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A review of current development in natural fiber composites for structural and infrastructure applications

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***Abstract*—Natural fiber composites (NFC) as the name implies is made of natural resources thus possesses environmentally beneficial properties such as biodegradability. With its natural characteristics, NFC is obtaining more attention in recent years in various application including automotive, merchandise, structural and infrastructure. Several studies have shown that NFC can be developed into a load-bearing structural member for applications in structural and infrastructure application. As an engineered material, similar with synthetic fiber composites, the properties of NFC can be tailored to meet certain requirements. The challenge in working with NFC is the large variation in properties and characteristics. The properties of NFC to a large extent influenced by the type of fibers, environmental condition where the plant fibers are sourced and the type of fiber treatments. However, with their unique and wide range of variability, natural fiber composites could emerge as a new alternative engineering material which can substitute the use of synthetic fiber composites.**

Keywords-Natural fiber; Bio composite; plant fiber; infrastructure; fiber composites

I. INTRODUCTION

Fiber composites offer many benefits such as high strength, light weight, water resistance, chemical resistance, high durability, electrical resistance, fire resistance and corrosion resistance. Moreover, the properties and performance of fiber composites can be engineered according to the requirements and thus prove cost effective in most usage. Fiber composite materials such as glass fiber, carbon fiber and aramid have been widely used in automotive and aircraft industries and are now being used in structural and infrastructure application.

In structural and infrastructure applications, fiber composites have been used to rehabilitate existing structures such as bridges and buildings [1-3], especially those that are subjected to marine environment or corrosive environment. Fiber composites also have been used for constructions that are exposed to different types of loading and environment. Examples of such are windmill, roof, bridge, girder, railway sleepers, floating river walkway, monocoque fibre composite trusses, structural portal frames and truss system for deployable shelter [1, 4-9]

The principle in fiber composites is to utilize fibers as reinforcement in matrix of resin. Fibers usually provide the greatest share of strength while resin provides binding to the fibers. Fibers by themselves cannot be used to sustain actual loads. Therefore, resin is used to bind and protects the fibers. Depending on the type of fibers, type of resin, the proportion of fiber-resin and the type of manufacturing process, the properties of fiber composites can be tailored to achieve the desired end product. In similar manner, natural fibers can also be used to produce fiber composites.

Due to the need for more environmental friendly materials, natural fiber composites are regaining the attention that once has been shifted to synthetic products. The first known utilization of natural fiber composites was straw reinforced clay for bricks and pottery [10]. Many of the early research and development in fiber composites are dominated by the use of synthetic fibers. Although synthetic fiber composite materials such as glass fibers, carbon fibers and aramid are high performance materials, they are less biodegradable and are sourced from non renewable resources. Therefore, the use of natural fibers may bring environmental benefits as well as cost benefits.

The fact that natural fibers are sourced from plants which are renewable in origin and the fact that they can be easily biodegraded has encouraged more research into this field. Examples of natural fibers that have been used in research and development of fiber composites system are hemp, jute, cotton, flax, coir, kenaf, pineapple leaf fiber (PALF), banana leaf fiber and several others. The use of natural fibers is particularly beneficial to local usage and industries.

This paper aims to inform the existing development of natural fiber composites in structural and infrastructure applications.

II. NATURAL FIBERS

Natural fibers in simple definition are fibers that are not synthetic or manmade. They can be sourced from plants or animals. Hence, these fibers are actually in abundance stock around the world. Several plants from which fibers can be sourced are Sisal (*Agave sisalana*), Hemp (*Cannabis sativa*), Bamboo, Coconut (*Cocos nucifera*), Flax (*Linum* *usitatissimum*), Kenaf (*Hibiscus cannabinus*), Jute (*Corhorus capsularis*) and Ramie (*Boehmeria nivea*). Fibers from animals are for example wool (Sheep) and feathers (Chicken). This paper is focused only to plant fibers.

From part of the plant where the fibers are sourced, the fibers can be classified into bast fibers (jute, flax, hemp, ramie and kenaf), leaf fibers (banana, sisal, agave and pineapple), seed fibers (coir, cotton and kapok), core fibers (kenaf, hemp and jute), grass and reed (wheat, corn and rice), and other types of fibers [11].

Traditionally, especially in rural developing countries, natural fibers have been cultivated and used extensively for non-structural applications such as multipurpose rope, bag, broom, fish net and filters. The fibers have also been used for applications in housing as roof material and wall insulation.

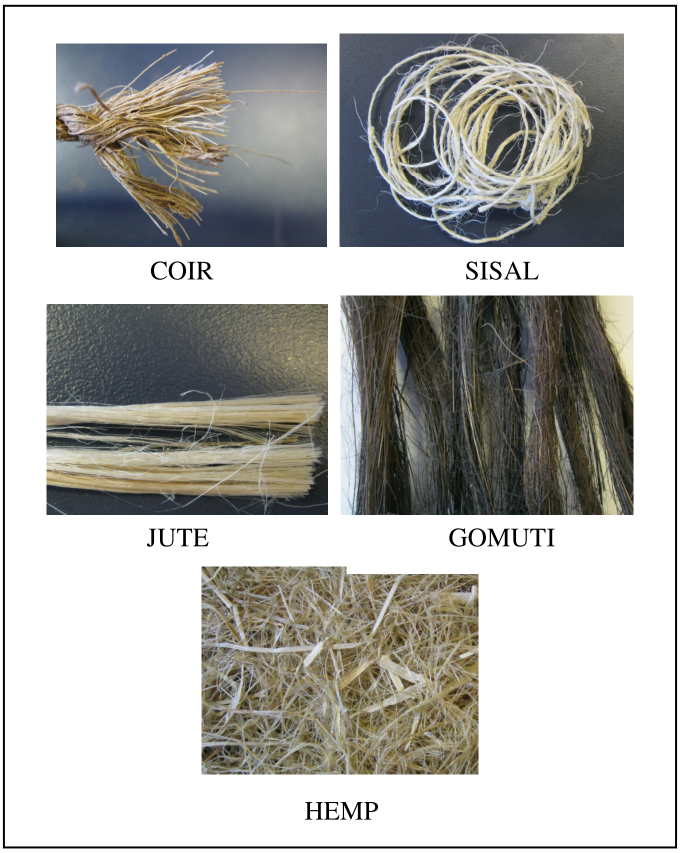

Figure 1. Pictures of several natural fibres.

Figure 1 shows the picture of coir, sisal twine, jute, gomuti and short hemp fiber. Coir fibers are fibers obtained from the husk of coconut fruit. The fibers generally have coarse texture and have white to dark brown color. Sisal fibers are extracted from the leaves of sisal plant. Sisal fibers are stiff and have relatively coarse texture even though less coarse than coir. Gomuti fibers are generally black and stiff fibers that are obtained from *Arenga Pinnata* (sugar-palm) tree. Hemp and jute fibers have finer texture and smaller diameter compared to coir, gomuti and sisal. However, compared to glass fiber (diameter: 2.5-10 μm) [12], hemp and jute have larger diameter. Table 1 outlines the physical appearance of natural fibers depicted in Figure 1.

TABLE I. PHYSICAL APPEAREANCE OF SOME NATURAL FIBERS

Type of fibers	Diameter (μm)	Texture and color
Hemp	26.5	Silky-fine; White to light brown
Jute	25-200 [13]	Fine; Light brown
Sisal	50-200 [13]	Coarse-stiff; White
Coir	100-450 [13]	Coarse; White to brown
Gomuti (Sugar-palm fiber)	50-800	Coarse-stiff; brown to black

A large variation is found in the properties of natural fibers. The properties are affected by several factors such as type of fibers, moisture content and form of fibers (yarn, woven, twine, chopped, felt, etc). Moreover, the properties are also affected by the place where the fibers are grown, cultivation condition, the part of the plant they are harvested from, growing period and retting or extracting process [14-16].

TABLE II. TYPE AND PROPERTIES OF THE COMMON NATURAL FIBERS

Type of fibers	Density (g/m^3)	Tensile strength (MPa)	Young's modulus (GPa)	Ref.
Hemp	1.48	514	24.8	[17, 18]
Jute	1.3 – 1.45	393-773	13 – 26.5	[13]
Flax	1.50	345-1100	27.6	[13]
Sisal	1.45	468-640	9.4 – 22	[13]
Coir	1.15	131-175	4 – 6	[13]
Ramie	1.51	500	44	[18]
Cotton	1.51	400	12	[18]
Gomuti (Sugar-palm fiber)	1.29	190.29	3.69	[19]

Table II shows the type and properties of the common natural fibers. It is shown in the table that flax and jute have the highest tensile strength. Although the values are lower than the tensile strength of synthetic fibers, natural fibers offer lower density and competitive Young's modulus.

III. NATURAL FIBER COMPOSITES (NFC)

Natural fiber composites can be a combination of either natural fibers/synthetic resin or natural fibers/bio-resin. Bio-resin means bio-degradable resin. Both synthetic and bio-resin can be either in the form of thermoset or thermoplastic type of resin. Natural fibers/thermoplastic composites have been used in automotive applications [14]. However, most composites for infrastructure are made out of thermoset resins [3]. NFC has been used also in biomedical applications for bone and tissues repair and reconstruction [20].

Several studies have been done in an attempt to investigate the properties of natural fiber composites. Table III shows a summary of several natural fiber composites that have been reported in the literatures. As can be inferred from the table, the property (tensile strength) of natural fiber composites varied depending on the type of fibers, type of resin and manufacturing process. Fiber fraction and treatment also affect the properties of natural fiber composites.

In table III, sisal/LDPE (low density polyethylene) composites have lower tensile strength compared to sisal/polyester composites. Among all the listed composites in the table, flax/polyester composites produced by vacuum infusion has the highest tensile strength.

TABLE III. SEVERAL NATURAL FIBER/SYNTHETIC RESIN COMPOSITES

Type of fibers	Resin	Manufacturing process	Tensile strength (MPa)	Ref.
Flax	Polyester	Vacuum infusion	61.00	[21]
Jute	Polyester	Hand lay-up	60.00	[22]
Hemp	Polypropylene	Extrusion & Inj. mold.	50.50	[17]
Hemp	Polypropylene	Compression moulding	52.00	[23]
Hemp	Polyester	Resin transfer molding	32.90	[24]
Coir	Epoxy	-	17.86	[25]
Coir	Polyethylene	Extrusion-compr. mold.	26.20	[26]
Coir	Polypropylene	Compression moulding	10.00	[23]
Sisal	Low density polyethylene	-	16.50	[27]
Sisal	Polyester	-	47.10	[28]
Sugar-palm fiber	Epoxy	Hand lay-up	51.73	[29]
Sugar-palm fiber	Polyester	Hand lay-up	24.49	

Coir reinforced composites have significantly low tensile strength. However, the composites have higher impact strength which is beneficial in automotive applications or applications that require considerable impact resistance. Cotton reinforced composites also showed high impact strength (approximately 50-80 kJ/m^2) when epoxy resin or agro-based resin is used [30].

Even though synthetic resins provide good protection to the fibers, they are mostly products of petrochemical materials hence not fully biodegradable. Bio resin has environmental benefits over petroleum-based synthetic resin because it is biodegradable. Several developed biodegradable resins are cellulose acetate, copolyester, polycaprolactone (PCL), poly(ester amide), poly(ethylene terepthalate), (PET)-modified, polyglycolide (PGA), polyhydroxyalkanoates (PHA), poly(lactic acid) (PLA), poly(vinyl alcohol) (PVOH), starch and starch blends, and other blends [13].

In a number of researches, natural fibers/bio-resin composites have revealed comparable or better properties than natural fibers/synthetic resin composites. Chopped hemp/cellulose acetate composites have shown better flexural strength and modulus of elasticity compared to hemp/polypropylene composites [31]. A significantly high tensile and flexural strength (365 MPa and 223 MPa, respectively) have been achieved in a study by Ochi [32] which combined the use of emulsion-type biodegradable resin and Manila hemp fiber bundles with 70% fibre volume fraction.

Unidirectional hemp fibers and cashew nut shell liquid (CNSL) composites have shown tensile strength of 56.37 MPa and Young's modulus of 24.31 GPa [33]. The result is higher than the tensile strength of hemp/polypropylene composites (Table III). When treated with alkali treatment, the tensile strength of unidirectional hemp fibre/CNSL improved to 83.29 MPa and the Young's modulus to 29.79 GPa [33]. These value are within the range of the value of tensile strength of glass fiber/polyester composite [12].

Treatment to natural fibers may influence the overall properties including tensile strength and modulus, and flexural strength and modulus. Basically, treatments to the fibers are intended to enhance the adhesion between natural fibers and the matrix to improve the interface of the composites. However, depending on the type of treatments and amount of treatment agents, the properties of the natural fiber can be enhanced or reduced. Stronger and better composites can be achieved with the correct and optimum treatment. Examples of the treatments are alkali treatment, heat treatment, hot water treatment, silane treatment, and saltwater treatment. When carefully treated and developed, natural fiber composites can have comparable properties to the existing synthetic fiber composites.

IV. NFC FOR STRUCTURAL AND INFRASTRUCTURE APPLICATIONS

More interest is now shown in the investigation of the suitability of natural fiber composites in structural and infrastructure applications where moderate strength, lower cost and environmental friendly features are required. The application of natural fiber composites has started in automotive industries and productions of non structural elements. In 1986, a study has been published where it is reported that coir/polyester composites have been used to produce mirror casing, paper weights, projector cover, voltage stabilizer cover, mail-box, helmet and roof [12]. In structural applications and infrastructure applications, natural fiber composites have been used to develop load-bearing elements such as beam, roof, multipurpose panel, water tanks and pedestrian bridge.

Beam is one of the basic components in buildings, bridges and other structures. A beam is considered as a structural element that is in bending or flexural mode. Beams can have square cross section or rectangular depending on the design and requirements. Structural beams are tested for their flexural capacity with three points or four points bending test which will give results of load capacity, flexure stress, strain, deflection, and modulus of elasticity.

Traditionally, beams are made of timber, reinforced concrete, steel profiles, laminated veneer lumber (LVL) or glulam. Recent developments have shown the possible cost, weight, installation and time advantages of using fiber composites beams. Therefore, an opportunity exists for the applications of NFC in the development of structural beams and pedestrian bridge girders which requires low to moderate design loads. The idea of using natural fiber composites in beam development is prompted by the lower density of natural fibers, lower cost and environmental benefits.

Composite sandwich beam is one of many feasible concepts. This type of beam incorporates the use of several layers of materials. Usually, the same material is used for the thin top and bottom part and the thick core material placed in between. The material for top and bottom (skins) is usually of higher strength than the core. Sandwich beams made of cellulose fibers (from recycled paper) reinforced Acrylated Epoxidized Soy-bean Oil (AESO) and foam core have been developed and studied by Dweib et al. [34].

Another concept of natural fiber composite beam was an I-shaped beam. A composite of woven jute fabric (burlap) and soybean oil based resin system has been successfully used to develop an I-shaped beam using vacuum assisted resin transfer molding (VARTM) method [35].

In structural design, the most commonly used primary design criteria are bending strength, bending stiffness, tensile strength and tensile stiffness [36]. However, for certain applications such as roof, impact strength is also important. In Australian standard (AS 4253.3-2006), for glass fiber reinforced polyester to be used as roof materials, it has to show impact resistance of 1.96 J and has the tensile strength not less than 50 MPa with no visible cracking or crazing or hole after testing. Roof material has to be designed to sustain dead load, live load, wind load and in some cases, snow load. The material has to be lightweight, fire resistant, water resistant and weather resistant (such as resistant from ultraviolet light).

Roofing sector has the second largest percentage (after electricity) of glass fiber usage in building and construction in Europe while usage for industrial infrastructure including corrosion resistance, pipes and tanks has the third rank in percentage [36]. These sectors where moderate strength is required and high demand is shown, offer significant opportunity where natural fiber composites can be easily introduced.

Roof materials made of natural fiber composites that have been developed are for example woven mat sisal fiber/cashew nut shell liquid (CNSL) [37] and recycled paper reinforced AESO with a foam core [38]. The recycled paper reinforced AESO composites is in the form of sandwich panel and was used to construct a monolithic roof for a single story A-frame house.

Composite panel is usually a flat surfaced element on both sides although corrugated panels are also possible. It is usually of uniform thickness and can be produced with different dimension. A panel can be made from homogenous material, composite laminate or sandwich panel. LOC Composites Pty Ltd has developed and produced a fiber composites sandwich panel which uses plant based polymers that can be used in several applications such as balcony construction, walls, roofs, floors and fire doors [39]. A natural fiber composites panel suitable for housing construction materials, furniture and automotive parts has also been developed using recycled paper/AESO composites [14].

In the area of structural rehabilitation, jute mats reinforced composites have been used for trenchless rehabilitation of underground drain pipes and water pipes [40].

The previously mentioned studies have highlighted that natural based materials can be used effectively to develop load bearing materials such as for roofs, beams and panels. Furthermore, for infrastructure applications where the use of synthetic fibers is not suitable, natural fibers can be a suitable substitute.

The main and current drawbacks of natural fiber composites in structural and infrastructure applications are mostly related to the large variation in the properties of the natural fibers, treatments and manufacturing optimization. These concerns need to be addressed in order to develop and produce improved structural elements that can be used both for structural and infrastructure applications.

V. SUMMARY

Previous researches have shown the feasibility of the usage of natural fiber composites in various civil engineering applications including roofing and bridges. The all-natural composites which are composites made of natural fibers and biodegradable resins are an important development that shows feasibility not only for non load bearing construction elements but also for structural elements. Thus natural fiber composites offer precious environmental benefits.

Currently the growing use of natural fiber composites is based more on the environmental and low-cost benefits rather than on their strength capabilities. Therefore, more research is needed to obtain better strength and modulus properties including optimizing the interfacial bond between the fiber and resin by means of fiber treatment.

More research into the application of natural fiber composite in structural and infrastructure is needed especially with regard to the issues of cost of fiber and the supply of fiber for mass production of the composites.

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