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Natural Fiber Reinforced Polymer Composites: a Green Alternative

S. M. Sapuan[1,2], Y.A. El-Shekeil[1]
[1]Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[2]Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malysia, 43400 UPM Serdang, Selangor, Malaysia
E-mail: drsapuan@yahoo.com

Abstract

Composites are materials that consist of two or more materials; one of them serves as a matrix and one or more serve as fillers or reinforcing agents. Polymers are divided into petroleum based and biobased. Biobased polymers come to replace petroleum based once to reduce the impact of synthetic polymers on the environment. Fibers can be synthetic (e.g. carbon and glass fiber) or natural fibers such as kenaf, jute and sisal. Due to huge amount of plastics and synthetic fiber-plastic composites, and their negative effect on environment, shortage of landfill space, depletion of petroleum resources –which is needed to produce plastics- the need of biobased plastics and composites is growing. The importance of natural fiber composites has become more apparent due to their numerous benefits such as low cost and density. They have less abrasiveness to equipment and they need less energy for processing if compared to synthetic fiber composites. They are also renewable and biodegradable. This paper overviews the natural fiber reinforced polymer composite; its background, polymers, natural fibers, composite mechanical properties and natural fiber composites.

Keywords: Natural fiber composites, eco-friendly materials, renewable fibers.

1. Background

Composites are materials that consist of two or more materials; one of them serves as a matrix and one or more serve as fillers or reinforcing materials. The properties of the composite material vary from the properties each individual component. By 1960s fiber reinforced polymers were too expensive, therefore used in the niche market only. By the 1980s and 1990s decreased to be used in broad applications [1]. Polymers are divided into petroleum which is popular and biobased polymers that come to replace petroleum based once to reduce the impact of synthetic polymers on the environment. Fibers can be synthesis such as; carbon, and glass fibers and can be natural fibers such as kenaf, jute and sisal. Due to huge amount of plastics and synthetic fiber-plastic composites, and their negative effect on environment, shortage of landfill space, depletion of petroleum resources –which is needed to produce plastics- the need of biobased plastics and composites is growing. The new trend of biobased plastics and composites is based on renewable plant and agricultural stock [2]. It will be difficult to substitute petroleum-based products with 100% biobased ones. A viable solution is to combine petroleum and bioresources to produce useful products [2].

The importance of natural fiber composites has become more apparent due to their numerous benefits such as low cost and density. They have less abrasiveness to equipment and they need less energy for processing if compared to synthetic fiber composites. They are also renewable and biodegradable. On the other hand there are some obstacles facing today’s very promising natural fiber composites industry. The first point raises when natural fiber composites are discussed is the fiber-polymer incompatibility. The reason behind incompatibility is the hydrophilic nature of natural fibers vs. hydrophobic nature of most polymers used in this field. In the trail to reduce incompatibility many methods have been used including but not limited to chemical and physical treatments for natural fibers, using coupling agents in the interface between fibers and polymers etc.

2. Polymers

Polymers and polymer composites are gaining more importance as structural materials and replacing materials for metals in applications within the aerospace, automotive, marine, sporting goods and electronic industries. Polymers are divided into two main groups; thermoplastics and thermosets.

Molecular structure of thermoplastics is simple. Their macromolecules are independent. Thermoplastics can be softened or melted by heating; therefore they can be shaped, formed and solidified when cooled. Thermoplastics can be recycled and reprocessed without sever damage [3].

Thermosets have independent macromolecules before hardening, just like thermoplastics, however hardening creates three dimensional structures by chemical cross linking during processing.

Using thermoplastic composite in structural application will need the help of fiber reinforcement in order to have more stiffness to withstand the load. Fiber reinforced polymers started after World War II. Combining fibers with polymers resulted in better mechanical properties than either the components alone. By 1960s fiber reinforced polymers were too expensive, therefore used in the niche market only. By the 1980s and 1990s decreased to be used in broad applications [1].

Based on chemical structure types of thermoplastics can reach more than 50. There are thermoplastic in the group of polyolefins (e.g polyethylene, polypropylene), vinyls (e.g, poly-vinylchloride), styrenics (e.g polystyrene), fluoropolymers (e.g polychlorotrifluoro-ethylene), acrylics (e.g polymethylmetacrylate), polyesters (polyethylene terephthalate), polyimides (e.g polyetherimide), polyamides (e.g nylon 66), Sulfur-containing polymers (e.g polysulfone), Polyethers (e.g polyacetal), and others like thermoplastic polyurethane [4].

Advantages of thermoplastics compared to thermosets [3, 5, 6]:

It is rational to justify using thermoplastic despite their higher cost rather than using thermoset polymers:

- Thermoplastics can be melted, reformed and reshaped without losing its properties, while thermosets are cross-linked after the first curing and cannot be reformed or remelted.
- Thermoplastic processing time is a fraction of the long curing time of thermosets.
- Thermoplastics have near infinite shelf life with less cost to be stored, while shelf life of thermosets is less than six months with added refrigerating expenses.
- Thermoplastics have greater toughness than thermosets, which means a better impact strength.
- Thermoplastics can be completely recycled, and little to no volatile organic compounds (VOCs) are released during processing. Thermosets materials, on the other hand, can only be ground filled.
- Reduction in cycle time at temperature, the processing energy of the thermoplastics is less than processing energy for thermosets.

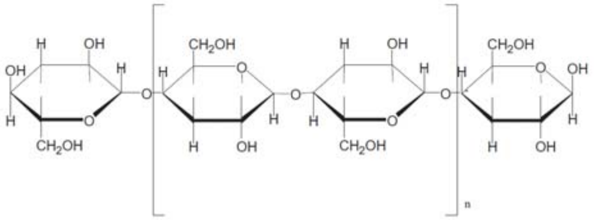
Disadvantages of thermoplastics compared to thermosets

The biggest disadvantage of thermoplastics compared to thermoset is that viscosity of thermoplastics is higher than viscosity of thermosets. Thermoplastics can have melt viscosities from 500 to 1000 times more than thermosets [7]. Therefore; it will need higher pressure in processing. High matrix viscosity of thermoplastics can cause other problems during processing thermoplastic composites such as de-alignment of reinforcing fibers during consolidation and the formation of voids within the final composite product. Another disadvantage of thermoplastics is the creep and relaxation of the material if the temperature rises. This is because thermoplastics have no chemical links between macromolecules [3]. Policies to use recyclable materials are increasing, therefore, in some applications industry is going towards using thermoplastics despite its disadvantages.

3. Natural fibers

Natural fibres are considered as composites of hollow cellulose fibrils with lignin and hemicelluloses as matrix. [8]. Natural fibers are divided into three main divisions based on their origins; plants, animals and minerals as shown in Figure 1. The term “natural fibers” in this research will be directed to plant (lignocellulosic) fibers. Plant fibers include straw, bast, leaf, seed, or grass fibers. Properties of natural and synthetic fibers are shown in Table 1. Typical structure of a natural fiber is shown in Figure 2.

The main component of plant fibers is cellulose followed by hemicelluloses and lignin. Cellulose is a linear macromolecule consisting of ($C_6H_{11}O_5$) repeating units. Chemical structure of cellulose is shown in Figure 3. Cellulose has an average molecular weight between 130,000 and 190,000 with an average degree of polymerization of approximately 800 to 1200. Hemicelluloses consist of polysaccharides of comparatively low molecular weight built up from hexoses, pentoses, and uronic acid residues [9]. Lignin is a complex chemical compound –it’s thought to have three-dimensional copolymer of aliphatic and aromatic constituents with very high molecular weight. It gives the rigidity to the plants [2, 9]. Chemical composition of some natural fibers is



shown in Table 2

Fig. 3. Chemical structure of cellulose

Table.

Cellulose is the main component of natural fibers. Main component of cellulose is anhydro-d-glucose, which contains three hydroxyl groups. These hydroxyl groups make natural fibers hydrophilic in nature [10, 11]. Natural fibers are increasingly being used due to their lightweight, non-abrasiveness, combustibility. They are also non-toxic, lower in cost than synthetic fibers with biodegradable properties.

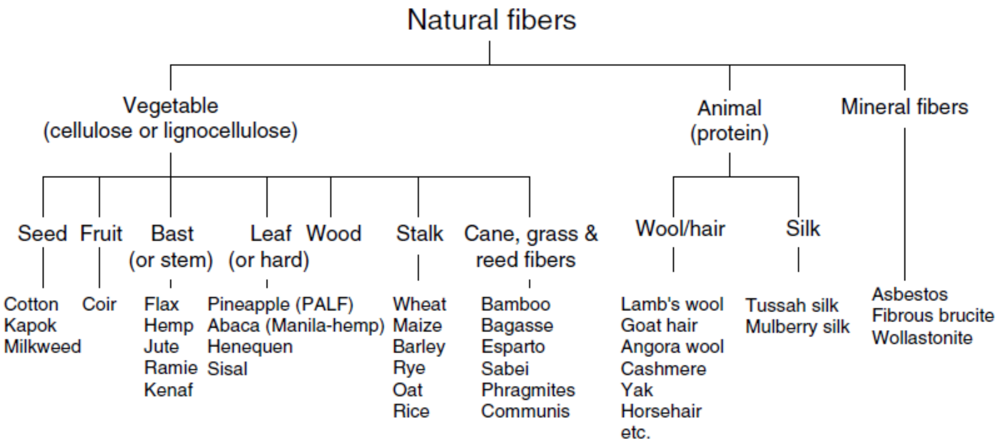


Fig. 1. Classification of natural fibers [12].

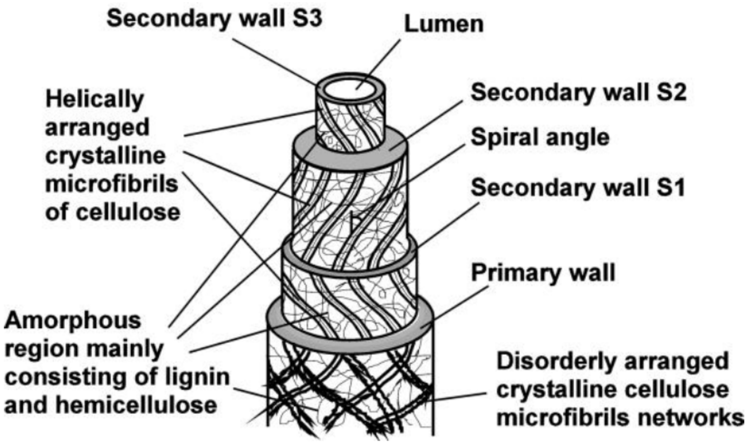
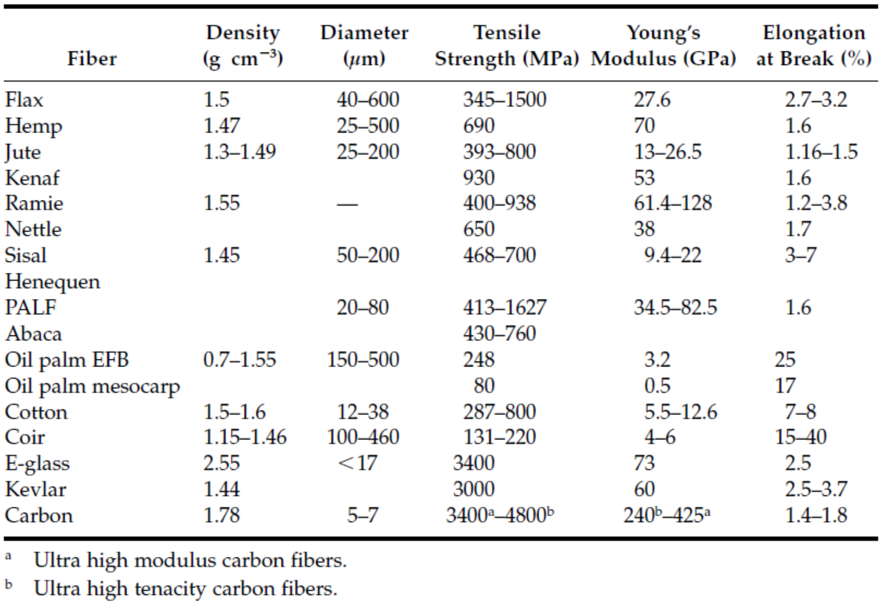


Fig. 2. Typical structure of natural fiber [8]

Table 1. Properties of natural and synthetic fibers [16]



Fiber	Density (g cm^{-3})	Diameter (μm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
Flax	1.5	40–600	345–1500	27.6	2.7–3.2
Hemp	1.47	25–500	690	70	1.6
Jute	1.3–1.49	25–200	393–800	13–26.5	1.16–1.5
Kenaf			930	53	1.6
Ramie	1.55	—	400–938	61.4–128	1.2–3.8
Nettle			650	38	1.7
Sisal	1.45	50–200	468–700	9.4–22	3–7
Henequen					
PALF		20–80	413–1627	34.5–82.5	1.6
Abaca			430–760		
Oil palm EFB	0.7–1.55	150–500	248	3.2	25
Oil palm mesocarp			80	0.5	17
Cotton	1.5–1.6	12–38	287–800	5.5–12.6	7–8
Coir	1.15–1.46	100–460	131–220	4–6	15–40
E-glass	2.55	<17	3400	73	2.5
Kevlar	1.44		3000	60	2.5–3.7
Carbon	1.78	5–7	3400[a]–4800[b]	240[b]–425[a]	1.4–1.8

[a] Ultra high modulus carbon fibers.

[b] Ultra high tenacity carbon fibers.

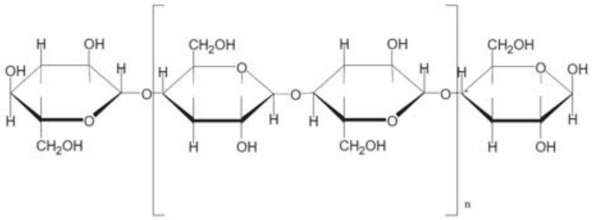


Fig. 3. Chemical structure of cellulose

Table 2. Chemical compositions of some plant fibers [13]

Type of fiber	Cellulose	Lignin	Pentosan	Ash	Silica	Spiral Angle (deg)
Stalk Fiber						
Straw						
Rice	28-48	12-16	23-28	15-20	9-14	-
Wheat	29-51	16-21	26-32	4.5-9	3-7	-
Barley	31-45	14-15	24-29	5-7	3-6	-
Oat	31-48	16-19	27-38	6-8	4-6.5	-
Rya	33-50	16-19	27-30	2-5	0.5-4	-
Cane fiber						
Bagasse	32-48	19-24	27-32	1.5-5	0.7-3.5	-
Bamboo	26-43	21-31	15-26	1.7-5	0.7	-
Grass fiber						
Esparto	33-38	17-19	27-32	6-8	-	-
Sabai	-	22	24	6	-	-
Reed fiber						
Phragmites Communis	44-46	22-24	20	3	2	-
Bast Fiber						
Seed flax	43-47	21-23	24-26	5	-	8-10
Kenaf	44-57	15-19	22-23	2-5	-	8
Jute	45-63	21-26	18-21	0.5-2		8
Hemp	57-77	9-13	14-17	0.8	-	6
Ramie	89-91	-	5-8	-	-	8

Core fiber						
Kenaf	37-49	15-21	18-24	2-4	-	-
Jute	41-48	21-24	18-22	0.8		-
Leaf fiber						
Abaca			-			
(Manila)	56-63	7-9	15-17	1-3	-	-
Sisal						
(agave)	43-62	7-9	21-24	0.6-1	-	10-25
Seed Hull fiber						
Cotton	85-96	0.7-1.6	1-3	0.8-2	-	-
Wood fiber						
Coniferous	40-45	26-34	7-14	<1	-	-
Deciduous	38-49	23-30	19-26	<1	-	-

4. Composite materials

A composite material can be defined as a material containing two or more materials which after mixing in a controlled manner can produce a new material with new properties. These properties are unique and superior in some respects to the properties of individual components [14]. Composites can be classified into three of the following: ceramics, metals and polymeric composites. This research is concerned only about the polymeric composites. From another point of view the composite material can be defined as a material that consists of fibers or fillers plus a resin. Fibers work as carriers of the load, therefore increase the stiffness of the composite. Fillers serve to reduce the cost. Sometimes additives are added to the composites to enhance mechanical and physical properties. Composite materials can be classified based in two main categories: based on size of fibers, or type of fibers. First, by size: short or long fiber size. Second, synthetic or natural fibers. This research is concerned about a short natural fiber composite.

4. Composite mechanical properties

Composite mechanical properties are considered the most important even though the composite may not be designed for load bearing applications. At least shape of the composite product should be maintained stable during usage [13]. Mechanical properties for short fiber reinforced composites are not easy to be estimated. There are some reasons behind that such as: (1) fiber dispersion, (2) fiber orientation distribution, (3) fiber volume fraction and (4) the quality of interface between fiber and matrix that influence the composite properties [13]. These factors, due to variation in fiber length and fiber length distribution in short fibers, along with inherent process variability, cannot be controlled precisely during manufacturing from part to part or from batch to batch [13, 15, 16]. Significant change in properties of the composite can be achieved by changing factors like aspect ratio and volume fraction [17]. If the aspect ratio is too small there will be insufficient stress transfer to fibers and thus the reinforcement is improper and sometimes fiber will act as a filler. In contrast if the aspect ratio is too high, the fibers may get entangled during processing leading to poor mechanical properties, due to poor dispersion. At low level of fiber loading the fibers are not able to transfer the load to one another leading to decrease in the strength. At higher levels of fiber content the fibers are not sufficiently wetted by the matrix, and the increased population of fibers leads to agglomeration and stress transfer gets blocked [18-20].

5. Natural fiber composites

Natural fiber reinforced polymers are gaining more and more awareness due to benefits such as renewability, biodegradability and reduction in weight and cost. Further advantages of natural fibers are [21]:

- As plants they contribute to CO2 consumption;
- At the end of natural fiber's life if burned or landfilled, the amount of CO2 is neutral;
- The abrasive nature of natural fiber is low which make it easy to process and more recyclable.

Factors like worldwide environmental concern, very fast consumption of petroleum, since plant resources 100,000 times faster than petroleum resource can be renewed [22], these factors are forcing the whole world to "go green".

Joshi et al. [23] have studied the life cycle of natural and glass fiber composites and found that natural fibers are environmentally superior to glass fibers in most cases. The following reasons justify this conclusion: 1- processing natural fibers has less impact into the environment; 2- an application requires a higher percentage of natural fiber than glass fiber to get the same performance, which reduces the percentage of polymer needed. This contributes to lower the cost and reduce the pollution caused by the polymers; 3- less density of natural fiber composites results in a better efficiency, and less emission in the usage stage -in the automotive applications; 4- burning the natural fibers at the end of its life results in energy and carbon credits. However, fertilizer use in natural fiber cultivation results in higher nitrate and phosphate emissions which can lead to a negative effect on local water [24]. Energy consumed to produce a glass fiber is much more than the energy of producing a natural fiber. The energy needed to produce a fiber like flax is approximately 17% of the energy needed to produce the same amount of glass fiber [25].

Research by Mohanty et al. [26] has shown that natural fiber composites show comparable or even better mechanical properties over glass fiber reinforced plastics. However, utilizing natural fibers and replacing glass fibers is still challenging. Lots of work needs to be done in order to overcome the shortcomings of natural fibers. Some of the common drawbacks of utilizing natural fibers with polymer composites are: high moisture sorption, which affects the properties of the final product and low processing temperature due to the degradation of natural fibers at high temperature. The high moisture sorption limits the applications of the composites, and the low processing temperature limits the matrix selection to the low melted matrices. Another problem facing natural fiber reinforced polymers is the poor adhesion (i.e. incompatibility) between fibers and polymers due to the hydrophilic nature of cellulose and the hydrophobic nature of polymers. There are three main solutions for the poor adhesion; pre-treating natural fibers to enhance their properties, using coupling agents or compatiblizers to modify the polymers, and selecting suitable processing methods for producing the composites [26].

Uniformity and shape of natural fibers gives them another challenge to be produced. Along the length of the fiber different there are always different cross-sections. This makes difficulty in the prediction of the mechanical properties of the composites. Natural fiber composites are not considered totally green unless growth, separation and processing of the fibers are well controlled. Durability of the composite product is another issue where it should be comparable to glass fiber composites [24].

6. Acknowledgment

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