Mechanical Characterization of Natural Fiber Polymer Matrix Composites – A Review

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Abstract:

By the turn of the century, there have been numerous studies on fibers – Synthetic and natural – and their properties due to their immense application in structural, automotive, defense industry and other engineering fields. Moreover, there has been a remarkable shift in the study of fibers and this, in recent years has been mainly with natural fibers. This paradigm shift has taken place because of the ability of these materials to replace the conventional materials. This has helped us in better understanding, getting better results and achieving better material properties based on existing applications. This review paper deals with the existing natural fibers and the mechanical material properties of these fibers. Many different fibers along with their properties have been studied. These natural fibers were then mixed with resins and furthermore, the mechanical testing was then done on these fibers and the tests involved were mainly tensile, flexural, impact and hardness tests. All these tests have followed the regulations specified by the American Society of Testing and Materials (ASTM). The results derived from the literature review have been concluded in this review paper.

Keywords

Natural fiber, Natural fiber polymer matrix composite, Mechanical characterization.

1. Introduction

Material engineering and design has now become a direct function of environmental consideration. Multiple environmental variables need to be considered for the utility of fibers – synthetic or natural. Currently, synthetic fibers are being widely incorporated in polymer-based composites due to their high mechanical properties. But, these fibers lack in terms of their biodegradability, initial processing costs, recyclability, machine abrasion, health hazards, etc. [1-2]. So, an alternative to tackle these drawbacks can be found in natural fibers. The major positive here is that these fibers can be obtained from annually renewable resources. These natural fibers are used as reinforcements in polymer matrix. Apart from these properties, natural fibers exhibit sufficient mechanical properties, have low density, are cheap and possess a good calorific value. This environmental friendly feature makes the material very popular in the engineering market such as the automotive and construction industry [3]. Since there has been a significant increase in the automotive and construction industry, the need to find out an alternative to the conventional materials is required. These conventional materials can be replaced by natural fiber composite materials which have a considerable strength to weight ratio, favourable for design considerations. Presently, four group classification has been done which consist of Polymer Matrix Composites (PMCs), Metal Matrix Composite (MMCs), Ceramic Matrix Composites (CMCs) and Carbon-Carbon Composites (CCCs). Out of these four, PMCs are widely used because of its less weight, self-lubrication properties and good mechanical properties. India has rich accessibility of natural fibers such as jute, banana, cotton, sisal, pineapple, oil palm, bamboo, etc. [4]. Often, mechanical characterization is the last step in any manufacturing process, yet it is a major contributing factor. The need for this lies in its applications, which undergo variable loading conditions. So, to withstand these conditions - based on the application - mechanical testing is done. In this article, major focus has been given to natural fiber composites along with their properties. Also, the effect of mechanical characterization on different fibers has been discussed.

2. Literature Review

Composites are a combination of two or more different materials in such a way that the new material has better, distinct properties than that of parent materials [5]. Fiber-reinforced composites, because of their transcending properties, are used in aerospace, defense, engineering applications etc. Jartiz [6] stated that "Composites are multifunctional material systems that provide characteristics not obtainable from any discrete material. They are cohesive structures made by physically combining two or more compatible materials, different in composition and characteristics and sometimes in form." Berghezan [7] has defined that "The composites are compound materials which differ from alloys by the fact that the individual components retain their characteristics but are so incorporated into the composite as to take advantage only of their attributes and not of their demerits.", in order to obtain improved materials. Composites are selected for certain applications because they have high strength to weight ratio, better creep resistance, good tensile strength at elevated temperature and increased toughness.

Over the years, the growth in understanding the properties and utility of natural fibers in the industry and for research purpose, has increased considerably. They are cost-effective, reusable, biodegradable and renewable. Plants like hemp, jute, sisal, banana, bamboo etc. are more often applied as reinforcement to the composite. Also, these fibers are inexpensive, light weight, have high stiffness, low density and are abundant. Natural fiber composites have been able to prove their credibility by establishing themselves as cost effective materials for various applications. Broadly, they have been used in building and construction industry as false ceilings, partition doors, wall, window, pre-fabricated building. They have also been used in the furniture industry for tables, chairs etc., electrical devices and the transportation industry [8]. We have been able to classify composites based on their matrix, mainly Metal, Ceramic and Polymer matrix composites. Out of these, the most commonly used are polymer composites. Generally, the mechanical properties of polymers are insufficient for functional usage. Specifically, their stiffness and strength are low compared to metal and ceramic. But, this discrepancy can be avoided by bolstering other materials with the polymer. Moreover, the operating conditions of polymer matrix composites does not involve high pressure and temperature. Also, the manufacturing hardware needed is also simple compared to those in ceramic and metal. These are the two major reasons why there has been a rapid development in polymer matrix composites for various applications. PMCs can be classified into two types: Fiber reinforced polymer (FRP) and Particle reinforced polymer (PRP) [8]. There are various parameters through which we can find out the mechanical properties of natural fibers. Some of them have been mentioned below.

2.1. Effect of Fiber Volume Fraction

Jai Inder Preet Singh [9] used Jute, sisal and banana fibers at constant 40% fiber volume fraction with Araldite AW106 epoxy resin as matrix. For mechanical testing, tensile test (ASTMD3039 standard), flexural strength (ASTM D790-02 standard) and impact test was done. His results showed that there was a significant increase in the tensile strength of non-treated Jute fiber epoxy resin than those of non-treated sisal and banana based composites. Also, the three-point bending test indicated that there was an increase in flexural strength for non-treated jute fiber epoxy composites than other composite base. For Charpy's test, it was observed that non-treated jute epoxy resin showed better impact strength compared to other non-treated composites.

Muhammad Khusairi Bin Bakri [10] used banana fibers for the characterization with Bisphenol-A as matrix and used polyoxypropylene diamine and diethylenetriamine hardeners. For mechanical characterization, tensile strength and yield strength were obtained according to ASTM D638-14 [11]. The results obtained show that the treated banana epoxy composites show better tensile and yield strength than that of non-treated banana epoxy composites. Also, it was noticed that as there was an increase in the fiber concentration factor or the fiber volume factor, there was a slight reduction in both tensile and yield properties of banana epoxy composites. But as the fiber volume fraction was increased to 20 weight percent ratio, there was a furthermore increase in its mechanical properties. Muhammad Khusairi Bin Bakri [12] used oil palm fibers with Bisphenol-A as matrix and polyoxypropylene diamine and diethylenetriamine as hardeners. The mechanical testing of these involved tensile strength and yield strength which were in accordance to ASTM D638-10 [13]. The results of this showed that as the fiber concentration was increased, there was an increase in the average tensile and yield strength. This increase was shown because of presence of fibers [14].

Barari et al. [15] using Cellulose nano-fiber (CNF) aerogel with a bio-based epoxy (super sap entropy) and liquid composite molding as a manufacturing technique performed tensile tests and the results shown were that the treated CNF showed better tensile properties than those of non-treated composites. Nan Feng [16] used recycled carbon fiber and Nylon-6 as matrix. The composite was manufactured using Simple melting extrusion process. Results of the tensile test, flexural test and impact test showed that there was an increase properties of surface treated carbon fiber composite, as the tensile, flexural and the impact strengths increased.

Table 1. Mechanical characterization of natural fiber poylmer matrix composites

Research	Fiber	Matrix	Treatment/ Filler	Manufacturing Technique	Variables	Tensile Strength	Flexural Strength	Yield Strength	Impact Strength
Jai Inder Preet Singh et al. [9]	Jute, Sisal, Banana	Araldite AW106 epoxy resin	-	Hand Layup	Reinforcement	Increase	Increase	-	-
Muhammad Khusairi Bin Bakri et al. [10]	Banana	Bisphenol-A	Alkaline. Hardener: polyoxypropylene diamine and diethylenetriamine	Compression molding	Fiber Concentration Factor	-	-	Increase	Decrease
Muhammad Khusairi Bin Bakri et al. [12]	Oil Palm	Bisphenol-A	Alkaline. Hardener: polyoxypropylene diamine and diethylenetriamin	Compression molding	Fiber Concentration factor	Increase	-	Increase	-
Bamdad Barari et al. [15]	Cellulose nano-fiber (CNF) aerogels	bio-based epoxy (Super-Sap Entropy)	Acid hydrolysis, TEMPO (tetramethylpiperidine-1-oxyl) oxidation	Liquid Composite molding	Fiber Concentration factor	Increase	-	-	-
Nan Feng, Xiaodong Wang, Dezhen Wu [16]	Recycled carbon fiber	Nylon 6	-	Simple Melting Extrusion	Fiber Concentration factor	Increase	Increase	-	-

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Table 2. Mechanical characterization of natural fiber poylmer matrix composites

Research	Fiber	Matrix	Treatment/ Filler	Manufacturing Technique	Variables	Tensile Strength	Flexural Strength	Yield Strength	Impact Strength
Goulart, S.A.S et al. [36]	Palm fibers	Polypropylene	Maleic anhydride grafted polypropylene (MAPP)	Injection molding process	-	-	Increase	-	-
Beata Szolnoki et al. [37]	Twill woven hemp fabrics	Ipox MR 3016 (tetraglycidyl ether of pentaerythritol) type applied with Ipox MH 3122 curing agent (3,30-dimethyl-4,40-diamino-dicyclohexyl-methane)	Phosphoric acid	Hand layup	Treated and untreated fabrics	Increase	Increase	-	-
Tao Yu et al. [38]	Ramie fiber	Poly(lactic acid)	Alkaline and Silane	Two-roll mill	Treatment methodology	Increase	Increase	Increase	-
Piyush P. Gohil et al. [40]	Banana(30% wt), Sisal (40%wt) and Coir (30%wt)	Polyester	-	-	Fiber volume fraction	Increase	-	-	-

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Table 3. Mechanical characterization of natural fiber poylmer matrix composites

Research	Fiber	Matrix	Treatment/ Filler	Manufacturing Technique	Variables	Tensile Strength	Flexural Strength	Yield Strength	Impact Strength
Syed Altaf Hussain et al. [18]	Green coconut fiber	High density polyethylene	Alkaline	-	Fiber Length	Decreases as length increases	Decreases as length increases	-	Decreases as length increases
K.J. Wong et al. 19]	Bamboo fibers	Polyester	Alkali treatment on interfacial adhesion	-	NaOH concentrations	Increase	-	-	-
XI Peng et al. [20]	Processed hemp fibers	Polyester, polyurethane , vinyl ester	-	Pultrusion process	Fiber Length	Maximum for polyurethane	Maximum for polyester	-	-
A. Gowthami, K. et al. [41]	Sisal fiber	Unsaturated polyester resin	-	Hand layup	Composite without silica	Increase	-	Increase	-
S. Raghavendra et al. [21]	Banana fibers	Natural rubber	-	Compression molding	Fiber Length	Increase	-	-	-
M R Ishak, Z Lemon, SM Sapuan, M Y Salleh and S Misri [17]	Sugar palm fibers	Epoxy	Sea water	Rotational cutting	Fiber Volume fraction	-	Increase	-	Increase

M.R Ishak [17] used sugar palm fibers and epoxy as the matrix for the composite. This mixture was treated with sea water and the composite was manufactured using rotational cutting method. The results of the mechanical testing showed that as the weight percent ratio increases, the tensile strength and the flexural strength increases compared to that of other non-treated composites.

2.2. Effect of Fiber Length

Syed Altaf Hussain [18] did the mechanical characterization on green coconut fiber and HDPE as matrix. This was chemically treated by alkylation and the mechanical tests showed that the tensile, the flexural and the impact strengths decrease with increasing fiber length.

K.J Wong [19] used bamboo fibers and polyester as matrix. The results of tensile tests showed him that there was an increase in tensile strength upto a specific NaOH concentration. After that, the tensile strength decreases with increase in fiber length.

Xi Peng [20] used processed hemp fibers with variable matrix materials like polyester, polyurethane and vinyl ester. The manufacturing of this composite was done using Pultrusion process. The results of the tensile and flexural tests showed that the tensile strength for hemp reinforced polyurethane matrix composite is maximum compared to other polymer composites. Also, the flexural strength of hemp reinforced polyester matrix composite is maximum compared to other polymer composites.

S. Raghavendra [21] used natural rubber as matrix and banana fibers as reinforcement. The manufacturing of this composite was done using compression molding technique. After performing the tensile tests on the composite, it was shown that as the length of the fiber increases, the tensile strength also increases.

2.3. Effect of Surface Treatment

The main reason of performing surface treatment operations is because of the hydrophillic nature of fiber and the hydrophobic nature of matrix. This proves to be incompatible between the two phases and hence weakens the bonding at the interface. Surface treatment or chemical treatment on these natural fibers can help in reducing the hydrophillic nature and hence, reduce the incompatibility with the matrix [22-23].

2.3.1. Effect of Alkali Treatment

Li X [24] used Flax-epoxy fiber matrix composite and applied alkali treatment to this composite. The corresponding result on the mechanical and thermal properties was that there was a 30% increase in the tensile strength and modulus. When he used Sisal-polyester [24] fiber matrix composite, he performed 0.5%, 1%, 2%, 4%, 5%, 10% NaOH treatment at atmospheric temperature. The corresponding results showed that the 4% alkali treatment exhibited maximum tensile properties. Mwaikambo et al. [25] used Hemp (non-woven) mat with euphorbia resin fiber matrix. He treated this composite with 0.16% NaOH for 48 hours. The results obtained were that the tensile strength increased by 30% compared to those of untreated fiber composites. Also, he used Jute-vinylester [26] fiber matrix composite and treated this chemically with 5% NaOH for 4, 6 and 8 hours. The observation showed that the 4 hour treated composite resulted in 20% increase in its flexural strength in contrast to the other composites.

Cyras VP [27] used Sisal-polycaprolactone composite and he treated it with 10% NaOH for 1, 3, 24 and 48 hours. He observed an increase in elastic modulus. Ouajai S [28] performed 8% NaOH treatment on hemp fiber matrix composite. The corresponding mechanical properties exhibited were that the thermal stability increased by 4%. Prasad SV [29] performed 5% NaOH treatment for 72 hours on coir-polyester and he observed that the flexural, impact strength increased by 40% correspnding to untreated fiber composites.

2.3.2. Effect of Silane Treatment

Seki Y [30] used Jute-epoxy and jute-polyester composites and performed alkali treatment (5% NaOH) and silane treatment (1% oligomeric siloxane with 96% alcohol solution). The results obtained were that silane treated jute-epoxy composites showed approximately 12% higher strength and 7% higher modulus properties in contrast to alkali treatment. Similary, for silane treated jute-polyester composites, there was a 20% increase in strength and 8% increase in modulus.

2.3.3. Effect of Anhydride Treatment

Mohanty et al. [31] used jute fiber reinforced polypropylene matrix with the jute fiber having 30% fiber loading and 6 mm fiber length. He treated this with 0.5% maleic anhydride polypropylene (MAPP) concentration in toulene for 5 minutes. The results showed that there was a 72% increase in flexural strength properties compared to those of untreated fiber composites. He also used sisal fiber reinforced polypropylene matrix composite [32] and treated it with 1% maleic anhydride polypropylene (MAPP). The corresponding results shown were that there was a 50%, 30% and 58% increase in the tensile, flexural and the impact properties respectively.

2.3.4. Effect of Benzoyl Treatment

Joseph et al. [33] used alkali pre-treated sisal fibers and performed benzoylation (benzoyl chloride) treatment on this mixture. The results after characterization were that the treated sisal fibers were thermally more stable. Similarly, treatment on flax fiber reinforced in LDPE composite by Wang et al. [34] showed that that there was a 6% increase in the tensile strength.

2.3.5. Effect of Peroxide Treatment

Joseph et al. [33] experimentally found out the optimum configuration of benzoyl peroxide (6%) and dicumyl peroxide (4%) by treating short sisal fiber reinforced polyethylene composites and reported that there were improved tensile strength properties shown. Sapieha S. [34] reported that higher mechanical properties were shown in benzoyl or dicumly peroxide pre-treated fiber.

2.3.6. Effect of Permanganate Treatment

Paul et al. [35] reported that permanganate treatment on banana fiber polypropylene composites improve the mechanical intermeshing with the matrix. Also, the flexural and modulus properties increase by 5% and 10%. Li X [24] incorporated 0.2% potassium permanganate ($KMnO_4$) solution in 2% acetone to the alkali treated (2% NaOH) pre-treated flax fiber. The corresponding results showed that the treated low and high density polyethylene fiber composites had greater tensile properties in compared to original composites.

3. Summary

The purpose of this paper is to analyze the work done on different types of natural fibers, their properties and their composites formed. By the use of different treatments, we have been able to establish a qualitative and relative impact on the mechanical properties of different natural fibers. This has enabled us in understanding or finding out suitability of different fibers, their scope of enhancing the desirable properties and further possibilities of developing different composite materials of desirable features.

Fibers are the major load bearing component in the composite and so with the increase in the number of fibers, the structural and functional properties of the composite should improve. This is confirmed by the results obtained by various researchers that are presented in Table 1 and 2 that is, with the increase in the fiber concentration factor the various properties of the composites like tensile, flexural and the impact strengths increase.

Fiber length is one of the major agent that affects the properties of the composites and so numerous tests were carried out to find the relation between the fiber length and the properties of the composites, specifically the mechanical properties. The tensile strength of the composites that were reinforced with NaOH treated fibers increased with the increase in the fiber length. Surface treatment of fibers is required as they are hydrophilic in nature and due to this, there arises incompatibility between the fibers and the matrix during bonding and thus to improve the bonding, the fibers are treated before composite manufacturing. The different surface treatments done on the fibers include alkali, silane, anhydride, benzoyl, peroxide, permanganate and many more. It was observed that after the treatment of the fibers, the mechanical properties of the composites improved significantly in most of the cases while in some cases the properties showed only a slight improvement.

Jute, banana, bamboo, sisal, hemp etc. can be of significant interest in meeting the industrial needs of composites by virtue of their high annual availability, renewability, wide occurrence and adequate raw material supply which would be a key factor when dealing with bio-based material. Developing natural fiber composites has vast socio-economic merits with forward and backward linkages.

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