Research Journal of Engineering Sciences ISSN 2278 – 9472
Vol. **2(3),** 46-53, April **(2013)** *Res. J. Engineering Sci.*

Review Paper

Natural Fiber as a substitute to Synthetic Fiber in Polymer Composites: A Review

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Available online at: www.isca.in
Received 12th February 2013, revised 21st March 2013, accepted 19th April 2013

Abstract

This work presents a brief overview of the improvement of the mechanical properties (tensile and flexural strength and the corresponding modulus of elasticity) of natural fiber reinforced polymer materials. The mechanical strength of the natural fiber reinforced polymer composites (NFRPCs) has been compared with that of glass fiber reinforced polymer composites and it is found that for achieving equivalent mechanical strength of the material, the volume fraction of the natural fiber should be much higher than that of the glass fiber. The eco-friendly nature (emission, economy of energy) of the production of components of NFRPCs has also been briefly discussed. It is concluded that NFRPCs have already been proven alternative to SFRPCs in many applications in automotive, transportation, construction and packaging industries, and the production of natural fiber being labor-intensive, the NFRPC industry will create new employment and will contribute to the poverty alleviation program in developing countries.

Keywords: Polymer composites, natural fiber, biodegradable composites, mechanical strength improvement, light composites.

Introduction

Fiber reinforced polymer materials are composites consisting of high strength fibers (reinforcement) embedded in polymeric matrices. Fibers in these materials are the load-carrying elements and provide strength and rigidity, while the polymer matrices maintain the fibers alignment (position and orientation) and protect them against the environment and possible damage. A pure polymer does not usually have requisite mechanical strength for application in various fields. The reinforcement by high strength fibers provides the polymer substantially enhanced mechanical properties and makes the fiber reinforced polymer composites (FRPCs) suitable for a large number of diverse applications ranging from aerospace to sports equipment.

The FRPCs are developed primarily using synthetic fibers such as glass, carbon, aramid, Kevlar etc. Synthetic FRPCs have unique advantages over monolithic polymer materials. Besides high strength and high stiffness, these composites have long fatigue life and adaptability to the intended function of the structure. Additional improvements can also be realized in the synthetic FRPCs with regarding corrosion resistance, wear resistance, appearance, temperature-dependent behavior, environmental stability, thermal insulation and conductivity[1].

Specific properties of these materials (such as high-stiffness, high-strength, and low-density as compared to metals) make the material highly desirable in primary and secondary structures of both military and civilian aircraft. These FRPCs are also used in various forms in the transportation industry. Ship structures incorporate composites in various forms. Kevlar or equivalent aramids have many applications in aerospace such as landing gear doors, aircraft cabin and jet engines.

Although the SFRPCs possess exclusive mechanical strength, they have got some serious drawbacks such as high cost, high density (as compared to polymers), and poor recycling and non-biodegradable properties. For these reasons, over the last few years natural plant fibers reinforced polymer composites are increasingly gaining attention as viable alternative to SFRPCs[2-4].

In certain composite applications bio-fibers have shown to be competitive in relation to glass fiber[5]. Natural fiber reinforced composites with thermoplastic matrices have successfully proven their qualities in various fields of application. The growing interest in using natural plant fibers as reinforcement of polymer-based composites is mainly due to their availability from renewable natural resources, satisfactorily high specific strength and modulus[6,] light weight, low cost and biodegradability[7]. The biodegradability of the natural plant fibers may present a healthy ecosystem while the low costs and good performance of these fibers are able to fulfill the economic interest of industry[8].

But still the mechanical strength of a natural fibers reinforced polymer composite (NFRPC) could not match that of a SFRPC and the natural fibers would not replace synthetic fibers in all applications. For the last decades, extensive research is underway in order to improve the mechanical properties of NFRPC, while the intrinsic properties of the natural fibers such as biodegradability and low specific gravity of the fibers remain unchanged. These researches include search of varieties of fibers from plant origin such as jute[9], Flax[10], Coir[11] etc. to be introduced in treated or untreated form in the polymer matrix. A number of review papers have also appeared describing different aspect of NFRPCs. Saheb and Jog[3] reviewed the works on NFRPCs with special reference to the type of fibers, matrix polymers, treatment of fibers and fiber-matrix interface. Taj et. al.[12] reviewed the properties, processing and application of polymer composites based on different types of natural fibers. Holbery and Houston[13] reviewed different aspects of the application of NFRPCs in automotive applications. Ticoalu et al.[14] discussed the potential of NFRPCs for structural and infrastructural applications. This work aims at i. briefly summarizing the reports in the literature concerning the improvement of the properties of the polymer composites consisting of various types of polymers and natural fibers, and discussing the reproducibility and the long term preservation of the material properties, ii. presenting a short comparative analysis of the mechanical strength of NFRPCs and SFRPCs, and iii. throwing some light on the environmental aspect and the socio-economical impact of the substitution of synthetic fiber by natural ones in polymer composites in the developing countries. Finally, the potential of the agriculture sector of the developing countries in contributing to the NFRPCs production has been briefly described.

Researches in search of an alternative to synthetic fiber

Since the 1990s, researchers have begun to focus attention on NFRPCs in response to the increasing demand for environmentally friendly materials and the desire to reduce the cost of traditional fibers (i.e., carbon, glass and aramid) reinforced polymer composites. Besides ecological considerations natural fibers exhibit many advantageous properties which promote the replacement of synthetic fibers in polymer composites. They are a low-density material yielding relatively lightweight composites with high specific properties and therefore natural fibers offer a high potential for an outstanding reinforcement in lightweight structures. Natural fibers are derived from a renewable resource and do not have a large energy requirement to process, and are biodegradable[15]. These fibers also offer significant cost advantages and therefore the utilization of lightweight, lower cost natural fibers such as jute, flax, hemp, sisal, abaca, coir offer the potential to replace a large segment of the synthetic fibers in numerous applications.

A number of thermosetting and thermoplastic polymers have been studied as binding materials in NFRPCs. Among the most studied thermosetting materials are epoxy resins and unsaturated polyesters, and among the thermoplastics, poly-olefins such as low and high density polyethylene as a well as polypropylene are the most studied. Different natural fibers have been introduced into the polymer compositions with a view to improve their mechanical properties. The reinforcement data of some NFRPCs have been collected from the literature and has been summarized below.

Natural fibers reinforced thermoset composites

The mechanical properties of a composite depend on the nature of the resin, fiber, resin-fiber adhesion, cross-linking agents and not the least on the method of the processing. Therefore, any improvement in the property is evaluated as compared to that of the polymer matrix undergone the same processing. The fibers are impregnated by the liquid resin usually at room temperature and then treated with some cross-linking agent for hardening. Usually with an increase in the fiber content in the composition, the tensile and flexural property gradually improves. Beyond certain limit of the fiber content, however, depending on the method of processing, the adhesion between the resin and the fiber decreases resulting in the decrease in the strength of final products. Epoxy resin has excellent adhesion to a large number of materials and could be further strengthened with the addition of fiber. Table-1 represents the improvements of the mechanical properties of some epoxy-based polymer composites.

Table-1
Improvements of the mechanical properties of some epoxy based polymer composites

Resin	Reinforcing fibers	Investigated mechanical properties	Properties of the base polymer (MPa)	Property improvement*, %	Corresponding Fiber content^w, %	References
Epoxy	Banana Coconut	Tensile strength	23.98 -	90 307.82	- 30 w	16 11
	Banana Bagasse (treated) Coconut	Flexural strength	53.38 - -	38 23.34 39.40	- 30 w 30 w	16 17 11
	Pineapple-leaf (treated)	Interfacial shear strength (IFSS)	-	152	-	18
	Banana Coconut	Young's modulus	1390 -	36 54.89	- 30 w	16 11
	Banana	Flexural modulus	1563.2	17.37	-	16

* Increment in relation to pure polymer (%), w = Fiber content in weight (%)

Polyester composites

Table-2 represents the improvements of the mechanical properties of some polyester-based polymer composites. Polyester has been studied more intensively than the epoxy resin, and the property enhancement is much higher with polyester.

Thermoplastic composites and their mechanical properties: Unlike the liquid thermosetting resins, thermoplastic polymers are in solid state of aggregation and are mixed with the fibers in molten state. Various fibers have been used in thermoplastic polymer-based composites and the effect on the mechanical properties have been studied. The literature data on the improvement has been presented in Table-3 and 4.

The thermoplastic polymers (PE and PP) investigated by different authors are with different molecular mass and their properties varies in a large range. Similar is the case with the resins. Different authors use different cross-linking agent and in different proportions. Thus the reference value for calculating the improvement in mechanical properties of the compositions described in the tables-1 through 4 varies from compositions to compositions. Still the trend in the improvement of the mechanical properties with the introduction of fiber in the composition is quite obvious. The extent of the improvement depends on the nature and strength of the resin/polymer and the fiber and also the interaction between them.

Table-2
Improvements of the mechanical properties of some polyester-based composites

Resin	Reinforcing fibers	Investigated mechanical properties	Properties of the base polymer (MPa)	Properties increment*, %	Corresponding Fiber content^{w,v}, %	References
Polyester	jute (untreated)	Tensile strength	250	900	60 v	19
	pineapple-leaf (untreated)		22.9	176	40 w	20
	okra (treated)		28	135	27.61 v	21
	Coir (untreated)		-	30	25 w	22
	Bagasse (treated)		10.6	152	65 w	23
Polyester	pineapple-leaf	Flexural strength	80.2	13	30 w	20
	coir(untreated)		-	27	25 w	22
	bagasse(treated)		-	315	65 w	23
Vinyl Ester	hemp(treated)		-	7	20 w	24
Polyester	jute	Young's modulus	4000	775	60 v	19
	pineapple-leaf		580	335	40 w	20
	okra(treated)		525	81	37.5 v	21
Vinyl Ester	hemp(treated)		-	10	20 w	24
Polyester	pineapple-leaf	Flexural modulus	1300	105	30 w	20
Vinyl Ester	hemp (treated)		-	22.5	20 w	24

* Increment in relation to pure polymer (%), w = Fiber content in weight (%), v = Fiber content in volume (%)

Table-3
Improvements of the mechanical properties of some polyethylene-based composites

Polymer	Reinforcing fibers	Investigated mechanical properties	Properties of the base polymer (MPa)	Properties increment*, %	Corresponding Fiber content^{w,v}, %	References
LDPE	Sisal (untreated)	Tensile strength	9.2	60	30 w	28
	Sisal		9.0	245	21.5 v	25
	Wood(treated)		9.8	67	40 w	27
LDPE	Sisal (untreated)	Young's modulus	140	458	30 w	28
	Sisal (untreated)		140	853	21.5 v	25
	Wood (treated)		350	272	40 w	27
HDPE	Hemp		1070	555	60w	26
	Rice hulls			181	60 w	
	Hardwood-A			349	60 w	
	Hardwood-B			349	60 w	

LDPE- Low Density Polyethylene, HDPE-High Density Polyethylene
* Increment in relation to pure polymer (%), w = Fiber content in weight (%), v = Fiber content in volume (%)

Table-4
Improvements of the mechanical properties of some PP-based composites

Polymer	Reinforcing fibers	Investigated mechanical properties	Properties of the base polymer (MPa)	Properties increment*, %	Corresponding Fiber content^{w,v}, %	References
PP	sisal fiber(treated)	Tensile strength	35	27	30 w	28
	bamboo(untreated)		22.5	56	50 w	29
	Pineapple-leaf(treated)		24.50	43	20 v	31
	Banana(treated)		24.50	34	15 v	32
	Abaca		-	45	30 w	33
	Bamboo(treated)		24.50	106	50 v	34
	Jute(treated)		-	120	60 w	9
	Rice hulls	Flexural strength	19.43	130	50 w	30
	Kenaf		19.43	260	50 w	30
	Pineapple-leaf(treated)		38	53	10 v	31
	Banana(treated)		38	48	15 v	32
	Abaca		-	35	30 w	33
	Bamboo(treated)		38	82	50 v	34
	Jute(treated)		-	100	60 w	9
	sisal fiber(treated)	Young's modulus	498	140	30 w	28
	bamboo(untreated)		1.8	160	50 w	29
	Rice hulls(treated)		869	214	50 w	30
	Kenaf		869	505	50 w	30
	Pineapple-leaf(treated)		560	32	20 v	31
	Banana(treated)		560	83	15 v	32
	Bamboo(treated)		560	192	15 v	34
	Banana(treated)	Flexural modulus	1650	125	15 v	32
	Bamboo(treated)		1650	150	50 v	34

* Increment as compared to the properties of the pure polymer, w = Fiber content in weight (%), v = Fiber content in volume (%)

Disadvantages of using natural fiber and the remedy

Although natural fibers are obtained from renewable sources and the polymer composites based on them are environmentally friendly as compared to the SFRPCs, there are also some disadvantages, which are related to the utilization of unmodified/raw fibers in the preparation of the composites. These disadvantages are as quality variations, high moisture uptake and low thermal stability of the raw fibers[35-37].

High moisture uptake is the major drawback of the natural fibers. This phenomenon weakens the interfacial bonding between the polymer matrix and fiber and causes deterioration of the mechanical properties. The high moisture sensitivity of some fiber such as lingo-cellulosic fiber causes even the dimensional instability[38-39] and limits the use of natural fiber as reinforcement in composite materials. In order to overcome this problem and ultimately to improve the fiber-matrix adhesion, in many cases, a pre-treatment of the fiber surface or the incorporation of surface modifier is required during the composite preparation. Many investigations have been reported in the literature on the influence of various type of chemical treatment on the physical and mechanical properties of NFRPCs[32-34, 40, 41].

Different treatments of the fibers give significant improvements in tensile and flexural strength, ranging from 10 to 120%[9,17] whereas for tensile and flexural modulus, the improvements were from 80 up to 214%[21, 28, 30].

The moisture absorption can be reduced substantially by the chemical treatments of fibers. Various types of chemicals such as, alkali (sodium hydroxide), isocyanate, $KMnO_4$ (permanganate), CTDIC (cardanol derivative of toluene diisocyanate), peroxide, enzyme etc. have been used for the treatment and a considerable change in the mechanical and physical properties of the composites have been obtained[42].

Tensile strength of NFRPCs as compared to some SFRPCs

The tensile strength of the fibers (synthetic or natural) is much higher than that of the polymer. Therefore, it is expected that the fiber reinforced polymer composites will show higher tensile strength than the polymer itself. Such improvement in mechanical strength is really achieved and the strength is usually found to increase with an increase in the fiber contents, although in most cases the strength of the composites does not strictly follow additive rule. The tensile strength of some NFRPCs has been compared with that glass fiber reinforced composites in figure-1. It should be noted that the polymer matrix used by different authors is not exactly the same. Although the matrix bears the general name 'polypropylene', due to different molecular mass distribution and preparation condition, it shows different characteristics. But still the data in figure-1 provides information about rough estimation. Thus as the figure-1 shows, the glass fiber yields much higher tensile strength in polypropylene (PP)-based composites than a number of natural fibers do. The same desired level of tensile strength (at some low level of strength) could be achieved for glass fiber reinforced composite as well as for NFRPCs; but the required fiber content for the purpose is much higher in latter composition than that in the first. For example, to achieve a tensile strength of 48 MPa, the required fiber content is 12 wt% for glass fiber, and 15wt%, 35wt%, 38wt%, and 38wt% for pineapple, abaca, kenaf, and aspen fiber respectively. Such approach to achieve high desired tensile strength is limited by the maximum natural fiber content that can be introduced in a given composition. Mueller and Krobjilowski[43] on the other hand, claim to have achieved almost identical tensile strength for PP composites with glass and Flax fiber. They showed that to achieve the tensile strength of 28 MPa, the required fiber content is 30wt% for glass fiber and 33wt% for flax fiber.

For equivalent strength performance, the specific gravity NFRPCs is lower than that of SFRPCs and hence the NFRPCs will be much lighter than the corresponding SFRPCs. Thus, although the NFRPCs do not still match SFRPCs concerning mechanical strength, as lighter material, they can meet the standard of other applications[43, 44]. Recently, hybrid composites reinforced by plant-synthetic fibers in a single polymer has been studied and enhanced mechanical strength have been achieved[45].

Industrial application of NFRPCs at this stage

Due to the low density and satisfactorily high specific properties of natural fibers, the composites based on natural fibers have very good implications in the automotive and transportation industry. There are numerous examples of the use of NFRPCs in automotive applications. In the past decade, natural fibers such as hemp, flax, jute, kenaf etc. have been introduced as reinforcement in both thermoplastic and thermoset polymer-based composites and have found extensive applications in transportation (automobile and railway coach interior, boat etc), construction as well as in packaging industries worldwide[50-54]. Polymer composites reinforced by flax, jute, kenaf, and sisal fibers are used to make the interior and exterior automotive body panels[5, 55-57].

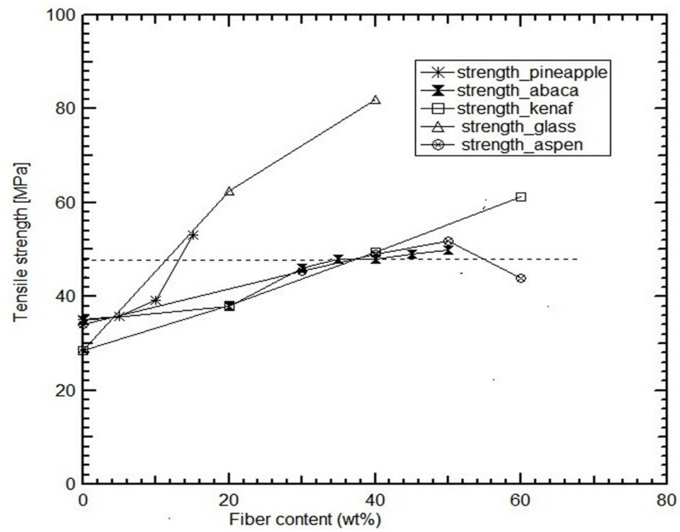

Figure-1
Tensile strength of composites based on different fiber materials and PP. The data were collected from Somjate and Gunter[46], Xue et al.[47], Rungsima et al.[48], A.K Bledzki et al.[10] and Rajeev et al[49]

Abaca fiber reinforced polypropylene composite has got remarkable and outstanding interest in the automobile industries owing to low cost availability, high flexural and tensile strength, good abrasion and acoustic resistance, relatively better resistance to mould and very good resistance to UV rays[58].

Comparison of the environmental impacts between the NFRPCs and SFRPCs

Production of natural fibers causes less severe environmental impacts as compared to that of synthetic fibers. Natural fibers cultivation depends mainly on solar energy, and for the fiber production, processing and extractions, relatively small amount of fossil fuel energy is required. On the other hand, the production of synthetic fiber depends mainly on fossil fuels and needs nearly ten times more energy as compared to natural fiber. As a result, the pollutant gas emissions to the environment from synthetic fiber production are significantly higher than that from the natural fiber production[44, 59].

Both the energy-consumption and the emissions for the production of polymers used as matrix in composites are significantly higher than those for the production of natural fibers. For example, PP production requires about 20 times more energy than natural fiber production and correspondingly the emissions are also higher. Therefore the reduction of polymer content at the expense of increase of natural fiber in the composition will improve the environmental performance of NFRCs compared to pure polymer and SFRCs as well[60].

Socio-economic impact of NFRPCs in developing countries

The production of synthetic fiber is capital-intensive, and that of the natural fiber is labor-intensive. In most part of the world, the vegetable and fruit plants are being harvested manually and the natural fiber extraction machine can easily be operated by unskilled labor. Therefore, the urban people as well as rural uneducated people can be appointed for the production and extraction of natural fiber. Sometimes some natural fibers (e.g. jute, coconut) can be extracted manually. Thus the production and extraction of natural fibers involve huge human resources. A 'natural fiber production' project is quite appropriate for developing and moderately developed countries as it could create a lot of employment opportunities in urban and rural sectors.

Potential of South-East Asia for contribution in NFRPCs production

The most common natural fibers which exhibit moderately high mechanical strength and are used for the reinforcement of polymer composites are jute[9], rice husk[26], bamboo[34], coconut[22], banana[32], flax[7], hemp[49], pineapple[48], sisal[41] and wheat husk[61]. Most of these products are cultivated extensively in this region, but most of their wastes are abundant and do not have any useful utilization. If the entrepreneurs take initiatives for the collection of these agriculture wastes for NFRPCs, the new application of natural fibers may present an economic interest for the whole agricultural sector. A lot of employment opportunities in urban as well as in rural sectors would be created by this natural fiber project and the poverty alleviation program will be enhanced.

Conclusion

NFRPCs have already been proven alternative to SFRPCs in many applications in automotive, transportation, construction and packaging industries. Ongoing researches find varieties of natural fibers, which improve the mechanical strength of polymer composites. Natural fibers result in lighter composite materials as compared to SFRPCs with equivalent mechanical strength. Natural fibers are biodegradable and their productions are associated with lower emission than that in the production of synthetic fiber. Also high natural fiber contents in composites at the expense of polymer itself results in the economy of energy in wide aspect, since the production of polymer is more energy-consuming than that of the natural fiber. Production of natural fiber is labor-intensive and hence NFRPC industry will create new employment and will contribute to the poverty alleviation program in a number of developing countries.

Acknowledgement

The financial support from the Ministry of Science and Technology, Bangladesh (Grant No. EAS-7/582/1(5)/2012) for conducting this research is highly appreciated. The author Khurshida Begum is thankful to the Ministry of Science and Technology, Bangladesh for providing her with NST fellowship (Grant No. 363(105)/2011) for this research purpose.

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