A Review on the Tensile Properties of Bamboo Fiber Reinforced Polymer Composites

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This paper reviews the tensile properties of bamboo fiber reinforced polymer composites (BFRP). Environmentally friendly bamboo fibers have good mechanical properties, which make them suitable replacements for conventional fibers, such as glass and carbon, in composite materials. Better fiber and matrix interaction results in good interfacial adhesion between fiber/matrix and fewer voids in the composite. Several important factors improve matrix-fiber bonding and enhance the tensile properties of BFRP. Coupling agents, such as maleic anhydride polypropylene (MAPP), improve the adhesion of bamboo fibers in the polypropylene (PP) matrix. A high percentage of lignin content in bamboo fibers limits fiber separation, which leads to less matrix absorption between fibers. Steam explosion is the best extraction method for bamboo fibers, although an additional mechanically rubbing process is required for fiber separation. Generally, high fiber content results in good composite performance, but at a certain limit, the matrix does not adhere well with a saturated amount of fibers, and the composite tensile strength decreases. However, the tensile modulus of BFRP is not affected by excess fiber content. Hybridization of bamboo with conventional fibers increases the tensile strength of BFRP. The addition of micro/nano-sized bamboo fibrils into the carbon fabric composites slightly enhances composite strength.

Keywords: Bamboo fibers; Polymer composites; Tensile properties; Maleic Anhydride Polypropylene

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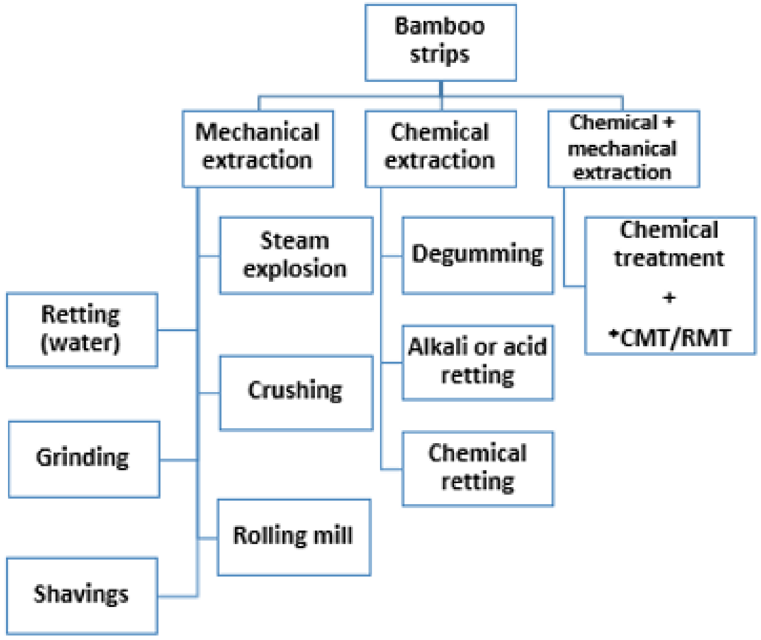
INTRODUCTION

A composite material is a material consisting of two or more constituents with different natures and complimentary features, resulting in a new material having unique and outstanding properties compared with its original constituents. Two basic constituents of a composite material are matrix and reinforcements, which are essentially insoluble to each other. The matrix acts as a binder to the reinforcement that encloses the composite material, while the reinforcements provide the shape and internal structure (Groover 2010; Campbell 2010). Composite materials can be classified based on the type of matrix, which are polymer matrix composite (PMC), metal matrix composite (MMC), and ceramic matrix composite (CMC). The strength and stiffness of polymers, metals, and ceramics are low, medium, and high, respectively. Metal matrixes have ductile properties, while ceramics are brittle. During the last few decades, the consumption of polymers has increased in many fields. There are two classes of polymers, thermoplastics and thermosets (Materials and Campbell 2010). Polypropylene (PP), polyethylene, and poly vinyl chloride (PVC) are commonly used thermoplastics; thermosets include epoxy, polyester resins, and phenolics (Malkapuram *et al.* 2009). The wide use of synthetic fibers in daily applications, however, has negative effects on the environment.

As synthetic fibers are non-degradable, emit poisonous gases to the air, especially when burned, and are expensive, natural fibers such as kenaf, flax, hemp, and sisal have gained attention as replacements for synthetic fibers in composites (Soutis 2005; Faruk *et al.* 2012; Sanjay *et al.* 2015). They possess fairly good mechanical properties and a long-term continuous supply, and they are low cost, biodegradable, and eco-friendly. These natural composites have potential in the aerospace, automotive, construction, and sport industries (Bledzki *et al.* 2006; Holbery and Houston 2006; Davoodi *et al.* 2011).

Bamboo is a natural fiber that exhibits comparable mechanical properties to conventional fibers (Mahdavi *et al.* 2012). Bamboo is one of the fastest-growing plants in the world, growing at a rate of 3 cm per hour (Lobovikov *et al.* 2007). In Malaysia, bamboo is abundant throughout the country. Bamboo is utilized traditionally in low-cost houses, bridges, and construction platforms (Bahari and Krause 2015). Bamboo in natural composites has been used widely in various applications, such as the interiors of vehicles and aircrafts, bicyclist helmets, and decks for leisure activities (Nabi Saheb and Jog 1999; Tanaka *et al.* 2007; Abdul Khalil *et al.* 2012; Mahdavi *et al*. 2012; Qiu *et al.* 2013; Ibrahim *et al.* 2015). Many factors influence the performance of bamboo fiber reinforced polymer composites (BFRP) (Okubo *et al.* 2004; Liu *et al.* 2012). The naturally high lignin content of bamboo fibers considerably reduces the effectiveness of resin impregnation into the fibers. Therefore, suitable extraction methods are needed to ensure that the maximum amount of lignin is removed from the fibers (Okubo *et al.* 2004; Malkapuram *et al*. 2009; Yueping *et al*. 2010; Shi *et al.* 2012; Zakikhani *et al.* 2014).



*CMT = compression moulding technique; RMT = roller mill technique

Fig. 1. Methods of extraction for bamboo fibers (modified from Zakikhani *et al.* 2014)

Several methods of extraction have been reported (Fig. 1). Different fiber content, different fabrication methods, and the addition of coupling agents during fabrication also influence the properties of BFRP (Abdul Khalil *et al*. 2012; Liu *et al*. 2012; Suhaily *et al.* 2013). This review examines the effect of fiber loading, fiber size, fiber extraction method, chemical treatments, inclusion of coupling agent, and process parameters on the tensile properties of BFRP.

BAMBOO TREE

There are more than 1000 species of bamboo found worldwide, and many new species are recorded every day (Liese and Grosser 1971; Londoño *et al.* 2002; Lobovikov *et al.* 2007; Soreng *et al*. 2015). In Malaysia, the four most common bamboo species are *Bambusa vulgaris*, *Gigantochloa scortechinii*, *Dendrocalamus asper*, and *Schizostachyum brachycladum* (Forest Research Institute Malaysia 2013).

Bamboo varieties range from tropical woody bamboo to herbaceous bamboo, and they contain monopodial and sympodial rhizomes. Malaysia grows sympodial bamboo, while monopodial bamboo is famous in China and Taiwan (Jain *et al.* 1992; Lobovikov *et al.* 2007; Gratani *et al.* 2008; Soreng *et al*. 2015). Various reports state that bamboo can grow 11 to 21 cm per day or up to 2 inches per hour, which is approximately 122 cm per day (Farrely 1984; Guinness 2014). Depending on the species, bamboo can attain maturity in 3 years, but most mature in 4 to 6 years (Sealy 2006; Lobovikov *et al.* 2007; Gratani *et al.* 2008). However, bamboo stops growing in terms of height around 6 to 7 months after the shoot emerges. The shoot grows vertically to form a culm in the shape of a hollow cylinder with several dividers called diaphragms from inside the culm and nodes from the outside. The culms between two nodes are called internodes (Nogata and Takahashi 1995; Londoño *et al.* 2002; Tanaka *et al*. 2014). The length of internodes and some other physical characteristics, such as wall thickness, culm diameter, and moisture contents, are varied through the length of culms and among species. For certain species, these characteristics are almost constant along the length of the culm (Chung and Yu 2002).

Table 1. Bamboo Regions

Bamboo Region	Countries
1. Asia-Pacific	China, India, Burma, Thailand, Bangladesh, Cambodia, Vietnam, Japan, Indonesia, Malaysia, Philippines, Korea, and Sri Lanka
2. America (Latin America, South America, and North America)	Mexico, Guatemala, Costa Rica, Nicaragua, Honduras, Columbia, Venezuela, and Brazil
3. Africa	Mozambique and Eastern Sudan
4. Europe	England, France, Germany, Italy, Belgium, Holland, United States, and Canada have introduced a large number of bamboo species from Asian and Latin American bamboo-producing countries

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The bamboo fibers are aligned longitudinal to the length of culm, which makes its strength comparable to a mild steel (steel containing a small percentage of carbon, strong and tough but not readily tempered) when it attains maturity (Shin *et al.* 1989; Okubo *et* *al*. 2004). Bamboo has been used as the main material for structural applications, such as long houses, scaffoldings, and suspension bridges. Its fast-growing ability and comparable strength to conventional material makes bamboo a sustainable alternative for future material industries (Riaño *et al.* 2002; Okubo *et al.* 2004; Lobovikov *et al.* 2007; Suhaily *et al*. 2013). Furthermore, the natural root system of bamboo holds the soil and prevents erosion. This wide and strong root system helps reduce landslides and soil erosion (Lobovikov *et al.* 2007). Bamboo can be found in a wide region between approximately 46° north and 47° south latitude on almost every continent (Table 1; Riaño *et al*. 2002). Although bamboo grows in many countries, it is most abundant in Asia and South America. However, bamboo has not been fully utilized especially in Asian countries due to the limited information about its strength and industrially potential values (Shin *et al*. 1989; Okubo *et al*. 2004; Lobovikov *et al.* 2007; Gratani *et al*. 2008; Phong *et al*. 2013).

BAMBOO FIBER

The strength of bamboo culm is made up from numerous bamboo fibers aligned longitudinally along its length. Bamboo fibers form bundles, which are components of vascular bundles dispersed within the diameter of the culm. Several studies on the microstructure of bamboo culms identified that there are certain trends in the distribution of vascular bundles within the diameter and along the length of the culm. The size of vascular bundles is smaller at the outer section, near the epidermis of the culm and bigger at the middle, near the hollow part. The concentration of vascular bundles increases from the middle to the outer part of the culm. Vertically, the size of vascular bundles decreases from the bottom to the top with increasing percentage of fiber bundles. However, ageing does not affect the percentage of fibers significantly (Liese and Grosser 1971; Londoño *et al*. 2002; Habibi and Lu 2014).

All lignocellulosic natural fibers can be considered as composites, as they consist of cellulose microfibrils in an amorphous matrix of lignin and hemicellulose. Bamboo fibers have a considerably high percentage of lignin compared with other natural fibers (Table 2), resulting in its high strength. Stronger fibers form stronger culm structures. However, excess lignin hinders the extraction process, meaning the separation of individual fibres. Lignin remaining on the fiber surface after extraction creates strong but brittle fibers (Okubo *et al*. 2004; Malkapuram *et al*. 2009; Shi *et al*. 2012; Zakikhani *et al*. 2014).

Table 2. Composition of Several Natural Fibers

Types of Fiber	Cellulose (%)	Lignin (%)	Others (%)
Bamboo	60.8	32.2	7
Coir	36 to 43	41 to 45	13 to 24
Banana	63 to 68	5	19
Sisal	67 to 78	8 to 11	22 to 26
Jute	61 to 72	12 to 13	14 to 21
Hemp	70 to 74	4 to 6	19 to 24
Kenaf	31 to 39	15 to 19	21.5
Flax	71	2.2	22 to 25
Ramie	69 to 76	0.6 to 0.7	15 to 19

Note: Data from Okubo *et al*. 2004 and Malkapuram *et al*. 2009

Several extraction methods produce different forms of bamboo fibers. Generally, bamboo fibers can be extracted mechanically or chemically or by the combination of both methods. Figure 1 illustrates several extraction methods that are applied to bamboo culms, which are split into strips before extraction (Zakikhani *et al*. 2014). Different methods vary the quality of fibers especially in strength. Tensile testing of single bamboo fiber, according to ASTM D3379 (1989), indicates that steam explosion is the best method of extraction in terms of producing high strength bamboo fiber (Materials 2000). Table 3 shows the mechanical and physical properties of bamboo fibers extracted by different methods.

Table 3. Mechanical and Physical Properties of Bamboo Fibers based on Extraction Procedures

Extraction Procedure	Tensile Strength (MPa)	Young's Modulus (GPa)	Fiber Length (mm)	Fiber Diameter (μm)	Density (g/cm^3)
Mechanical					
Steam explosion	516	17	-	-	-
Steam explosion	441 ± 220	36 ± 13	-	15 to 210	-
Steam explosion	383	28	-	-	-
Steam explosion	441	35.9	-	0.8 to 125	-
Steam explosion	615 to 862	35.45	-	-	-
Steam explosion	308 ± 185	25.7 ± 14.0	-	195 ± 150	-
Rolling mill	270	-	220 to 270	100 to 600	-
Grinding	450 to 800	18 to 30	-	-	1.4
Retting	503	35.91	-	-	0.91
Crushing	420 ± 170	38.2 ± 16	-	262 ± 160	-
Chemical					
Chemical	341	19.67	-	-	0.89
Chemical	450	18	10	270	1.3
Chemical	329	22	-	-	-
Alkaline	419	30	-	-	-
Alkaline	395 ± 155	26.1 ± 14.5	-	230 ± 180	-
Combined mechanical and chemical					
Chemical + Compression	645 Max: 1000	-	> 10	50 to 400 HC: 150 to 250	0.8 to 0.9
Chemical + Roller mill	370 Max: 480	-	120 to 170	HC: 50 to 100	-

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Table 3 shows that bamboo fiber has the lowest tensile strength of 270 MPa after the rolling mill method. However, several other methods produce fibers of considerably high tensile strength. Table 4 compares the tensile properties of steam-exploded bamboo fibers, which exhibit the highest tensile strength, with other natural fibers. The strength of bamboo fiber is slightly lower than kenaf, ramie, and flax. However, the range of 615 to 862 MPa recorded by bamboo fibers is considered high compared with others. Many parameters need to be considered to make a clear comparison between natural fibers. The data depicted from different research activities as shown in Table 4 might be slightly unacceptable, but a rough comparison still can be made to give overall values about the selected fibers. Different parameters from different research activities such as type of chemical used, controlled temperature for drying process, length of single fibers selected for the tensile testing, and density of single fibers could affect the data recorded.

In addition, all natural fibers, including bamboo fibers, have many significant differences in microstructures although they come from the same species as their growth cannot fully be controlled. Different from man-made fibers, which the production is properly observed and standardized, the quality of natural fibers depends on the growth of their plants and trees. Significant differences in microstructure will influence the fibers' strength, thus affect their application in composites.

Table 4. Tensile Properties of Several Natural Fibers

Fibre	Tensile Strength (MPa)	Young's Modulus (GPa)	Density (g/cm^3)	References
Bamboo (steam explosion)	615 to 862	35.45	-	(Zakikhani *et al.* 2014)
Jute	393 to 773	26.5	1.3	(Ku *et al.* 2011)
Flax	500 to 1500	27.6	1.5	(Ku *et al.* 2011)
Hemp	690	70	1.47	(Ku *et al.* 2011)
Kenaf	930	53	1.45	(Ku *et al.* 2011)
Ramie	400 to 938	61.4 to 128	-	(Ku *et al.* 2011)
Sisal	511 to 635	9.4 to 22	1.5	(Ku *et al.* 2011)
Coir	593	4.0 to 6.0	1.2	(Ku *et al.* 2011)

BAMBOO FIBER REINFORCED POLYMER COMPOSITES (BFRP)

The high strength to weight ratio of bamboo has attracted researchers' attention to maximize its potential in composites. BFRP is an eco-composite that is lightweight, environmental friendly, and has comparable strength to conventional materials (Abdul Khalil *et al*. 2012). Today, some bamboo-based composites, such as ply bamboo and bamboo medium density fiberboard (MDF), are widely used in daily lives (Sen and Reddy 2011; Mahdavi *et al*. 2012; Suhaily *et al*. 2013). In bamboo composite fabrication, several factors affect the properties of the end products, and the three main factors that need to be clearly addressed to differentiate bamboo composites are types of fibers, types of matrices, and method of fabrication. These three factors are inter-related to each other in producing good properties of bamboo composites.

Generally, the tensile strength of bamboo fibers themselves has a stochastic nature, with considerable variability in strength. Stochastic nature is a randomly determined properties of material which can be analyzed statistically but may not be predicted precisely. Having stochastic nature in bamboo fibers will significantly influence the mechanical properties of the composites as the strength of the reinforcements varies (Xue and Fang 2016).

Woven bamboo mat is easy to handle and has good strength properties. Although there is no recorded data on the tensile strength of woven bamboo mat, there are similarities with woven glass fibers; woven type glass fiber is stronger than chopped strand and single short glass fiber. In a recent study (Samanta *et al.* 2015), bamboo mat from *Bambusa tulda* was combined with plain woven E-glass fiber to transform it into a hybrid composite and bound with epoxy resin as the matrix. A hand lay-up method was applied to prepare the composite sample. As bamboo mat is a type of natural fiber, it was dried in sunlight before fabrication to eliminate moisture that reduces resin absorption.

Bamboo strip is a strong type of fiber because numerous fiber bundles are still tied together in the natural matrix of lignin. The unidirectional alignment of fibers within the bamboo strips eases the process of composite fabrication. Bamboo strips were impregnated with epoxy matrix before being placed in unidirectional alignment in the mold of hot press. After hot pressing was applied on the sample, a post curing step was carried out for 12 h at 40 °C (Hebel *et al*. 2014). However, this type of fiber limits the design of the composites because bamboo strips cannot deform or bend easily to fix certain designs of the composite mold.

Fibers extracted by steam explosion are high quality, as the maximum amount of lignin is detached from the fiber surface, resulting in better interfacial adhesion between fibers and matrix. Single long bamboo fibers were scattered between two layers of thin MAPP/PP matrix, and hot pressing was applied to prepare the composite samples. Physically, fiber bundles have some similarities with steam-exploded fibers. Therefore, any methods applied in the fabrication of composites from fiber bundles can also be applied to steam exploded fibers (Okubo *et al*. 2004).

Bamboo powder can easily be obtained from the bamboo culm through several machining steps. However, bamboo powder needs extra care during composite fabrication, especially during matrix addition, to ensure the powders are evenly distributed. Although it possesses a very low strength, its inclusion into the matrix could enhance the mechanical properties compared to the pure matrix sample. In a previous study, bamboo powder was mixed with glass fibers sized 3 and 6 mm to improve the strength of the composites (Thwe and Liao 2002). Both fibers were dried to completely remove the moisture before being melt mixed using a torque rheometer together with the PP matrix. The mixture was then poured homogenously in a stainless steel mold, and a hot press was applied to the mold. To fabricate composites from bamboo powder, the use of a mold is compulsory, which is the limitation for this type of fiber.

Table 5. Properties of Typical Thermoplastic Polymers used in Bamboo Fiber Composite Fabrication

Property	Polypropylene (PP)	Polyvinyl Chloride (PVC)	Polylactic Acid (PLA)	Polystyrene (PS)	High-density Polyethylene (HDPE)
Density (g/cm^3)	0.899 to 0.920	1.42 to 1.81	1.26	10.4 to 10.6	0.94 to 0.96
Tensile strength (MPa)	26.0 to 41.4	14 to 52	25 to 30	25 to 69	14.5 to 38.0
Elongation (%)	15 to 700	20 to 40	1.8	1.0 to 2.5	2.0 to 130
Young's modulus (GPa)	0.95 to 1.77	1.12 to 3.66	2.34	4 to 5	0.4 to 1.5
References	(Holbery and Houston 2006)	(MatWeb 2015)	(Facca *et al.* 2007)	(Holbery and Houston 2006)	(Holbery and Houston 2006)

Table 6. Properties of Typical Thermoset Polymers used in Bamboo Fiber Composite Fabrication

Property	Epoxy	Polyester	Elastomer (natural rubber)
Density (g/cm^3)	1.1 to 1.4	1.2 to 1.5	0.91 to 0.93
Tensile strength (MPa)	35 to 100	30.9	20 to 30
Elongation (%)	1 to 6	2	750 to 850
Young's modulus (GPa)	3 to 6	3.1	0.001 to 0.005
References	(Holbery and Houston 2006)	(Holbery and Houston 2006; Gere 2008)	(MATBASE 2015)

Different types of bamboo fibers can be used as reinforcements in composites. Woven bamboo mat, bamboo strips, and long and short bamboo fibers have been used by researchers in different studies. The types of fibers determine the methods of composite fabrication. The types of matrices also influence the choice of fabrication method. Tables 5 and 6 illustrate the properties of polymer matrix used in BFRP by previous researchers.

TENSILE PROPERTIES

The ability of a material to sustain load until it breaks when a pulling force is applied is known as tensile strength. Tensile strength can be measured using a universal tensile machine (UTM) (ASTM 638 2003; ASTM D3039 2008; Gere and Goodno 2008). Load or tensile stress is applied in the form of pulling force to the materials. Based on stress-strain characteristics from the tensile testing, materials can be classified as either being ductile or brittle. A ductile material, such as mild steel, endures a large strain before it ruptures. In design application, these kinds of materials exhibit large deformations when overloaded before failing. Compared with ductile material, a brittle material exhibits little or no yielding before failure. Most composites are classified as brittle materials. However, most materials can be brittle and ductile depending on their mixtures. For example, steel with high or low carbon content exhibits brittle and it or ductile behavior, respectively.

Stress-strain diagrams of tested materials contain two important pieces of information. The highest peak within the linear region indicates the tensile strength, while the ratio of stress over strain from the same region represents the Young's modulus or modulus of elasticity (E). Young's modulus or tensile modulus (E) measures the resistance of materials to elastic deformation. Stiffer materials have higher E values, which is better because they have less tendency to deform along an axis when opposing forces are applied (Gere and Goodno 2008).

Fiber Loading

By combining the tensile strength of bamboo fibers in Table 3 with the tensile strength of polymer matrices in Tables 4 and 5, the tensile strength of their composites can be considered (Facca *et al.* 2007). Generally, higher fiber content results in better tensile properties in composites, as fibers have higher tensile strength than matrices (Tables 3 through 5). However, at a certain point, the matrices cannot bind all the fibers completely. Therefore, the effect of fiber content on composite tensile strength has been studied (Ismail *et al.* 2002; Facca *et al.* 2007).

Short bamboo fiber from a species of *Bambusa paravariabilis* was ground to a size range of 180 to 270 µm and mixed in rubber compounding to produce bamboo fiber reinforced natural rubber composites (BFRNR) using the two roll mill machine (ASTM D3184-80 2001). Different fiber loadings were used for every sample to study its effect on the tensile strength and tensile modulus of BFRNR. The tensile tests conducted in accordance with ASTM D412 (2006) showed that the tensile strength of BFRNR decreased when the fiber loading increased (Fig. 2).

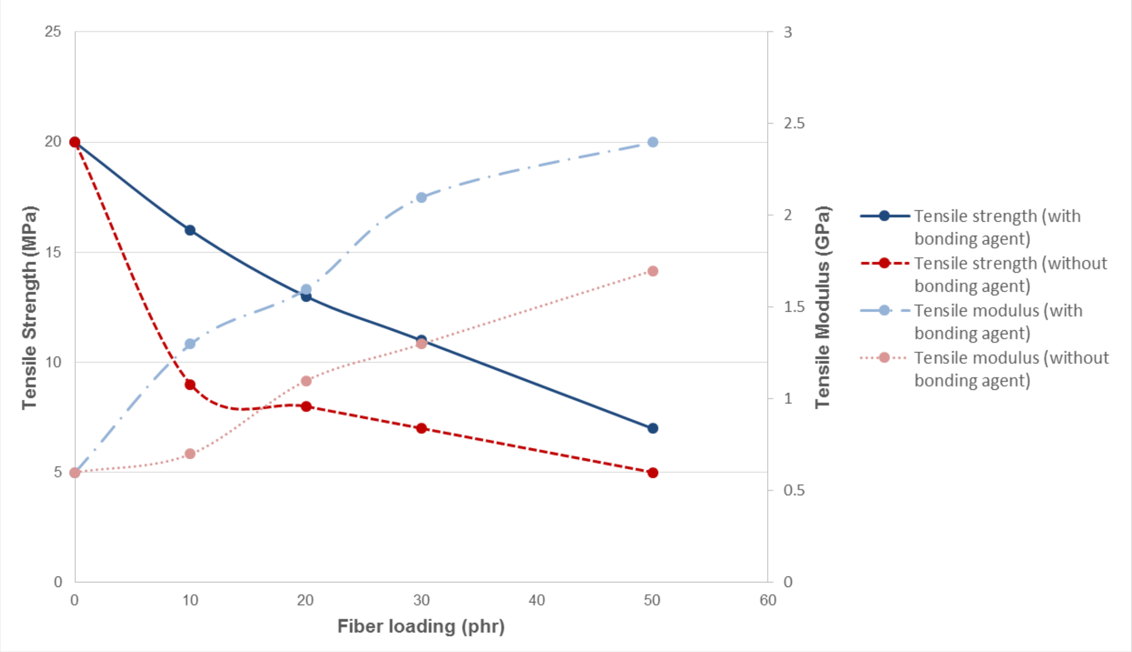

Fig. 2. Tensile strength and tensile modulus of bamboo fiber reinforced natural rubber (BFRNR) with and without phenol formaldehyde with varying fiber loading. Figure redrawn from Ismail *et al*. (2002).

The inability of the irregularly shaped bamboo fibers to support the stresses transferred from the polymer matrix led to the loss of composite strength. Furthermore, the decreased strength of BFRNR was influenced by the natural hydrophilic property of bamboo fibers, which cannot adhere well with hydrophobic natural rubber. The scanning electron microscopy (SEM) image of the fractured surface is one of the best ways to explain the interfacial adhesion between the fibers and matrix, which the author (Ismail *et al*. 2002) reported in his studies. In contrast to tensile strength, the tensile modulus of BFRNR composites increased with increased filler loading (Fig. 2). Thus, the inclusion of bamboo fiber into the rubber matrix enhanced the stiffness of the composites (Ismail *et al*. 2002).

The dependence of strength on fiber content was also studied by Thwe and Liao (2002), who found that increasing the percentage of bamboo fiber in bamboo fiber reinforced polypropylene (BFRP) only slightly increased the tensile strength of the composites; further increasing the percentage had a negative effect on the tensile strength (Fig. 3). Increasing the percentage of bamboo fiber (by mass) from 10% to 20% and from 20% to 30% only increased the tensile strength less than 2 MPa for each 10% increment. At 40% (by mass) of fiber content, which is the largest percentage in this study, the tensile strength had dropped by 16% compared to the tensile strength of 10% (by mass) fiber content. Basically, high fiber content enhanced the tensile strength as more reinforcement could hold the load applied, but poor adhesion between the fiber and matrix reduced the tensile strength. Without proper handling during fabrication, higher fiber content could result in more, and probably larger, void formations in the composites, which then promote to micro crack formation under loading and reduce tensile strength.

Figure 3 shows that the tensile modulus of BFRP increased almost directly proportional to the fiber content. At 40% (by mass) bamboo fiber content, the tensile modulus increased by 60% compared to tensile modulus of 10% (by mass) bamboo fiber content in BFRP. Considering both trends of tensile strength and tensile modulus of BFRP, 30% was the optimum percentage of fiber content (by mass) for BFRP (Thwe and Liao 2002).

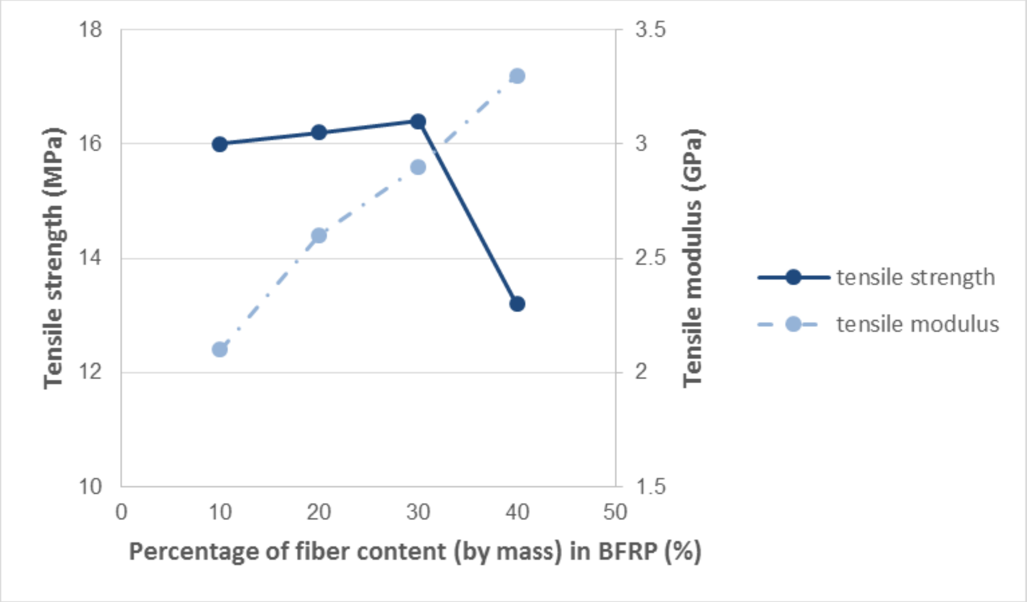

Fig. 3. Tensile strength and tensile modulus of bamboo fiber reinforced polypropylene with varying percentage of fiber content. Figure redrawn from Thwe and Liao (2002).

Takagi and Ichinara (2004) observed that despite the length of short bamboo fibers, the tensile strength of bamboo fiber reinforced green composites (BFGC) increased with increased fiber content from 10% to 50% percentage by mass. In this study, the tensile strength is increasing continuously from 10% to 50% fiber content without any decreasing value of strength.

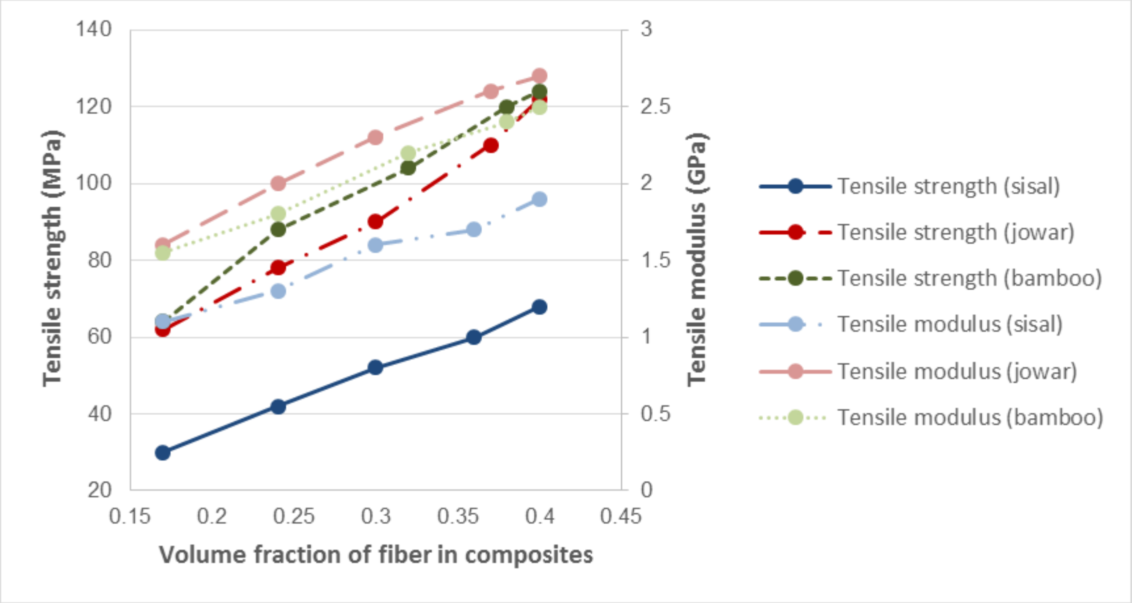

Fig. 4. Tensile strength and tensile modulus of various natural fibers reinforced polymer with varying volume fraction of fibers in composites. Figure redrawn from Prasad and Rao (2011).

Increasing the volume fraction of bamboo fibers in composites increased the tensile strength more than in sisal and jowar composites (Prasad and Rao 2011). Figure 4 shows that sisal, jowar, and bamboo composites showed increased tensile strength as the volume fraction of fibers increased. At maximum 0.4 volume fraction of fibers in composites, the ultimate tensile strength of bamboo is approximately 1.9 times to that of sisal composite. Similar to tensile strength, the tensile modulus of bamboo composites increased with the increased fiber volume fraction (Fig. 4). At 0.4 volume fraction, tensile modulus of bamboo composites increased by approximately 1 GPa compared to 0.15 volume fraction. However, at all volume fractions, the tensile modulus of bamboo composites was slightly lower than jowar composites but higher than sisal composites (Ratna Prasad and Mohana Rao 2011).

Hybrid Composite

Hybridizing bamboo fiber with glass fiber enhances the potential of bamboo fiber in polymer composites. The effect of bamboo to glass fiber ratio on the tensile properties of bamboo-glass reinforced polypropylene (BGRP) was studied by Thwe and Liao (2002). Based on the effect of fiber loading on the tensile properties of BFRP (Fig. 3), a sample of BFRP with 30% (by mass) bamboo fiber content was compared with hybrid BGRP. Two samples of BGRP with a fixed percentage ratio of fiber to a polypropylene (PP) matrix (30:70) were prepared. The BGRP samples had different ratios of glass to bamboo fibers (1:2 and 2:1). The bamboo fibers ranged from 1 to 6 mm, while the glass fibers were 3 mm. Inserting glass fiber into the BFRP to form BGRP increased the tensile strength (Fig. 5). The larger ratio of glass fiber to bamboo fiber resulted in higher tensile strength and tensile modulus. The better properties of BGRP were expected, as E-glass fiber has a higher tensile strength and tensile modulus than bamboo fiber. The tensile strength of bamboo fiber ranges between 150 and 810 MPa (Shihong *et al.* 1994), while E-glass fiber has a high value of 3450 GPa (Katz *et al.* 1987).

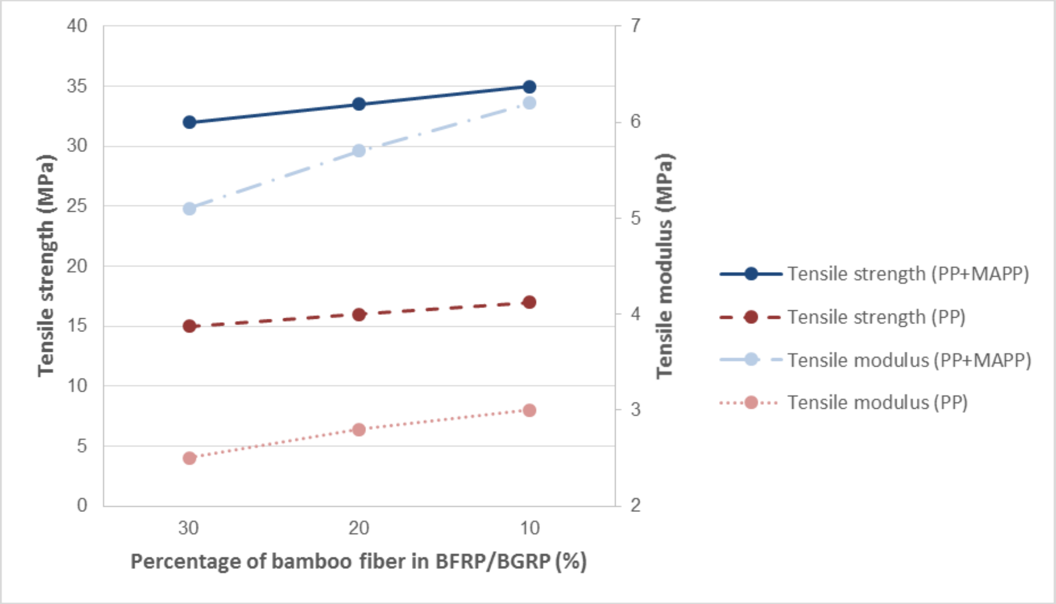

Fig. 5. Tensile strength and tensile modulus of hybrid bamboo-glass reinforced polymer with varying percentage of bamboo fiber in composites. Figure redrawn from Thwe and Liao (2002).

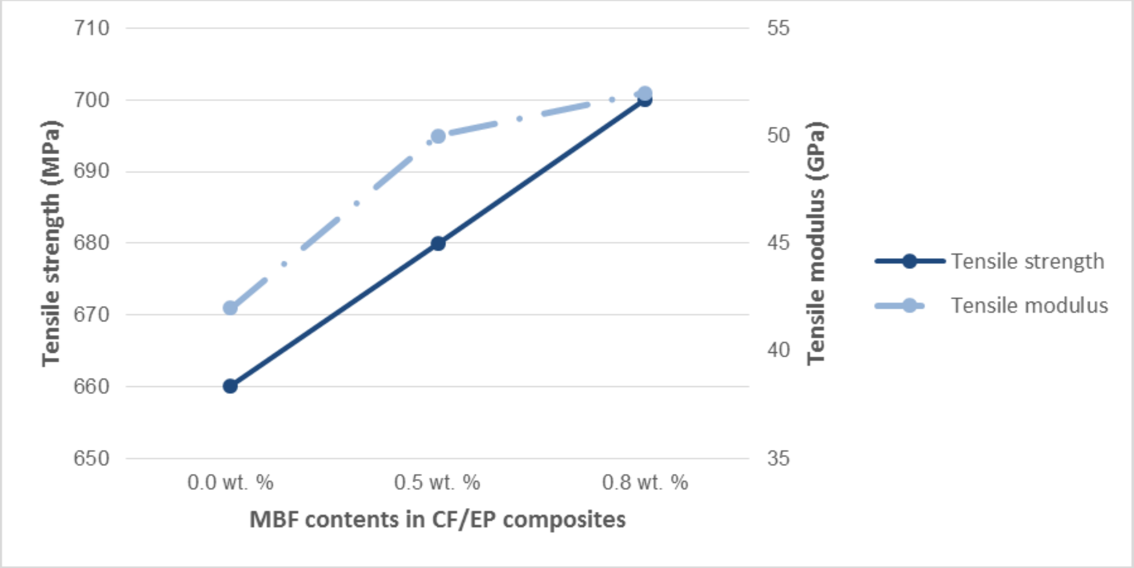

Fig. 6. Tensile strength and tensile modulus of carbon fiber/epoxy composites with varying contents of bamboo microfibrils (MBF) in hybrid composites. Figure redrawn from Phong *et al*. (2013).

Previous studies reported that micro/nano-sized bamboo fibrils (MBFs) have potential as mechanical performance enhancers in polymers and composites (Minelli *et al*. 2010; Suryanegara *et al*. 2011). Phong *et al*. (2013) compared the properties of carbon fabric composites made up of neat epoxy and modified epoxy with the inclusion of MBF. Three different CF/EP composites were prepared with various MBF contents (0.0 wt.%, 0.5 wt.%, and 0.8 wt.%). The carbon fiber volume fraction was fixed at 50 ± 2%, and modified aliphatic polyamines were used as the curing agent. The composites were prepared by hand lay-up with plain woven carbon fiber. The tensile strength of CF/EP composites had almost a constant value with only a slightly increase as the MBF content increased (Fig. 6). The Young's modulus of the modified composite showed a positive increasing value compared to the neat composite (Fig. 6). SEM analysis of the fractured surfaces showed extensive matrix deformation in the modified composite, suggesting that the addition of MBF did not strongly affect the tensile strength of the composites.

From different studies, bamboo fiber mat from *Bambusa tulda* and plain woven E-glass fiber were used for fabricating hybrid composites through the manual hand lay-up method (Samanta *et al*. 2015). Each sample was fixed to 4 laminas consisting of different ratios of bamboo fiber mat to woven E-glass fiber. All laminas were arranged in the same angle of fiber orientation to ensure the load was distributed at the same direction during the tensile testing. Epoxy resin, which acted as the matrix, was applied between the laminas. Five different samples were prepared (Table 7). Both bamboo and glass monolithic composites were also prepared to compare the effect of hybridization of both fibers to the non-hybrid composites. The tensile strength increased with the increasing ratio of glass fiber to bamboo fiber laminas (Fig. 7). With a starting value of 43.5 MPa marked by the pure bamboo composites (BB), the hybridization of one-layer glass fiber to three layers bamboo fibers (BG-1) increased the tensile strength to 72 MPa (65.7% increase). The tensile strength continued increasing to 119.5 MPa for the balanced BG-2 hybrid composite and marked the highest value of 190.0 MPa for the BG-3 hybrid composite. The tensile strength increased up to 340% compared with the bamboo pure composite. The highest tensile strength of the BG-3 hybrid composite reached 56% of 340.3 MPa, which is the tensile strength of the glass monolithic composite.

Similar to tensile strength, the tensile modulus of hybrid composites increased as the ratio of glass to bamboo fiber laminas increased (Fig. 7). The highest tensile modulus of the hybrid composite marked an impressive value of 15.57 GPa, which is 68% of the tensile modulus of the pure glass composites (22.84 GPa). The highest tensile modulus of the hybrid composite increased by 134.8% compared with the pure bamboo composite (6.63 GPa).

Table 7. Different Composite Samples with Varying Stacking Order of Laminas

Reinforcement Type and No. of Laminas		Lamina Arrangement	Composite Code Name	Type of Composite
Bamboo mat	Woven E-glass	1234		
4	0	BBBB	BB	Monolithic
3	1	BBBG	BG-1	Inter-ply hybrid
2	2	BBGG	BG-2	
1	3	BGGG	BG-3	
0	4	GGGG	GG	Monolithic

Note: Republished from Samanta *et al*. (2015)

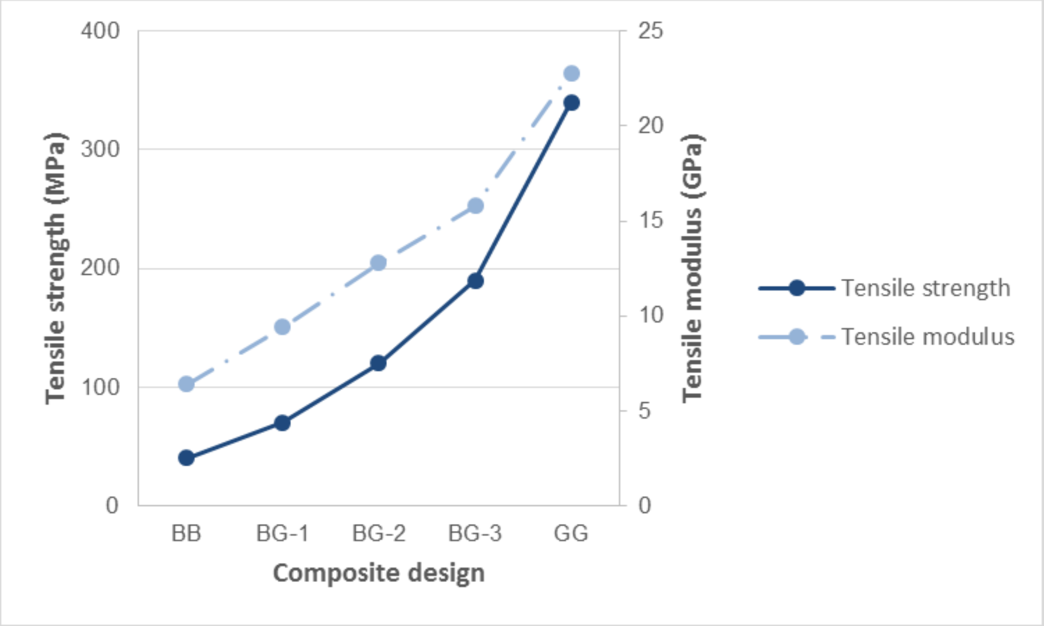

Fig. 7. Tensile strength and tensile modulus of hybrid bamboo/glass fiber reinforced polymer composites with varying ratio of glass to bamboo laminas. Figure redrawn from Samanta *et al*. (2015).

Fiber Pretreatment and Coupling Agent

Similar to other hydrophilic natural fibers, bamboo fiber shows poor interfacial adhesion with most matrices, which are generally hydrophobic. High hydroxyl groups in cellulose need to be modified to improve the compatibility between the fibers and matrix. Table 2 shows the chemical composition of bamboo fiber with unmodified hydroxyl groups.

To enhance the interfacial compatibility of natural fibers with the polymer matrix, hydrothermal pretreatment using hot water is one approach for dissolving hemicellulose, which offers a chemical-free alternative with minimum operational cost and a low potential for cellulose degradation. Moreover, this treatment modifies lignin and wax, and it eliminates sugar, starch, and protein, resulting in better quality of fibers for reinforcement in polymer matrix composites (Ma *et al*. 2013a, 2014b). The effect of different temperature during hydrothermal pretreatment on the tensile properties of moso bamboo particles reinforced polyvinyl chloride composites (PVC/BP) has been examined (Qian *et al*. 2015). Bamboo particles sized 200 to 400 μm undergo several steps of hydrothermal pretreatment before being ready to be mixed with granulated PVC (300 μm) to produce PVC/BP composites using moulding hot press method. Figure 8 illustrates the tensile strength of pure PVC and PVC/BP composites with different hydrothermal pretreatment temperatures. Increasing pretreatment temperatures up to 180 °C increased the tensile strength of PVC/BP composites. However, further increasing the temperatures led to loss of tensile strength in the PVC/BP composites. The highest strength marked by the composites was 15.79 MPa at the fiber pretreatment temperature of 180 °C. At this temperature, the tensile modulus of the composite also marked the highest value of 6.7 GPa (Fig. 8). Different changes in the amount of hemicellulose, cellulose, lignin, protein, and ash, which build up the strength of the bamboo particles, later affect the strength and modulus of the PVC/BP composites.

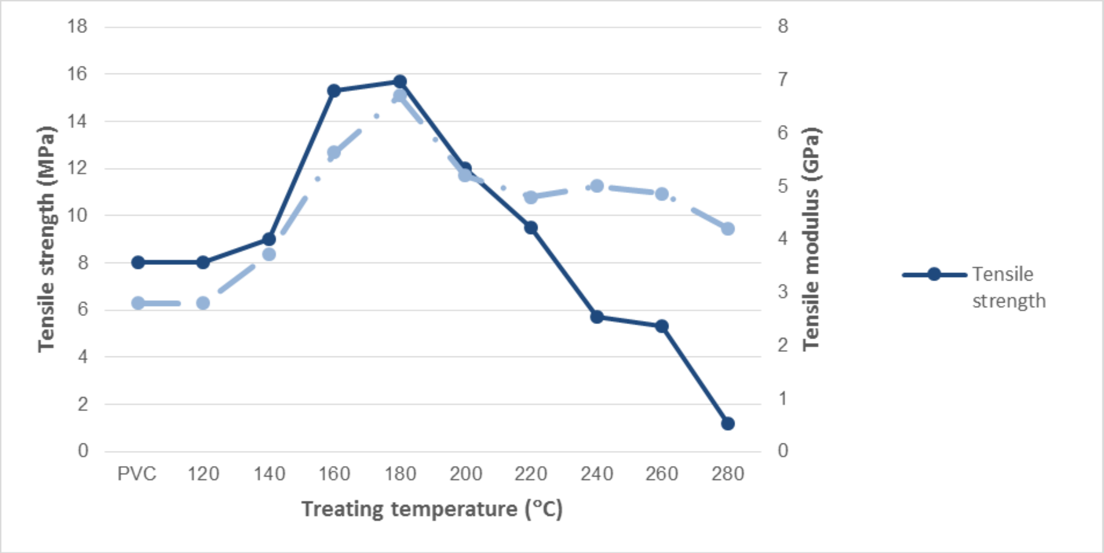

Fig. 8. Tensile strength and tensile modulus of polyvinyl chloride/bamboo particles (PVC/BP) composites with varying hydrothermal treating temperatures. Figure redrawn from Qian *et al*. (2015).

To explain the weak tensile strength of untreated PVC/BP composites compared to the highest strength of 180 °C-treated PVC/BP composites, Qian *et al*. (2015) examined the fractured samples through SEM images. It was reported that more cavities existed after the fiber pulled out in the untreated PVC/BP composites, which explained the poor interfacial compatibility of the fibers with the polymer matrix. After BP was treated at 160 °C, there were fewer and smaller cavities, indicating that hemicellulose and other impurities, such as lignin and wax, were eliminated by hydrothermal pretreatment and that there was better interfacial adhesion between fibers and matrix. To clarify the degradation of strength when the BP was treated at a temperature higher than 180 °C, SEM images of the fractured surface of treated PVC/BP composites at 260 °C were also analysed. At higher temperature, there were almost no cavities on the fractured surface because BP started to carbonize, and less bamboo fiber fracture occurred. All the images had been reported and discussed in the previous study by Qian *et al*. (2015).

Besides hydrothermal pretreatment, alkaline treatment is one of the basic treatments to the natural fibers, including bamboo fibers. This treatment can improve the properties of fibers and enhance the interfacial adhesion between fibers and matrix. Sodium hydroxide (NaOH) with different dissolved solids contents at 4%, 6%, and 8% by volume of water were used to treat the bamboo fibers produced from the steam explosion method. Three variations of composites were prepared with a fixed fiber fraction of approximately 20% by weight. Vacuum bagging was implemented during the composite fabrication. Figure 9 illustrates the average tensile strength of the composites with different percentages of NaOH solution during the pretreatment. The highest tensile strength, which is 10% higher than the untreated fibers, was found in composites with fibers treated with 6% NaOH.

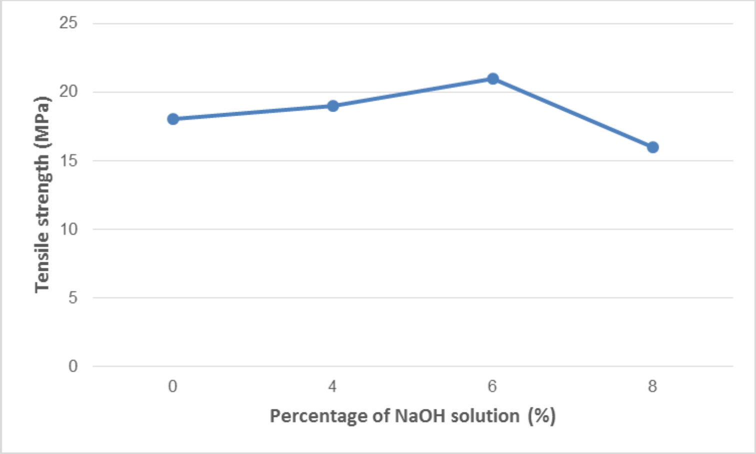

Fig. 9. Tensile strength of bamboo fiber-polyester composites with varying percentage of NaOH solution. Figure redrawn from Manalo *et al*. (2015).

Increasing tensile strength of composites with treated fibers explained that NaOH treatment helps to remove impurities on the fiber surface, and hence improves the adhesion between the fibers and matrix. Figure 10 shows the chemical modification of sodium hydroxide treated bamboo fiber. However, the drop in tensile strength at 8% NaOH could be explained by the excess removal of cellulose content at the surface of the fiber by the high concentration of alkali, which would damage the fiber's structure (Manalo *et al.* 2015). Different types of natural fibers have different optimum concentration of alkali during the pretreatment process, which later affects the performance of the composites (Misra *et al.* 2002; Lee and Wang 2006; Boopathi *et al.* 2012).

$$Fiber - OH + NaOH \rightarrow Fiber - O - Na + H_2O$$

Fig. 10. Probable reaction scheme of bamboo fiber with sodium hydroxide

The different chemical compositions between fibers and matrix limit their bonding. The addition of a chemical coupling agent with suitable composition could bridge the fibers and matrix, thus improving their interfacial adhesion (Lee and Wang 2006). To overcome the weak interface between bamboo fibers and rubber matrix, Ismail *et al*. (2002) studied the effect of inclusion of phenol formaldehyde and hexamethylene tetramine on the tensile strength of BFRNR composites. Figure 2 illustrates the tensile strength of BFRNR with the addition of bonding agent, which is higher than that of BFRNR without the bonding agent for similar fiber loading. The SEM image of the sample with the addition of bonding agent is reported in a previous study (Ismail *et al.* 2002). Less fiber pull-out on the fractured surface explained the improved interfacial interaction between the fibers and matrix, which leads to higher strength of composites. This study also explained that the chemical composition of phenol formaldehyde and hexamethylene tetramine is suitable to act as a bridge of chemical bonds between natural rubber and bamboo fiber.

Fractured surfaces of hybrid BGRP discussed earlier (Hybrid Composite section), were observed through SEM (Thwe and Liao 2002). Poor adhesion between bamboo and glass fibers to the PP matrix was observed in the SEM image, as reported in the study.

The bamboo fiber was seen to be essentially a stand-alone fiber, completely debonded from the matrix, while more pulled out glass fibers can be seen on the fractured surface of BGRP. These observations indicate that bamboo and glass fibers do not generally adhere well to the PP matrix. The hydrophilic nature of fibers and hydrophobic nature of PP is one of the reasons for the poor adhesion between them. To overcome the adhesion limit of the fibers and the PP matrix, Thwe and Liao (2002) studied the addition of MAPP as a compatibilizer into the BFRP and BGRP. Theoretically, maleic anhydride ($(CH_3CO)_2O$) of MAPP can be bonded strongly to the OH group on the bamboo fiber surface and the SiO group of the glass fiber, which leads to a better adhesion between both the fibers and the matrix. However, other factors such as the morphology of the constituents and the wetting phenomenon between the two surfaces are important when studying the effect of the compatibilizer.

Figure 5 illustrates the tensile strength of BFRP and BGRP with the inclusion of MAPP, as well as the comparison between the samples without MAPP. The tensile strength of BGRP samples with MAPP showed the same trend as the samples without MAPP, which is increasing strength with increasing ratio of glass to bamboo fibers. In comparison between the samples with and without MAPP, the tensile strength of BFRP and BGRP with the inclusion of MAPP was seen to slightly increase by 5 to 11%. This shows that MAPP improved the adhesion between the fibers and the matrix, leading to better stress transfer along the samples. The fractured surface of the BGRP sample with MAPP was also compared *via* SEM with the fractured surface of a BGRP sample without MAPP. All the SEM images were discussed and reported in the previous study. The improved adhesion between the fibers and the matrix with the inclusion of MAPP can easily being compared through the reported SEM images. Less debonding of glass fiber, good bonding of bamboo fiber to the matrix, and less fiber pullout were seen in the improved BGRP samples (Thwe and Liao 2002).

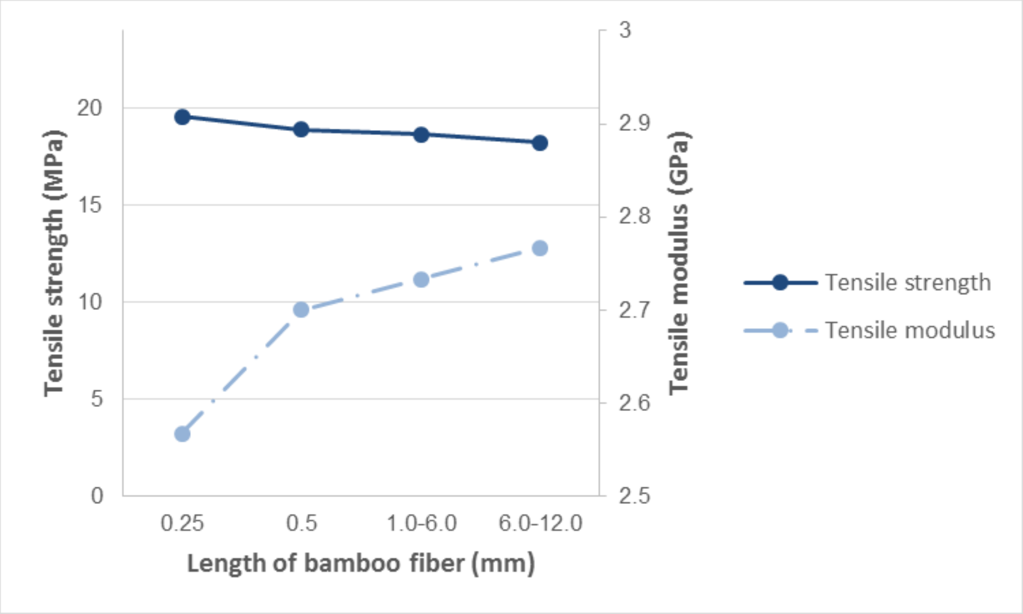

Fig. 11. Tensile strength and tensile modulus of hybrid BGRP (with MAPP) with varying length of bamboo fibers. Figure redrawn from Thwe and Liao (2002).

Properties of Fibers and Processing Conditions

Hybrid BGRP composites were fabricated with a fixed 2:1 ratio of bamboo to glass fiber and inclusion of 10% MAPP compatibilizer. The size of glass fibers was fixed to clearly observe the effect of different sizes of bamboo fibers to the tensile strength and modulus of BGRP (Fig. 11). Longer bamboo fibers slightly decreased the tensile strength of BGRP. During stress transfer along the short fibers, the fibers only act to deflect propagating matrix cracks because shorter fibers may never reach its breaking stress. A different situation happened during stress transfer along the longer fibers where fiber failures may occur although they can carry more stress. Fiber failures in longer fibers generate micro cracking, which cannot be avoided once it occurs. This somehow lowered the tensile strength (Thwe and Liao 2002).

Okubo *et al*. (2004) compared the tensile properties of bamboo fiber reinforced polymer composites using bamboo fibers extracted through two different methods. The first method produced bamboo fiber bundles with diameters of 125 to 210 µm. These fiber bundles were obtained from commercial bamboo chips passed through a mesh filter on a sifter machine. The second bamboo fibers were extracted by steam explosion, which effectively separates lignin from woody materials. The maximum amount of lignin, which binds fibers in woody plants, must be removed during extraction to ensure the full separation of fibers. The considerably higher lignin content in bamboo compared with other natural fibers (Table 2) led the authors to consider an additional process of mechanically rubbing the fiber bundles after steam explosion. The rubbing process was applied using a mixing machine, and it produced bamboo fiber cotton (BFC) fibers with diameters reduced to 10 to 30 µm. The composites fabricated from mechanically extracted fiber bundles showed lower tensile strength than composites fabricated from single fibers, which were extracted *via* steam explosion method (Fig. 12).

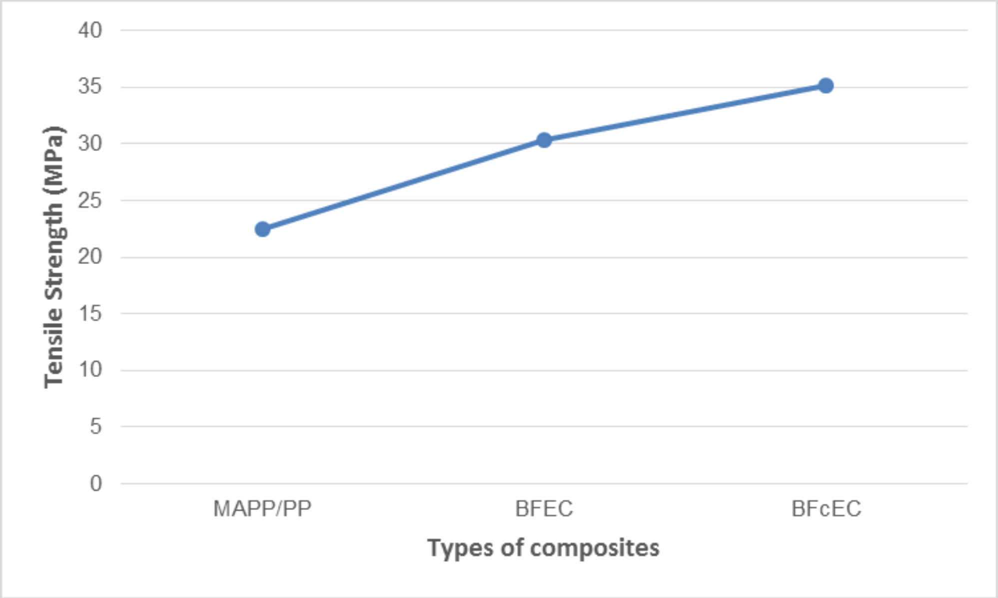

Fig. 12. Tensile strength of neat MAPP/PP, bamboo fiber eco composites (BFEC) and bamboo fiber cotton eco composites (BFcEC). Figure redrawn from Okubo *et al.* (2004).

In Fig. 12, the higher tensile strength of BFEC compared with pure MAPP/PP explained the ability of bamboo fiber bundles to act as reinforcement in BFEC. Compared to pure MAPP/PP, which has a strength of 22.5 MPa, reinforced MAPP/PP with bamboo fiber bundles had increased its tensile strength by 35% to a value of 30.3 MPa. However, the composite made from single fibers extracted *via* improved steam explosion method and mechanical rubbing showed the best properties. BFcEF had the highest tensile strength of 35.1 MPa compared to 30.0 MPa of BFEC and 22.5 MPa of pure PP/MAPP matrix. Thus, the additional process of fiber extraction resulted in further fiber separation, which allowed full impregnation of resin.

CONCLUSIONS AND FUTURE DEVELOPMENTS

The utilization of bamboo in composite materials provides useful solutions for new development in the material industries. Bamboo trees are renewable sources that grow quickly and mature in a very short period of time. Therefore, there is a confirmed continuous supply of bamboo fibers with low production cost compared with other conventional fibers. Furthermore, the tensile properties of bamboo fibers are very good, and they can replace conventional glass in reinforcing polymer matrices. However, different factors and properties affect the performance of bamboo composites. A suitable method of fiber extraction must be applied to maximize the removal of lignin from the surface of bamboo fibers, which can improve the interfacial adhesion between fibers and matrices. The inclusion of coupling agents and fiber pretreatment also enhance this bonding. The optimum amount of fiber loading results in composites with high tensile properties. Hybridization with glass and carbon fibers, which have better tensile properties, enhances the potential of bamboo composites. The high performance of bamboo composites can compete with conventional materials. The use of bamboo fibers instead of synthetic fibers develops eco-friendly products that reduce the environmental issues, especially in terms of energy consumption and solid waste treatment. However, further research must be carried out to provide better information about bamboo and develop its potential in advance technology. Bamboo composites have been used widely in interior design applications such as home paneling and furniture. Although the use of bamboo composites is still limited in automotive applications, continuous studies about bamboo can increase their potential not only in automotive applications but also in aerospace and other structural applications.

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