9 hours and pressed into continuous, unidirectional fiber sheets and random fiber mats, respectively. The fibers are then incorporated into the resin matrix by hand lay-up method, producing FRP laminates with the same uniform thickness but subjected to varying fiber loading conditions: (1) the stacking of long fiber sheets are done in cross-ply and parallel orientation; (2) the abaca and bagasse fibers are stacked in different alternating sequence patterns, and (3) the fibers are added into the ortho-UP matrix at increasing fiber fraction. The alkali-treated FRP laminates show an increase in fiber-matrix interfacial adhesion as compared to the untreated FRP's, based on the overall improvement in the composite mechanical strength, as well as from the lesser visible fiber pull-out observed from SEM images on their fracture surfaces. Also, as expected, the tensile and flexural strengths of the abaca/bagasse hybrid FRP measures intermediate to those of abaca and bagasse FRP's. The strength has also improved with increasing fiber content, although this increase has also caused an increased occurrence of void spaces that may consequently become detrimental to the NFR composite's performance.

***Keywords*:** hybrid composites; NFR; ortho-UP; abaca; bagasse

INTRODUCTION

Natural fiber-reinforced (NFR) composites are progressively finding market as a viable substitute to the traditional glass fiber-reinforced plastics (GFRP's), which have been playing a dominant role in various industrial and commercial applications for the past recent decades due to their high specific mechanical strength and modulus. In the production of fiber-reinforced thermosetting plastics (FRP's) for chemical process equipment and other commercial applications, the addition of natural fibers as FRP reinforcement provides long-term carbon fixation and offers other several advantages over glass fibers such as lower density, less process equipment abrasiveness and reduced material and energy costs. The main disadvantages are the significantly lower mechanical strength and high moisture affinity, which, according to numerous published studies, may be resolved by chemical fiber treatment- such as mercerization- or by increasing the fiber content (Kobayashi *et al.*, 2007).

Some of the commercially available natural fibers for the production of NFR composites are listed in Table 1 (Goda and Cao, 2007; John and Anandjiwala, 2008). It must be noted, however, that in the production and study of NFR composites, it must also be noted that these fibers are obtainable in varying forms, sizes and, consequently, mechanical performances. Abaca, for instance, are typically harvested as long fiber bundles of about 2 to 4 meters for technical grade fibers, which makes it ideal for producing ropes and large fishing nets; as a fiber reinforcement, it is currently used for the production of automobile parts, and is very suitable for fabricating long or continuous fiber-reinforced composites. On the other hand, bagasse can normally be obtained from sugarcane mills mainly as chopped fibers, which mostly limits their application to the fabrication of short fiber composites for boards and panels. And while long FRP composites offer better mechanical reinforcement, short FRP composites allow uniform stress distribution. Therefore, by combining long and short fibers, it may be possible to form a single composite which not only has the qualities of both abaca and bagasse FRP's, but also the characteristics of both long and short FRP's.

In this research, long abaca and chopped bagasse fibers are combined with unsaturated polyester resin (UP) to produce a hybrid FRP composite. The mechanical performance of such hybrid composite is expected to be intermediate between long and short FRP composites, and the objective of this study is to determine the strong dependence of mechanical strength on the fiber loading: fiber type and processing, concentration and orientation or arrangement.

MATERIALS AND METHODS

Materials

Ortho-type unsaturated polyester (Rigolac, Showa Highpolymer Co., Ltd., Japan) was used in the experiments as the polymer matrix, with methyl ethyl ketone peroxide (MEKP, NOF Corporation, Japan) as curing agent and cobalt naphthenate (Cobalt N, Wako Pure Chemical Industries, Japan) as accelerator. The applied mixing ratio for the matrix-curing agent-accelerator polymer solution was 100:1:0.5 by weight. The chopped bagasse fibers were procured from Okinawa, Japan and the raw, abaca fibers were obtained from the Philippines.

Methods

The dried abaca- cut 20 cm. long- and chopped bagasse fibers (Figure 1) were both immersed in aqueous 5 mass% NaOH solutions at 80°C for approximately 9 hours, and then allowed to cool down to room temperature before neutralizing with 5 mass% aqueous HCl solution, and washing with running water. The unidirectional fiber sheets and random fiber mats were pressed at 10 MPa and 50°C for 5 hours. After compression, the fiber sheets and mats were air dried to remove any excess moisture and then kept dry in an oven set at a temperature of 50°C.

The FRP sample sheets were prepared using the hand lay-up method, adding the matrix to the 2-mm thick sheet mold little by little to ensure that each fiber sheet/mat gets completely wetted by the resin. The lamination was attained using a hot press at 50°C and 40 MPa for 2 hours. For the hybrid FRP samples, the abaca fiber sheets and bagasse fiber mats are stacked at different fiber content and

Table 1. Mechanical Properties of Some Natural Fibers.

Fiber	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Density (g/cm^3)
Abaca	792	26.6	3-10	1.5
Bagasse	290	17	-	1.25
Cotton	287-597	5.5-12.6	7-8	1.5-1.6
Flax	345-1035	27.6	2.7-3.2	1.5
Hemp	690	70	1.6	1.48
Jute	393-773	26.5	1.5-1.8	1.3
Ramie	50	24.5	2.5	1.5
Sisal	511-635	9.4-22	2.0-2.5	1.5

orientation. The effect of fiber fraction was observed by preparing the hybrid FRP samples in varying bagasse fiber mat content.

The resulting FRP laminates were cut into test sample sizes and subjected to appropriate ASTM methods for measuring flexural and tensile properties: the three-point bending tests (ASTM D790M) were done using Shimadzu Autograph AGS-J-1kN Universal Testing Machine, while the tensile tests were done using Shimadzu Autograph DCS-R5000 Universal Testing Machine. Also, surface characterization to study the effects of alkali fiber treatment, as well as the fracture surface after conducting strength tests, was done by scanning electron microscopy using SEM (JEOL JSM-5310LV Scanning Microscope).

RESULTS AND DISCUSSION

Alkali treatment shows significant effect on the strengths and moduli of both types of green composite, although the change in flexural performance appears to be on the negative for the abaca FRP. It has already been reported that alkali treatment is considered as a good technique for overcoming the shortcomings of natural fiber-reinforced composites, such as high moisture absorption and poor fiber-matrix adhesion. Essentially, alkaline treatment has two main effects on the fiber: (1) an increase in surface roughness, resulting in better mechanical interlocking, and (2) an increase in the amount of cellulose exposed on the fiber surface, thereby increasing the number of possible reaction sites (Li, Tabil and Panigrahi, 2007).

This mercerization process reduces the number of hydrophilic hydroxyl groups in the cellulose fibrils, making them more thermodynamically compatible with the more hydrophobic polymer and thereby improving fiber-matrix interfacial adhesion (Bledzki and Gassan, 1999). The activation reaction of the hydroxyl groups of treated cellulose may be represented by the general reaction

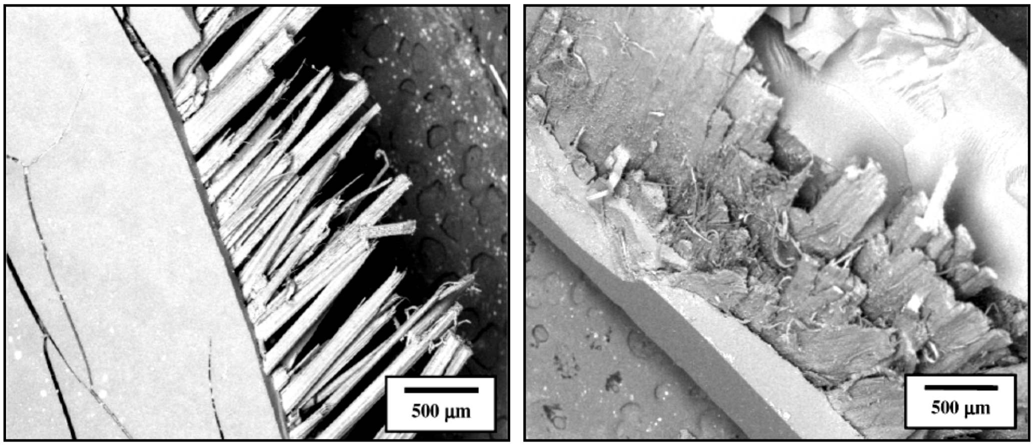
$$\text{Fiber–OH} + \text{NaOH} \rightarrow \text{Fiber–O}^{-}\,\text{Na}^{+} + H_2O \qquad (1)$$

The length of treatment period bears a significant effect on the composite performance. This depends on the type and form of fiber: for example, in the alkali treatment of chopped bagasse and continuous abaca fibers, the treatment period is approximately 9 hours in order to achieve optimum composite performance (Tumolva, Kubouchi and Sakai, 2009).

Figure 2 illustrates the effect of alkali treatment on the fiber-matrix adhesion of NFR composites in terms of fiber pull-out. The micrographs show the length of abaca fibers protruding from the fracture surface, which indicates the degree of strength of interfacial adhesion between the polymer and the fiber. Based on the SEM study, it can be concluded that the alkali-treated natural fibers have better compatibility with the resin compared with the untreated fibers.

(a) (b)

Figure 1. Chopped bagasse (a) and abaca bundles (b) were alkali-treated and pressed into fiber sheets, which will be laminated later to fabricate hybrid NFRP samples.



(a) (b)

Figure 2. SEM micrographs (at x35) of the fiber fracture of (a) untreated and (b) treated abaca FRP.

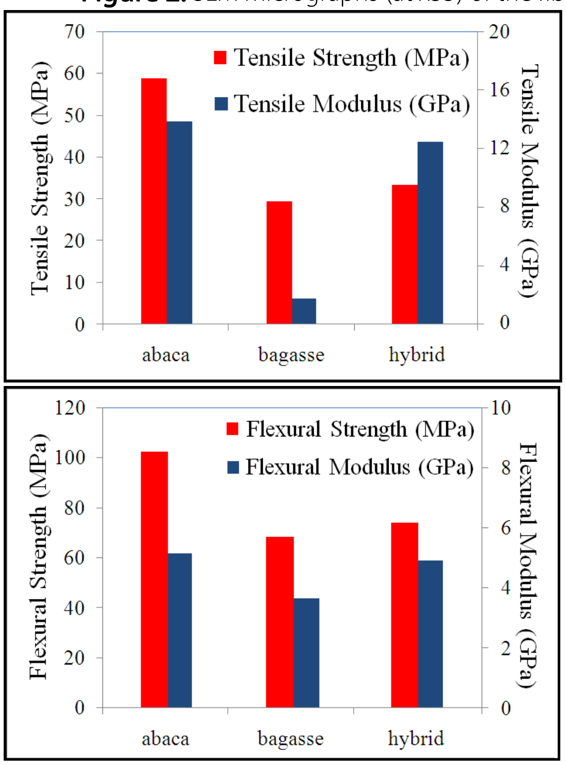


Figure 4. Mechanical Strengths and Moduli of Abaca, Bagasse and Abaca/Bagasse Composites.

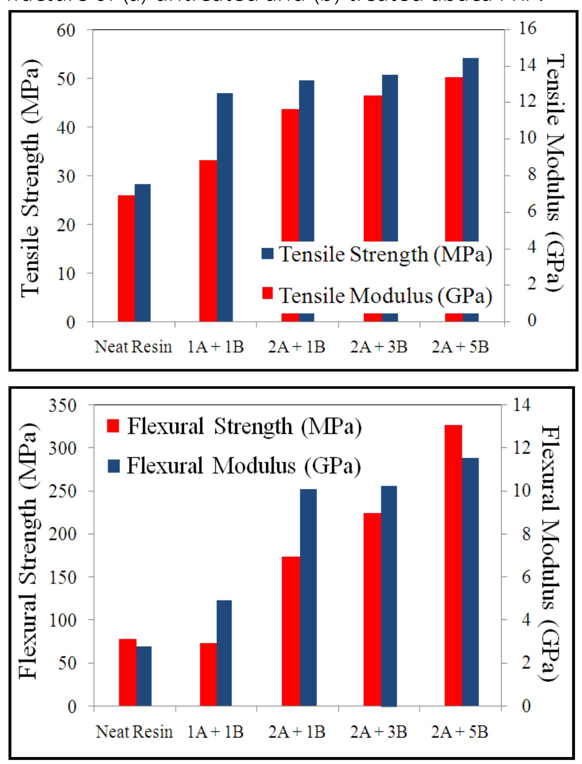
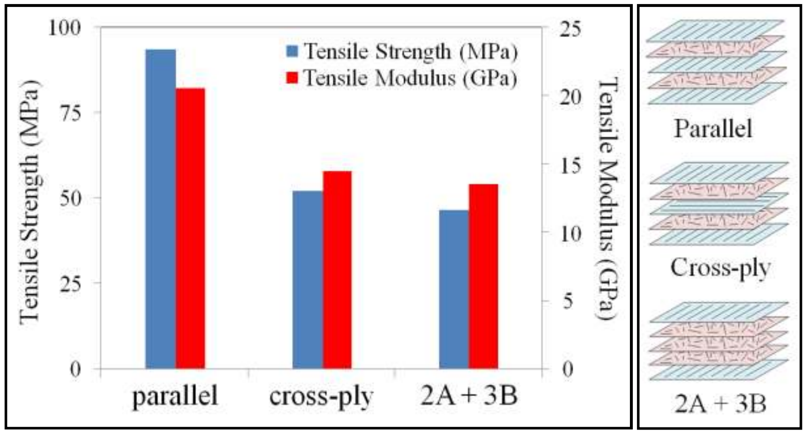


Figure 5. Mechanical Properties of Abaca / Bagasse Hybrid Composites at Different Fiber Fractions.

The SEM analysis of fiber pull-out has also been done on the short bagasse FRP's, but the micrographs do not provide a clear illustration of the effect of fiber treatment, unlike that of the long abaca FRP's. However, its effect on the mechanical properties of both abaca- and bagasse-reinforced composites is still exemplified in Figure 3. Alkali treatment is shown to have significant overall improving effects on the strengths and moduli for both types of green composite. Each prepared NFRP sample has been contains a single fiber sheet, which has been fabricated manually that may have resulted to some irregularities in fiber distribution. These have resulted to some scattering errors in strength measurements, and may be avoided next time by increasing the fiber sheets per FRP.

Aside from the interface strength, the transfer mechanism at which the applied stress is carried over from the polymer matrix to the fiber reinforcement is completely dependent on the fiber



2A + 3B FRP.

Figure 6. Tensile Properties of 3A + 2B Abaca/Bagasse FRP at Parallel and 90° Cross-ply Orientations, in Comparison with Those of The 2A + 3B Abaca/Bagasse FRP

length and orientation. Figure 4 shows a comparison of the mechanical strengths between of the abaca FRP, bagasse FRP, and an abaca/bagasse hybrid FRP reinforced of the same total fiber weight content. The measurement indicates that most of the load support is still supplied by the abaca fibers, whose content has been approximately halved in the single hybrid fiber mat. Therefore, the abaca fiber sheets can provide good reinforcement when applied to NFR composites made with of bagasse fiber mats, whose number may still be increased for further improvements.

The mechanical strengths and moduli of abaca/bagasse hybrid composites at different fiber weight content fiber sheet orientation are shown in Figure 5. The effect of fiber fraction is determined by increasing the bagasse fiber mats sandwiched between two abaca fiber sheets, which are placed at both ends of the fiber stack for additional strength; as expected, the increase in bagasse increases the strength of the composite since the mechanical properties of FRP laminates varies linearly with the volume fraction of the fiber (Thomason and Vlug, 1996). However, it must be noted that if the fiber fraction is too high, the mechanical strength also tend to decrease due to the increased occurrence of void spaces within the vicinity of the fiber-matrix interface.

The effect of orientation is illustrated in Figure 6, which shows a comparison between two NFR hybrid composites reinforced with 3 abaca sheets and 2 bagasse mats sandwiched in-between. Though the results show that the tensile strength for the 90° cross-ply orientation is lower than that of the parallel orientation, it has been previously established that cross-ply fiber sheet lamination allows for better load support along both axial and transverse directions. Therefore, for biaxial loading, cross-ply orientation would be a more suitable type. In any case, however, both 3A + 2B laminates would still yield a higher strength compared to the

CONCLUSIONS AND RECOMMENDATIONS

Alkali treatment is proven effective in improving the performance of hybrid green composites; however, other available chemical treatment methods can be applied in the future that would provide better results. For bagasse FRP, adding abaca fiber reinforcements produces a hybrid green composite that has a better mechanical performance, particularly when they are prepared at higher fiber fractions and at cross-ply orientations. Finding the limit of increase in fiber fraction is crucial not just for determining the critical fiber weight content which gives the highest mechanical strength, but also for establishing the extent of which these renewable materials may be utilized for long-term carbon fixation. Finally, additional testing must be done in the future in order to establish other pertinent NFRP properties such as moisture absorption and thermal properties.

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