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THE NATURAL FIBER COMPOSITES BASED ON BAMBOO FIBERS: A REVIEW

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ABSTRACT

Bamboo has found numerous applications in human life for centuries. In recent years however, bamboo has generated interest from researchers as a candidate to replace environmental unfriendly glass as fiber in fiber reinforced composites. This is due to the potential properties of bamboo that has high specific strength and stiffness besides being biodegradable, sustainable and renewable. This paper is to review on the properties of bamboo reinforced composites from numerous characterization studies of bamboo that are available in the literatures. The review is based on characterization studies on several types of bamboo reinforced composites such as laminated bamboo fiber reinforced composite, randomly oriented bamboo reinforced composite, hybrid fiber reinforced composite, bamboo fiber reinforced bio-composite and bamboo fiber sandwiched structure composite. It can be said that the laminated bamboo composite in general gives higher mechanical properties compare to other structural forms of bamboo composite. Even though bamboo bio-composite in general provides low mechanical properties, the properly design unidirectional bamboo bio-composite can also have high mechanical properties that are as good as the laminated bamboo reinforced composite. While specific tensile properties of laminated bamboo reinforced composite are at par with glass fiber reinforced composite, the mechanical properties of bamboo fiber reinforced composite are comparable to the mechanical properties of the best among natural fiber reinforced composites.

Keywords: natural fiber, bamboo fiber, biodegradable material, bamboo fiber reinforced composite, bamboo fiber reinforced sandwich structure, bio-composite.

INTRODUCTION

The application of natural fibers such as kenaf, jute, bamboo, flax and wood in fiber reinforced composites has become so important of late due to their high effective strength and stiffness, low cost, low production energy requirement, abundantly available and attractive environmental advantages of being renewable, biodegradable and sustainable compared to synthetic fibers such as glass and carbon [1-6]. The increased application of these natural fibers in such composites in industries such as automotive [7-9], marine [10] and construction [11-13] is a proof to this claim. Bamboo as compared to woods has overall mechanical properties that are comparable to those of woods while having advantages of lower weight and short harvesting time of 3-4 years counting from the time of plantation [14]. Furthermore, bamboo does not require re-planting as the extensive root base sprouts new shoots readily and these trees such as shown in Figure-1 [15] are abundantly available especially in Asia and South America. Compare to other natural fibers, bamboo fibers has a specialty of high strength and low density making it at par with glass in term of specific strength [14,16] while the specific strength of bamboo is 3 to 4 times to the specific strength of mild steel [16]. With these advantages, it is not a surprise that in term of production of fiber source, bamboo is one of the highest at 30 million ton per year [17].

The high strength of bamboo in fiber direction is due to the longitudinally alignment of its fiber to its body while at the same time this is attributed by its polylamelate wall structure that consists of alternating broad and narrow layers with different fibrillary orientation such as shown in Figure-2 [18]. Furthermore, high cellulose and lignin content and relatively small micro-fibril angle of bamboo plant contribute to this high strength of bamboo fiber [18]. As such bamboo fiber is also known as the natural glass fiber [19].

Figure-1. Bamboo trees in China [15].

Natural fiber such as bamboo fiber also comes with a disadvantage of having high water intake due to the presence of hydroxyl and other polar groups in various constituents of natural fibers. This leads to weak interfacial bonding between fibers and matrix that is usually relatively more hydrophobic. The wetting of the fiber within matrix will also be affected and consequently, the mechanical properties of the bamboo composite are

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ARPN Journal of Engineering and Applied Sciences

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low. However, as the advantage of natural fiber composite is so great, huge amount of research time has been spent to improve this disadvantage with much success [20-23].

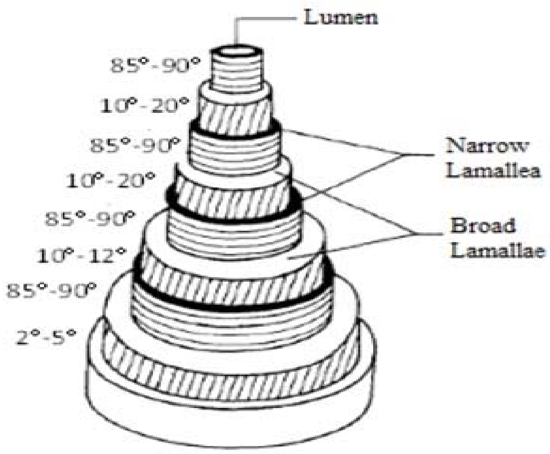

Figure-2. The polylamellate wall structure of a bamboo [18].

The attractive properties of bamboo have generated high interest in using bamboo as fibers in fiber reinforced composite. Bamboo fibers (BF) have been combined with thermoset matrix [16,18] and thermoplastic matrix [19-20] to form the bamboo fiber reinforced composite (BFRC). Bamboo also has been combined with polymer along with synthetic fiber such as glass to form the hybrid fiber reinforced composite (HFRC) [21-22]. At the same time, the natural bamboo fibers have been mixed with biodegradable polymers such as polylactide acid (PLA), poly-l-Lactide acid (PLLA), polyhydroxyalkanoate (PHA), polyhydroxybutyrate (PHB), polyhydroxybutyrate-co-valerate (PHBV) and cellulose acetate (CA) to form the bamboo fiber reinforced bio-composite (FRBC) [23-24]. This FRBC is also called the green composite. With the advanced of bamboo fiber extraction technology [25] whether the extraction is done mechanically or chemically, bamboo has been used as reinforced constituent of composite in several forms: strip, flake, long fiber, short fiber, sliver and powder such as shown in Figure-3. These forms of bamboo constituent determine the eventual forms of composites that are being designed such as laminated fiber reinforced composites (LFRC) [16-18,26-27], short or randomly oriented bamboo fiber reinforced composites (RFRC) [28-29] and bamboo fiber reinforced sandwich structures (FRSS) [30-31] to provide composite with characters that meet the industry requirements.

This paper is to discuss the mechanical characterization of bamboo reinforced composites in laminated, randomly oriented fiber and sandwich forms that includes the BFRC, HFRC and the FRBC.

MECHANICAL CHARACTERIZATION OF BAMBOO COMPOSITES

Mechanical properties of a designed bamboo composite depend on how bamboo fibers are extracted from the bamboo trees, the form of bamboo fibers and eventually the types of bamboo composites, the treatments on the fibers and the polymers and the fabrication process used.

Laminated bamboo composite

Shin *et al.* [16] fabricated LFRC that consists of bamboo strip and epoxy in 3, 5 and 7 layer forms where each layer consists of unidirectional bamboo strips. Tensile, compressive, flexural and inter-laminar shear tests were conducted on the three types of LFRC. The LFRC good results in tensile test (up to 243 MPa), compressive test (up to 129 MPa) and flexural test (up to 255 MPa) proof that the BFRC warrants its use for construction and other purposes. However the low value of the interlaminar shear strength (up to 16.8 MPa) is inherent shortcoming of this and most composite materials and needs to be improved.

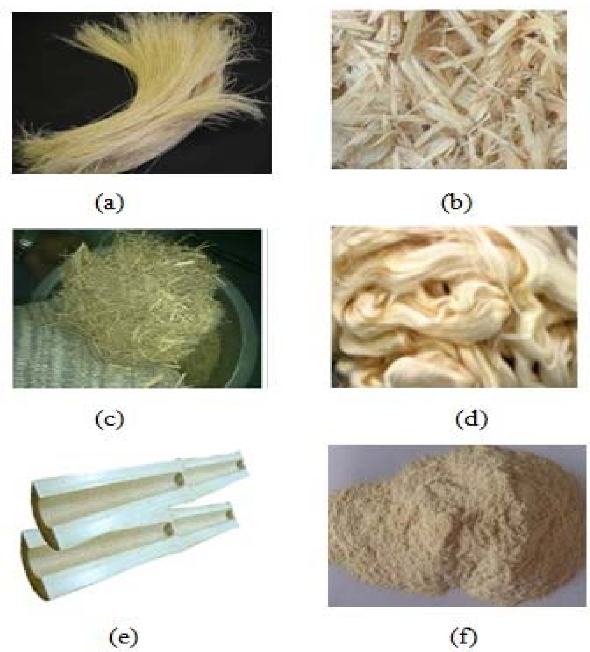

Figure-3. Forms of bamboo being used as composite reinforcement (a) long fibers (b) flake (c) short fibers (d) sliver (c) strips and (f) powder.

In a study by Jain *et al.* [18], LFRC was fabricated based on bamboo fibers and bamboo orthogonal mat while araldite resin was used as matrix in each case. Bamboo fibers were oven dried first and later mixed with resin and hardener while keeping the fibers unidirectionally adjacent to each other. The resulting composite plate was cut into several pieces and the pieces were fixed one over the other using resin hardener mixture to obtain the required multilayered composites. The maximum fiber volume fraction achieved was 65%. Tensile, flexural and impact strength tests were conducted on unidirectional, bi-directional, 7 and 9 layered multi-directional bamboo fiber and bamboo mat composites. The results were that the unidirectional composite gave the highest tensile strength of up to 175.27 Mpa, a behavior

ARPN Journal of Engineering and Applied Sciences

similarly found in the study by Shin *et al.* [16]. However the 9 layered multidirectional composite gave the highest flexural strength and in general bamboo fiber composite performed better than the bamboo orthogonal mat composite in all the three tests conducted. In this study, a composite with good strength in all directions was successfully developed.

A careful fabrication procedure was developed by Verma and Chariar [26-27] to produce laminated BFRC which combined bamboo slivers that were sliced from bamboo culms using sliver cutting machine and epoxy. Three configurations of laminated bamboo composite that were constructed using adhesives and butt joint were the unidirectional configuration, [0°/0°/0°/0°/0°] (UNI), the symmetric angle-ply configuration, [0°/45°/0°/45°/0°] (SAP) and the symmetric cross-ply configuration, [0°/90°/0°/90°/0°] (SCP). The specimens were than tested for their tensile, compressive and flexural properties in addition to testing the screw holding capabilities. Figure- 4 (a)-(c) shows the behaviours of the BFRC under tensile, compressive and flexural testing. It was observed that in tensile test, matrix failure started first, followed by fiber fracture that propagates spontaneously until the whole layer break. Compressive failure was attributed to microbuckling surrounded by delamination while in flexural test, the tension surface failed due to matrix and fiber breakage. Compared to teak wood in terms of mechanical properties and cost [27], the study showed that BFRC's properties are at par with the properties of the teak wood while fabrication cost of the BFRC is less than that of the teak wood. As such, BFRCC can be utilized as building and general purpose material for furniture, beam and column.

Short bamboo fiber composite

In a study by Rajulu *et al.* [28], bamboo fibers were chemically treated to remove the greasy material and lignin and later dried. These short bamboo fibers were then coated with blend of epoxy and various percentages of polycarbonate (PC) before tensile and chemical resistance tests were conducted on the composite. It was found that with the blend of PC with epoxy, tensile strength of the BFRC can be increased up to 42.3% as compared to the tensile strength of the bamboo fibers alone. Furthermore, it was found that the bamboo epoxy/PC composite can take the effect of acids and alkalis such as acetic acid, nitric acid, hydrochloric acid, sodium hydroxide, sodium carbonate and ammonium hydroxide.

Okubo *et al.* [19] fabricated firstly the so called bamboo fiber eco-composite (BFEC) by stacking alternatively thin film of maleic anhydride modified polypropylene (MAPP) and the randomly scattered bamboo fiber bundles. Later bamboo fibers were extracted from its bundle using the steam explosion method and the bamboo fiber cotton eco-composite (BfcEC) was fabricated using similar process to the BFEC. From the conducted tensile tests on BFEC and BfcEC, it was found that the tensile strength and the Young's modulus of the BfcEC were increased from those of the BFEC for about 15% and 30% respectively. This can be explained from the SEM photographs that show the great reduction in voids for the BfcEC as compared to the BFEC such as shown in Figure-5 (a) and (b). Furthermore, it was shown that the tensile strength of the BFcEC was increased with the increase of the volume fraction of bamboo fibers as compared to the BFEC where the reduction of tensile strength can be seen as the volume fraction reaches 50%.

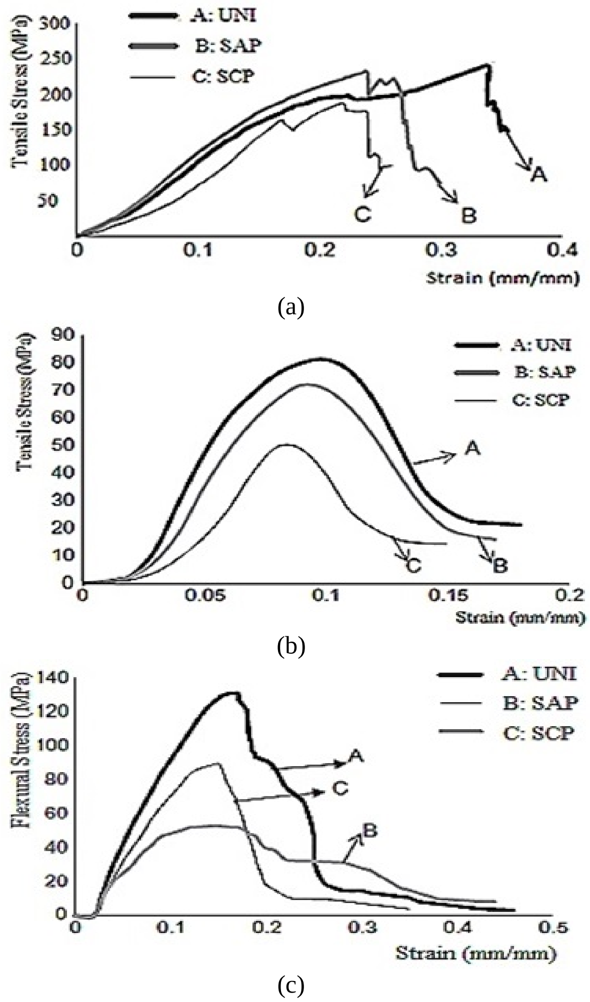

Figure-4. The plots of the (a) tensile test (b) compressive test and (c) flexural test of BFRCs [26].

Bamboo fibers were extracted via chemical (diluting in sodium hydroxide) and mechanical means before the fibers were thoroughly mixed with resin in a glass mold [29] to give randomly oriented BFRC and HBRC. Several samples were fabricated that combines bamboo/unsaturated polyester (USP) resin, bamboo/vinyl ester (VE) resin, glass/USP, glass/VE, bamboo/glass/USP resin and bamboo/glass/VE resin. Flexural properties and inter-laminar shear strength were measured using a universal testing machine. The BFRC produced this way at

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ARPN Journal of Engineering and Applied Sciences

45 wt% was found to give flexural strength that is slightly lower than the glass fiber reinforced composite (GFRC) and tensile modulus that is higher than the GFRC. However the inter-laminar shear strength of the BFRC is much lower than that of the GFRC. It was also found that the flexural modulus for all composites were increased as the volume fraction of the bamboo fibers was increased. It was concluded that 25% weight of glass can be substituted by bamboo fibers without lowering the mechanical properties of the composites.

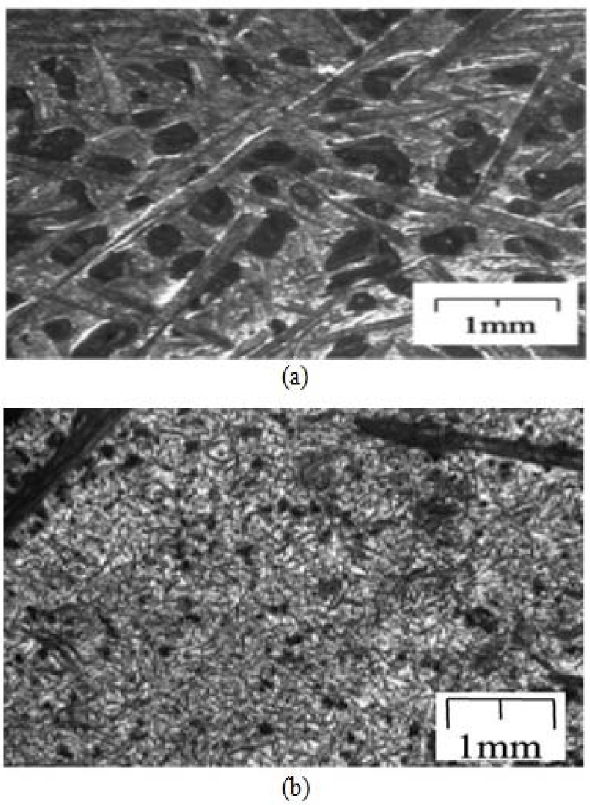

Figure-5. Resin impregnation state into bamboo fiber bindles in (a) BFEC and (b) BFcEC [19].

Chen *et al.* [32] developed BFRC by mixing bamboo chips, polypropylene (PP) and MAAP as compatabilizer with an objective as cheap substitute of wood. Bamboo fine pieces were produced by grinding bamboo chips using a blender. The mixing condition of bamboo, PP and MAAP was scrutinized to ensure the high composite's quality is obtained. SEM photomicrographs showed that the wetting of bamboo fiber by PP was improved greatly by the present of MAAP and as such the tensile modulus, tensile strength and impact strength were improved greatly. The maximum values of tensile strength (32-36 MPa) and tensile modulus (5-6 GPa) were obtained at 50 wt % of bamboo fibers. This tensile strength of the developed BFRC is three times higher than that of the commercial wood pulp board.

Hybrid fiber reinforced composite

The advantage of using a hybrid composite that contains two or more different types of fibers is the HFRC gives proper balance in performance and cost of the composite. In their work [33-34], the bahaviour of short BFRC and HFRC that consists of short bamboo and short glass fibers in a PP matrix subjected to hygrothermal aging and tensile-tensile cyclic load were studied. The effects of fiber length, fiber content and coupling agent were considered. Short bamboo fibers were prepared using a laboratory scale extraction technique. Upon extraction, small pieces of bamboo were obtained by grinding strips of bamboo using blenders. Bamboo fibers, glass fiber, PP and MAPP were melt-mixed using torque rheometer and later transferred through injection molding machine to give randomly oriented HFRC. It was found that the HFRC showed better resistance to environmental aging compared to BFRC. The increase of bamboo fiber content in the HFRC was found to increase the tensile strength of the HFRC. The increase of fiber length was seen to increase the tensile modulus initially. With further increase of fiber length, the tensile strength and modulus were decreased since longer fiber length may result in fiber agglomeration, fiber attrition and holes on the fractured surface such as shown in Figure-6. This also means that the hybrid approach of blending glass fiber and bamboo fiber is an effective way of improving the durability of bamboo fiber under environmental aging. Further improvement was obtained by including the MAPP as a compatabilizer that improved the interfacial adhesion between the matrix and the fibers.

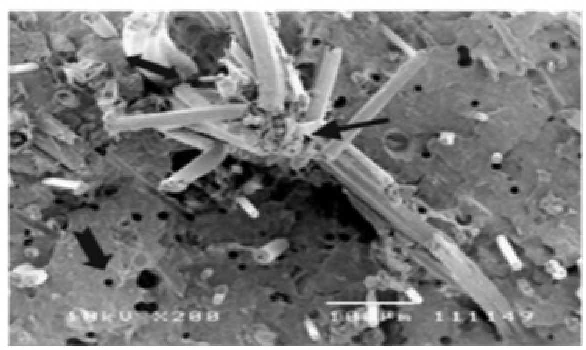

Figure-6. The SEM image of HFRC with MAPP compatabilizer. Double-headed arrow indicates fiber agglomeration, V-shape tail arrow indicates holes on matrix because of pull-out bamboo fiber and thin arrow indicates a broken fiber.

Sandwich bamboo fiber composite

In a study by Mallaiah *et al.* [30], polyurethane (PU) foam cored fiber reinforced polymer (FRP) sandwich structures were developed using laminates of e-glass/epoxy, jute/epoxy and bamboo/epoxy as the skins. Hand lay-up method was used and following that flatwise and edgewise compressive tests, three point bending and water absorption tests were conducted on the structures. It was found that the glass-jute hybrid composite structure gave the highest flatwise and edgewise compressive strengths while bamboo-glass hybrid structure gave the highest core shear and facing bending strengths such as shown in Figure-7. However in the water absorption test, the highest water absorption occurred in glass/bamboo hybrid composite.

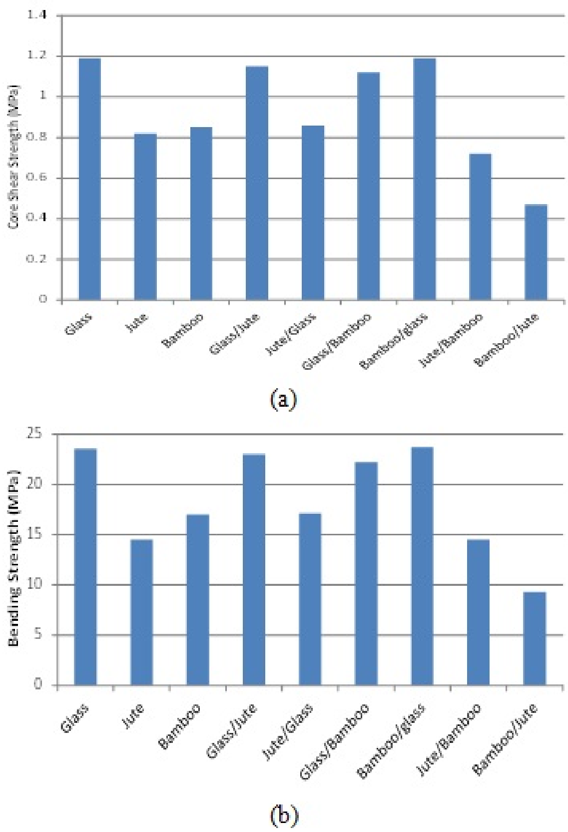

Figure-7. (a) Core shear strength and (b) facing bending strength for different sandwich structures.

In their recent study, Roslan *et al.* [31] conducted tensile tests on several unidirectional BFRC that consists of bamboo sticks and epoxy resin. The tests showed that the 0° unidirectional BFRC has the highest tensile strength of 138.8 MPa. Slotting technique [35] was then used to form square and triangular bamboo-epoxy honeycomb sandwich structures based on the 0° unidirectional BFRC. Compressive tests were conducted to determine the compressive properties of the honeycomb structures and to compare the specific energy absorption of the honeycomb structures to that of the medium density fiberboard and the aluminum hexagon sandwich structures. The force-displacement curves for the honeycomb sandwich structures are shown in Figure-8. It shows that in both cases of honeycomb structures, loading force decreased slightly as plastic region was approached before the force was reduced greatly as the structures buckled. The triangular honeycomb structure has higher tensile strength because of having greater cross-link support and smaller cell size that can provide a greater bonding area [35]. The bamboo-epoxy triangle honeycomb structure was also found to have the highest specific energy absorption. This study shows that the bamboo-epoxy triangle honeycomb structure is suitable to be used in honeycomb structures that require high strength and stability.

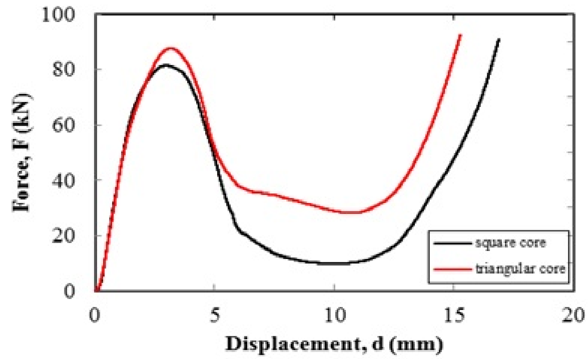

Figure-8. Force-displacement curves for square and triangular honeycomb sandwich structures [31].

Bamboo fiber bio-composite

A complete natural composite requires the combination of natural fiber and biodegradable polymers such as PLA and PBS. The main advantage of bio-composite is it can be decomposed naturally or through a composting process without releasing any toxics to the environment. Krishnaprasad *et al.* [36] conducted work to extract microfibrils from raw bamboos and fabricate the bamboo microfibril bio-composites by combining the fibers with PHB polymer. Bamboo microfibrils (BMF) were introduced to melted PHB in a mixer before the resultant pallets went through an injection molding machine to produce the FRBC. Tensile tests conducted revealed that the tensile strength of the FRBC increased with the increase of the fiber loading of up to 20%. Upon that, due to fiber agglomeration within the polymers matrix that resulted in low stress transfer between the matrix and the fibers and consequently the tensile strength is decreased. At the same time SEM of bamboo microfibrils such as shown in Figure-9 showed the irregular surface morphology of bamboo microfibril that helped to improve the adhesion between the polymer and the fibrils.

Lee and Wang [37] developed bio-composites from PLA and PBS and bamboo fibers while using lysine-diisocyanate (LDI) as a bio-based coupling agent. Mix of bamboo fibers and polymers went through mixer and compression molding to give sheets of the required BFRC. It was found that the LDI improved the tensile properties, water resistance and interfacial adhesion of both BF/PLA and BF/PBS composites. SEM showed that after compounding LDI of 0.65 wt%, the improvement of the interfacial adhesion between fibers and matrix can be seen as the BF appeared to be coated with matrix polymer. The improvement may be due to the compatible effect of graft co-polymer with LDI intermediates. This explains the

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improvement in the tensile strength and the water resistance of the BFRC by adding the LDI.

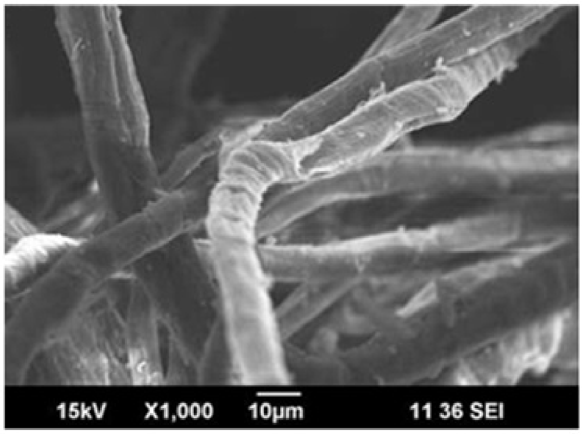

Figure-9. The SEM of bamboo microfibrils [36].

Singh *et al.* [38] conducted mechanical, thermo-mechanical and morphological property studies of bio-composites that consisted of bamboo fibers and polyhydroxybutyrate-co-valerate (PHBV). The fabrication process include stages at micro-extruder and mini-injection molding machine. It was found that tensile modulus at 40 wt.% fiber improved by 175% as compared to that of the neat PHBV. Furthermore the theoretical tensile modulus of the bio-composite that was calculated using the Cristensen's equation was found to be closed to the experimental values. Recently, Ochi [39] conducted tensile characteristic study on his own FRBC that combined bamboo fibers that were extracted through steam explosion method and a starch-based emulsion-type biodegradable resin. Preliminary composites were made by putting the resin onto bamboo fibers before the mixture was dried. The mixture was then heated at 130°C for 5 minutes before it was hot pressed at 10 MPa for 10 min. Volume fraction of bamboo fibers was varied between 30% and 70%. Tensile test conducted thereafter found that at 70% volume fraction of bamboo fibers, high tensile strength of 265 MPa and tensile modulus of 12.4 GPa were produced. Furthermore, unlike the results of the mentioned previous studies, the study here managed to fabricate FRBC that has tensile test and tensile modulus that were increased as the volume fraction was increased up to 70 %.

As a summary, Table-1 shows the mechanical properties of bamboo composites being reviewed in this work. It is clear that laminated bamboo reinforced composites give the higher values of the tensile strength and modulus as compared to that of the other forms of bamboo reinforced composite. Additionally, the unidirectional form of bamboo reinforced composite is a composite form that gives high tensile strength and modulus. This is especially true in the case of the FRBC where the values of tensile strength and modulus [39] are much higher compared that of others FRBC. Laminated bamboo reinforced composites were also shown to perform better than the glass mat thermoplastic composite (GMAT) that has been widely used in industries such as automotive and other transportation industries. As a comparison among natural fiber reinforced composites, Table-2 shows the tensile properties of some of the natural fiber reinforced composites that are available in literatures. It can be seen that bamboo composite belongs to a group of composites (along with sisal, jute and kenaf) that gives high tensile properties compared to other natural fiber reinforced composites. These high values of tensile properties are attributed its unidirectional form, chemical treatment of fibers and high percentage of natural fibers. The high tensile strength of the jute/glass/ polyester resin shows that such combination of jute and glass fibers can be an alternate material for glass fiber reinforced polymer composites [43]. The lignification on the jute slivers can bring about improved mechanical properties while a high percentage of fiber loading of up tp 50% wt can be achieved in the composite through the solution impregnation method [46]. Unidirectional flax fibers combined with epoxy showed significant improvement when several treatments were given to fibers [48]. Treatments in this study include treatments of alkali, silane, isocyanate, resin impregnation and latex modification that improved tensile properties of flax-epoxy composites up to 62.54 MPa. This value is however low. In contrast to wood based composite where polymers can be seen around lumen, the OM micrograph showed that the void content (including lumen) of the unidirectional sisal-epoxy composite cross-section was 17%. Nonetheless this composite that was manufactured using resin transferred method (RTM) was found to have high tensile properties of 211 MPa at 46% wt sisal [51]. Comparing the natural fiber reinforced composites to glass fiber reinforced composite [40-42], composite based on unidirectional bamboo and sisal fibers can have higher tensile strength and modulus. Even though it is known that the glass reinforced composite can have tensile strength of up to 817 MPa [52], this encouraging results of the tensile properties of the natural fiber reinforced composites shows that natural fiber composite such as that of the bamboo based composites can be on its way to replace glass reinforced composite in structural applications.

Table-1. Comparison of the mechanical properties of BFRC based on its structural forms (E_T = Tensile modulus, S_{UT}=Ultimate tensile strength).

Ref	Struct. Form	E_T (GPa)	S_{UT} (MPa)	Remark
[16]	LFRC	4.5	243	3 unidirectional fiber layer mixed with epoxy matrix
[18]	LFRC	-	175	9 multi-directional fiber layer with epoxy matrix
[26]	LFRC	4.5	210	4 unidirectional fiber layer with epoxy matrix
[27]	LFRC	17	240	4 unidirectional fiber layer with epoxy matrix
[28]	RFRC	-	39	Polyester matrix filled with alumina particulates
[32]	RFRC	6	36	Polypropylene matrix and 0.4% maleic anhydride-grafted polypropylene
[36]	FRBC	2	12	Bamboo microfibril randomly mixed with PHB.
[37]	FRBC	3	42	Bamboo fiber randomly mixed with PLA
[37]	FRBC	-	34	Bamboo fiber randomly mixed with PBS
[38]	FRBC	1.7	18.9	Bamboo fiber randomly mixed with PHBV at 40% wt of fiber.
[39]	FRBC	12	265.5	Unidirectional bamboo fiber mixed with starch
[40]	GFRC	5.25	70	Glass mat thermoplastic composite (GMAT)

Table-2. Comparison of the tensile properties of several natural fiber reinforced composite.

Fiber	Matrix	Ref.	Remark	Young's Modulus (GPa)	Tensile Strength (MPa)
Glass	PP	[41]	Glass mat thermoplastic (GMAT) with glass 40% Wt	6	100
Glass	Epoxy	[42]	Randomly oriented e-glass, epoxy and liquid epoxidized natural rubber	10	190
Bamboo	Epoxy	[16]	3 unidirectional fiber layer mixed with epoxy matrix	4.5	243
Bamboo	Epoxy	[27]	4 unidirectional fiber layer with epoxy matrix	17	240
Bamboo	Starch	[39]	Unidirectional bamboo fiber mixed with starch	12	265.5
Jute/glass	Polyester	[43]	5 layers: glass/jute/glass/jute/glass	-	229.54
Jute	Epoxy	[44]	Bi-directional jute mat	4.45	110
Jute	Epoxy	[45]	4 layered unidirectional jute fiber 50% Wt.	3.18	148.3
Hemp	Epoxy	[46]	Uni-directional hemp fiber	8.5	143
Silk	Epoxy	[47]	Woven silk	5.4	60.5
Flax	Epoxy	[48]	Woven silk epoxy	5.8-9.8	7.3-11.2
Flax	Epoxy	[48]	Unidirectional flax/epoxy plate with silane treatment	9.83	62.54
Cotton	Epoxy	[49]	33% cotton	4.2	71
Hemp	PE	[50]	Compression of randomly oriented hemp fiber mat situated in between 3 films of PE	6.8	52
Sisal	PE	[50]	Compression of randomly oriented sisal fiber situated in between 3 films of PE	5.4	34
Sisal	Epoxy	[51]	Unidirectional sisal fiber, 48% Wt	19.7	211
Kenaf	Epoxy	[52]	Kenaf bast fiber-reinforced epoxy strands	7.78	231.32

CONCLUSIONS

A review was conducted on the current research status of the bamboo fiber reinforced composites. This BFRC in forms of laminated composite, short fiber or randomly oriented fiber composite, hybrid composite, sandwich type composite and bio composites were discussed. The specific tensile properties of laminated bamboo reinforced composite are at par with glass fiber reinforced composite, while the mechanical properties of bamboo fiber reinforced composite are comparable to the mechanical properties of the best among natural fiber reinforced composites such as the kenaf, jute and hemp based composites.

REFERENCES

[1] E. Bodros, I. Pilin, N. Montrelay and C. Baley. 2007. "Could biopolymers reinforced by randomly scattered flax fiber be used in structural applications?," Composite Science and Technology, Vol. 67, pp. 462-470.

[2] A. Ashori and A. Nourbakhsh. 2010. Reinforced polypropylene composites: Effects of chemical compositions and particle size, Bio-resource Technology, Vol. 101, No. 7, pp. 2515 - 2519.

[3] PJ. Jandas, S. Mohanty and SK. Nayak. 2013. Thermal properties and cold crystallization kinetics of surface-treated banana fiber (BF)-reinforced PLA nanocomposites, Journal of Thermal and Calorimeter, Vol. 114, pp. 1265-1278.

[4] S. Mohanty, SK. Verma and SK. Nayak. 2005. Dynamic mechanical and thermal properties of MAPE treated jute/HDPE composites, Composite Sci. Technology, Vol. 2, pp. 538-547.

[5] A K. Mohanty, A. Wibowo, M. Misra and LT. Drzal. 2004. Effect of process engineering on the performance of natural fiber reinforced cellulose acetate biocomposites, Composites Part A: Applied Science and Manufacturing, Vol. 35, No. 3, pp. 363-370.

[6] AA. Yussuf, I. Massoumi and A. Hassan. 2010. Comparison of Polylactic Acid/Kenaf and Polylactic Acid/Rise Husk Composites: The Influence of the Natural Fibers on the Mechanical, Thermal and Biodegradability Properties, Journal of Polymer Environment, Vol. 18, pp. 422–429.

[7] Y. Chen, O. Chiparus, L. Sun, I. Negulescu, DV. Parikh and TA. Calamari. 2005. Natural Fibers for Automotive Nonwoven Composites, Journal of Industrial Textiles, Vol. 35, pp. 35-47.

[8] C. Alves, PMC. Ferra, AJ. Silva, LG. Reis, M. Freitas, LB. Rodrigues and DE. Alves. 2005. Eco-design of automotive components making use of natural jute fiber composites, Journal of Cleaner Production, Vol. 18, No. 4, pp. 313- 327.

[9] A. Leão, SM. Sartor and JC. Caraschi. 2006. Natural fibers based composites – Technical and social issues, Mol. Cryst. Liq. Cryst., Vol. 448, pp. 161–177.

[10] C. Baley and Y. Grohens. 2004. Application of interlaminar tests to marine composites: Relation between glass fiber/polymer interfaces and interlaminar properties of Marine Composites. Applied Composite Materials, Vol. 11, No. 2, pp. 77-98.

[11] SW. Kim, SH. Lee, J S. Kang and K H. Kang. 2006. Thermal conductivity of thermoplastics reinforced with natural fibers, International Journal of Thermophysics, Vol. 27, No. 6, 2006, pp. 1873-1881.

[12] TH. Nguyen, T. Shehab and A. Nowroozi. 2010. Use of bamboo composites as structural members in building construction, challenges, opportunities and solutions in structural engineering and construction, Taylor & Francis Group, London.

[13] K. Ghavami. 2005. Bamboo as reinforcement in structural concrete elements, Cement & Concrete Composites, Vol. 27, pp. 637–649.

[14] SC. Lakkad and JM. Patel. 1980. Mechanical properties of bamboo, a natural composite, Fiber Science Technology, Vol.14, pp. 319-22.

[15] T. Akihiro and A. Eka. 2001. Application of MDI binder towards environmental friendly wood-based industry. Seminar on Wood-Based Panel Products; 10-11 July 2001; Kuala Lumpur: Forest Research Institute Malaysia.

[16] FG. Shin, XJ. Jian, WP. Zheng and MW. Yipp. 1989. Analysis of the mechanical properties and microstructure of bamboo-epoxy composites. Journal of Material Science, Vol. 24, pp. 3483-90.

[17] O. Faruk, AK. Bledzki, HP. Fink and M. Sain. 2012. Biocomposites reinforced with natural fibers: 2000-2010, Progress in Polymer Science, Vol. 37, pp. 1552-1595.

[18] S. Jain and R. Kumar. 1992. Mechanical behavior of bamboo and bamboo composite, Journal of Material Science, Vol. 27, pp. 4598-4604.

[19] K. Okubo, K Fuji and Y. Yamamoto. 2004. Development of bamboo-based polymer composites and their mechanical properties, Composites: Part A, Vol. 35, pp. 377-383.

[20] KJ. Wong, S. Zahi, KO. Low and CC. Lim. 2010. Fracture characterization of short bamboo fiber reinforced polyester composites, Materials and Design, Vol. 31, pp. 4147–4154.

[21] MM. Thwea and K. Liao. 2003. Environmental effects on bamboo-glass/polypropylene hybrid composites, Journal of Materials Science, Vol. 38, pp. 363– 376.

[22] MM. Thwea and K. Liao. 2000. Characterization of bamboo-glass fiber reinforced polymer matrix hybrid composite, Journal of Materials Science, Vol. 19, 1873 – 1876.

[23] K. Okubo, T. Fuji and ET. Thostenson. 2009. Multi-scale hybrid biocomposite: Processing and mechanical characterization of bamboo fiber reinforced PLA with microfibrillated cellulose, Composites: Part A, Vol. 40, pp. 469–475.

[24] R. Krishnaprasad, NR. Veena, HJ. Maria, R. Rajan, M. Skrifvars and K. Joseph. 2011. Extraction of bamboo microfibrils and development of biocomposites based on polyhydroxybutyrate and

bamboo microfibrils, J. Composite Material, Vol. 45, pp. 1325–1329.

[25] P. Zakikhani, R. Zahari, M. T. H. Sultan and D. L. Majid. 2014. Bamboo Fiber Extraction and Its Reinforced Polymer, International Journal of Chemical, Nuclear, Metallurgical and Materials Engineering Vol. 8, pp. 287-290.

[26] CS. Verma and VM, Chariar. 2013. Stiffness and strength analysis of four layered laminate bamboo composite, Composites: Part B, Vol. 45, pp. 369–376.

[27] CS. Verma and VM, Chariar. 2012. Development of layered laminate bamboo composite and their mechanical properties, Composites: Part B, Vol. 43, pp. 1063–1069.

[28] AV. Rajulu, GB. Rao and RL. Reddy. 2001. Chemical resistance and tensile properties of epoxy/polycarbonate blend coated bamboo fibers, Journal of Reinforced Plastics and Composites, Vol. 20, pp. 335-340.

[29] S. Mandal, A. Alam, IK. Varma and SN. Maiti. 2010. Studies on Bamboo/Glass Fiber Reinforced USP and VE Resin, Journal of Reinforced Plastics and Composites, Vol. 29, No. 1, pp. 43-51.

[30] S. Mallaiah, KV. Sharma and M. Krishna. 2012. Development and Comparative Studies of Bio-based and Synthetic Fiber Based Sandwich Structure, International Journal of Soft Computing and Engineering Vol. 21, pp. 332-335.

[31] SAH. Roslan, ZA. Rasid and MZ. Hasan. 2015. Mechanical properties of bamboo reinforced epoxy sandwich structures, to be presented at 3rd International Conference on Mechanical Engineering Research (ICMER2015), 18-19 April, Kuantan, Malaysia.

[32] X. Chen, Q. Guo and Y. Mi. 1998. Bamboo fiber-reinforced polypropylene composites: A study of the mechanical properties, Journal of Applied Polymer Science, Vol. 69, pp. 1891–1899.

[33] MM. Thwea and K. Liao. 2003. Durability of bamboo-glass fiber reinforced polymer matrix hybrid composites, Composites Science and Technology Vol. 63, 375–387.

[34] MM. Thwea and K. Liao. 2002. Effects on environmental aging on mechanical properties of bamboo-glass fiber reinforced polymer matrix hybrid composites, Composite: Part A, Vol. 33, pp. 43-52.

[35] MYM. Zuhri, ZW. Guan and WJ. Cantwell. 2014. The mechanical properties of natural fiber based honeycomb core materials, Composites: Part B, Vol. 58. pp. 1–9.

[36] R. Krishnaprasad, NR. Veena, HJ. Maria, R. Rajan, M. Skrifvars and K. Joseph. 2009. Mechanical and thermal properties of bamboo microfibril reinforced polyhydroxybutyrate biocomposites, J Polym Environ, Vol. 17, pp. 109–114.

[37] SH. Lee and S. Wang. 2006. Biodegradable polymers/bamboo fiber biocomposite with bio-based coupling agent, Composites: Part A Vol. 37, pp. 80–91.

[38] S. Singh, AK. Mohanty, T. Sugie, Y. Takai and H. Hamada. 2008. Renewable resource based biocomposites from natural fiber and polyhydroxybutyrate-co-valerate (PHBV) bioplastic, Composites: Part A, Vol. 39, pp. 875–886.

[39] S. Ochi. 2012. Tensile properties of bamboo fiber reinforced biodegradable plastics, International Journal of Composite Materials, Vol. 2, pp. 1-4.

[40] M.M. Davoodi, S. M. Sapuan, D. Ahmad, A. Ali, A. Khalina and M. Janoobi. 2012. Effect of polybutylene terephtalate (PBT) on impact property improvement of hybrid kenaf/glassepoxy composite, Materials Letters, Vol. 67, pp. 5-7.

[41] A.K. Bledzki and J. Gassan, Composites reinforced with cellulose based fibers, Progress in Polymer Sciences, Vol. 24, 1999, pp. 221–274.

[42] YH. Muhammad and S. Ahmad. 2013. Mechanical and thermal properties of glass fiber-reinforced epoxy composite with matrix modification using liquid, Journal of Reinforced Plastics and Composites, Vol. 32, No. 9, pp. 612–618.

[43] M. Ramesh, K. Palanikumar and KH. Reddy. 2013. Mechanical property evaluation of sisal–jute–glass fiber reinforced polyester composites, Composites: Part B, Vol. 48, pp. 1–9.

[44] V. Mishra and S. Biswas. 2013. Physical and Mechanical Properties of bi-directional jute fiber epoxy, Composites Procedia Engineering, Vol. 51, pp. 561 – 566.

[45] HK. Mishra, BN. Dash, SS. Tripathy and BN. Padhi. 2000. A study on mechanical performance of jute-epoxy composites, Polymers-Plastics Technology Engineering, Vol. 39, No. 1, pp. 187-198.

[46] M. Robillard and G. Lebrun. 2010. Processing and mechanical properties of unidirectional hemp-paper/

epoxy, The 10th International Conference on Flow Processes in Composite Materials (FPCM10), Monte Verità, Ascona, CH – July 11-15.

[47] DU. Shah, D. Porter and F. Vollrath. 2014. Can silk become an effective reinforcing fiber? A properties comparison between flax and glass reinforced composites, Composite Science and Technology, Vol 101, pp. 173-183.

[48] J. George, J. Ivens and I. Verpoest. 1999. Mechanical properties of flax fiber reinforced epoxy composites, Die Angewandte Makromolekulare Chemie Vol. 272, pp. 41–45.

[49] PP. Gohil1 and AA. Shaikh. 2011. Cotton-epoxy composites: Development and mechanical characterization, Key Engineering Materials, Vol. 471-472, pp 291-296.

[50] P. Wambua, J. Ivens and I. Verpoest. 2003. Natural fibers: can they replace glass in fiber reinforced plastics?, Composites Science and Technology, Vol. 63, pp. 1259–1264.

[51] K. Oksman, L. Wallstrom, LA. Berglund and RDT. Filho. 2002. Morphology and mechanical properties of unidirectional sisal–epoxy composites, Journal of Applied Polymer Science, Vol. 84, pp. 2358–2365.

[52] Y. Xuea, Y. Dub, S. Elderc, K. Wang and J. Zhang. 2009. Temperature and loading rate effects on tensile properties of kenaf bast fiber bundles and composites, Composites Part B: Engineering, Vol. 40, No. 3, pp. 189–196.