Available online at
www.ijacskros.com

Indian
Journal of Advances in
Chemical Science

Indian Journal of Advances in Chemical Science S1 (2016) 267-274

Recent Developments of Natural Fiber Reinforced Thermoset Polymer Composites and their Mechanical Properties

G. S. Divya[1,2], B. Suresha[2]*

[1]*Department of Automobile Engineering, Dayanada Sagar College of Engineering, Bengaluru - 560 078, Karnataka, India.* [2]*Department of Mechanical Engineering, The National Institute of Engineering, Mysore - 570 008, Karnataka, India.*

Received 14th March 2016; Revised 16th June 2016; Accepted 16th June 2016

ABSTRACT

In recent years, due to the depletion of the non-renewable resources and increasing environmental consciousness, the researchers are working to develop biodegradable materials as a newer material for replacement of synthetic materials. The increasing demand for greener is advancing towards the innovations of natural fiber reinforced polymer based composites. The current focus of the commercial aerospace composites industry is on thermoset based composites for a number of reasons. The biodegradability of the natural fibers is considered as the most important and interesting aspects of their utilization in polymeric materials apart from their advantages like low-density, abundant availability, biodegradability, corrosion resistivity, low-cost, and non-abrasive processing characteristics. These advantages of the natural fiber reinforced composites support their potential across a wide range of applications in constructions and buildings, automotive, railway coaches, marine, aerospace, military, sports and packaging industries. However, these natural fibers have relatively poor moisture resistance, fiber wetting, and its adhesion to the matrix, which is affecting mechanical properties of Natural fiber reinforced composites. Fiber surface treatment and hybridization are two important mean to enhance the properties of the natural fiber reinforced thermoset composites. The mechanical properties of a natural fiber reinforced composite depend on parameters like fiber strength, fiber length, chemical treatment and orientation in addition to fiber-matrix interfacial bond strength. This review article aims at illumination about the research and development in the improvement of mechanical properties of natural fiber reinforced thermoset composites along with end applications.

Keywords: *Natural fiber, Thermoset, Surface treatment, Hybridization, Mechanical properties.*

1. INTRODUCTION

The heterogeneous mixture of two or more materials to obtain the high strength, wear resistance for the structural and dynamic applications is called as composites. One constituent of the composite is called as the reinforcing phase and the other one in which the reinforcements are embedded is called the matrix phase. The reinforcements can be of the forms such as fibers, particle, or flakes. They may be continuous or discontinuous. The matrix phase materials are generally continuous. Examples of composite systems include concrete reinforced with steel and epoxy reinforced with graphite fibers. [1]. In 1960, considerable research was focused on composites and this area, emerged as a distinct discipline [2]. Earliest benefactor of the composite technology was the aerospace industry where the search was toward a material that is efficient and lighter than the existing monolithic materials [3]. Composites could meet these demands of hi-tech applications where performance reliability of the products in use is given a pride of place. Subsequently, when the applications of the composites trickled down to other fields such as construction, consumer, electronic, and automotive industries. A composite is a combination of two or more materials that result in better properties than when the individual components are used alone. Two constituents of the composite are normally a fiber and a matrix [4]. Typical fiber includes glass, aramid and carbon, which may be continuous or discontinuous. Matrices can be polymers, metals, or ceramics [5]. The discontinuous or distributed phase, which is generally selected to possess superior mechanical properties, is aptly termed as "reinforcement." The properties of reinforcement greatly affect the resultant properties exhibited by the composites. Here, the interphase

*Corresponding Author:
*E-mail: sureshab@nie.ac.in,
sureshab2004@yahoo.co.in
Tel.: +91 821 2480475, Fax: +91 821 2485802*

involving reinforcement with the matrix assumes significance as load transfer has to be realized through "zones" or "regions" [5].

The matrix is significant in the sense that the aggregates have no use at all unless this binding agent, i.e., the matrix holds them in place. The matrix, which is not superior as the other phase in term of mechanical properties, tends to play the role of load transfer to the distributed phase. The matrix also acts as a barrier to protect against adverse environment, mechanical, and chemical degradation such as abrasion or corrosion [6]. Hybrid composites, which are made by the combination of fiber/filler/matrix or fiber/fiber/matrix, is resulting the good properties in structural applications. The use of fillers, reinforcements, and lubricants in the matrix, gives raise to many combinations that provide increasing load withstanding capability, reduced co-efficient of frictions, improved wear resistance and thermal properties, higher mechanical strength etc., [7].

There is a vast scope for renewable products now days due to the fact of biodegradability and eco-friendly nature. A significant research effort being done in utilizing the resources which are naturally available either in the form of fiber or filler by looking at the problems such as global waste, rising oil prices, exhaustion of landfill sites [8], and ill-effects on environment [9]. Reinforcing the natural fibers with the polymer based matrix is an emerging field of engineering [10], as natural fibers possess good number of advantages such as high specific strength and modulus, biodegradability, and renewability compared to glass fibers [11]. Because of the advantages of natural fiber reinforced polymer composites, numerous automotive companies, such as Mercedes-Benz, BMW, Audi, and Daimler, are replacing few glass fiber-based composites with natural fiber reinforced polymers [12].

2. FACTORS AFFECTING THE MECHANICAL PROPERTIES

The increased use of synthetic fibers reinforced polymer composites all over the world has resulted in an increase in environment burden. For this reason, the development of bio-based composites has been a subject of enormous interest in material science for both ecological and environmental perspectives. The need for efficient structural materials in an ecology-conscious world of finite resources has led advanced composites to be one of the key parts on going technology revolution in the world today. Because of the availability of light, stiff, and strong materials, it has been possible to achieve a number of marvels in aerospace technology. Materials technologist and designers have advantageously used these materials in the construction of modern fuel efficient aircraft, satellites, missiles, and other space vehicles. There are various factors affecting on the mechanical properties of the structural member.

2.1. Fiber Selection

Incorporation of the natural fiber to the polymer matrix material will lead to enhanced properties in terms of physico-mechanical strength, thermal properties, and tribological properties. These enhanced properties can be make use for suitable applications. According to the literature survey, the properties of the natural fibers are different from each other. It depends on the kind of fiber, composition of lignin, hemicelluloses, cellulose etc., in the fibers, sources, chemical and physical nature, climate and moisture condition. Sources may be animal, plant, minerals, or rocks which are available in the nature. Composites consists of polymer matrix and high strength natural fibers such as bagase, bamboo, cotton, hemp, and ramie are called as natural fiber reinforced composites (NFC). Table 1 shows the tensile properties of few natural fibers made up of natural fiber reinforced polymer composites. They are listed and explained in below paragraphs.

2.2. Polymer Selection

Numerous polymeric materials find engineering application as matrix materials for composites. While the selection of matrix materials is based on the application and the service condition of the component, the selection of reinforcement is based on two criteria, first, the properties of the reinforcement material and second, the cost it contributes to the total system's cost [6]. High performance composites

Table 1: Mechanical properties of natural fibers.

Fiber	Tensile strength (MPa)	Modulus (GPa)	References
Jute	393	55	[13]
Sisal	510	28	[13]
Flax	344	27	[13]
Hemp	389	35	[13]
Hemp	690	70	[14]
Kenaf	930	53	[14]
Flax	345-1035	27-60	[14]
Ramie	560	24-50	[14]
Bamboo	140-230	11-17	[14]
Jute	393-773	26-50	[14]
Coir	175	4-6	[14]
Banana	500	12	[14]
Cotton	287-597	5.50-12.70	[14]
Sisal	511-635	9.40-22	[14]
Oil palm	248	3-20	[14]
Pineapple		400-627	[14]
Bagasse	290	-	[14]

Table 2: Tensile strength of NFC.

Resin	Fiber	Strength (MPa)	References
Epoxy	Banana	23.98	[19]
Polyester	Jute (untreated	250	[20]
	Pineapple (untreated)	22.9	[17]
	Okra (treated)	28	[18]
	Bagasse	10.6	[20]
LDPE	Sisal (untreated)	9.2	[21]
LDPE	Sisal	9.0	[22]
PP	Sisal fiber treated)	35	[21]
PP	Bamboo (untreated)	22.5	[23]
PP	Pineapple leaf	24.50	[24]
PP	Banana (treated)	24.50	[25]
PP	Bamboo (treated)	24.50	[26]
LDPE	Wood-treated	9.8	[27]

NFC=Natural fiber reinforced composites, PP=Polypropylene, LDPE=Low density polyethylene

Table 3: Tensile modulus of NFC.

Resin	Fiber	Modulus (MPa)	References
Polyester	Jute	4000	[16]
	Pineapple-leaf	580	[17]
	Okra (treated)	525	[18]
Epoxy	Banana	1390	[14]
LDPE	Sisal (untreated)	140	[21]
	Sisal (untreated)	140	[22]
	Wood (treated)	350	[27]
PP	Sisal fiber (treated)	498	[21]
	Bamboo (untreated)	1.8	[23]
	SF (treated)	498	[21]
	Bamboo (untreated)	1.8	[23]
	Rice hulls (treated)	869	[28]
	Kenaf	869	[25]
	Pineapple-leaf (treated)	560	[24]
	Banana (treated)	560	[25]
	Bamboo (treated)	560	[26]

NFC=Natural fiber reinforced composites, PP=Polypropylene, LDPE=Low density polyethylene

such as polyamide (PA) resins reinforced with carbon or Kevlar fibers are the thermoplastics such as PA, polyetherketone or polypropylene (PP) reinforced with glass fibers are finding applications in almost all general engineering fields. These include transport, building technology, marine engineering, and chemical industry for plant, containers, and agriculture and earth moving equipment [15]. Sarawuth *et al*. [16] fabricated coconut fiber-filled polyvinylchloride/acrylonitrile (PVC/ASA) blend and conducted mechanical tests. The result revealed that the impact strengths of the PVC/ASA coconut fiber composites are significantly higher than the PVC wood composites or polyolefin wood composites when comparison was made at the same fiber content. Arrakhiz *et al*. [17] investigated the mechanical properties of Alfa, coir, and bagasse fibers reinforced PP composites with alkali treatment of the fibers. The mechanical properties of coir/PP composites are higher than those measured for Alfa/PP and bagasse/PP composites. They revealed that the better performance is because of lower cellulose and higher lignin contents of the coir fibers compared to other two fibers. Tables 2-5 represents the tensile strength, tensile modulus, flexural strength, and flexural modulus for the few combinations of natural fibers and polymersm, respectively [18].

Table 4: Flexural strength of NFC.

Resin	Fiber	Strength (MPa)	References
Polyester	Pineapple leaf	80.2	[17]
Epoxy	Banana	53.98	[14]
PP	Rice hulls	19.43	[28]
	Kenaf	19.43	[28]
	Pineappale-leaf (treated)	38	[24]
	Banana (treated)	38	[25]
	Bamboo (treated)	38	[26]
	Rice hulls (treated)	19.43	[28]
	Kenaf	19.43	[28]
	Pineapple-leaf (treated)	38	[24]
	Banana (treated)	38	[25]
	Bamboo (treated)	38	[26]

NFC=Natural fiber reinforced composites, PP=Polypropylene

Table 5: Flexural modulus of thermoset based NFC.

Resin	Fiber	Modulus (MPa)	References
PP	Banana (treated)	1650	[25]
	Bamboo (treated)	1650	[26]
Epoxy	Banana	1563.2	[14]
Polyester	Pineapple-leaf	1300	[17]

NFC=Natural fiber reinforced composites, PP=Polypropylene

2.3. Hybridization Fiber/Filler

The inherent deficiency of polymer could be altered successfully by using various special fillers namely short fibers, micro and nano-sized particulate filler in combination with the natural fiber. More and more polymer composites reinforced with either the combination of filer/fiber or fiber/fiber is now being used as structural materials which were formerly composed only of metallic materials. Nevertheless, new developments are still under way to explore other fields of applications for these materials and to tailor their properties for extreme load bearing and environmental temperature conditions [29]. Maries *et al*. [30] investigated the mechanical properties of the short randomly oriented banana and sisal hybrid fiber reinforced polyester composites, banana/ polyester composites, and sisal/polyester composites at different fiber loading. Here, tensile and flexural properties showed a positive hybrid effect while impact performance showed a negative hybrid effect. Ramesh *et al*. [31] developed sisal-jute-glass fiber reinforced polyester composites according to the fibers used (sisal-jute-glass, sisal-glass, jute-glass) and evaluated their mechanical properties. The results indicated that the incorporation of sisal-jute-glass fiber combination can improve the properties and used as alternate material for pure glass fiber reinforced polymer composites.

2.4. Treatment Fiber/Filler

The properties of NFC depend mainly on the combination of selected polymer matrix and other constituents and the adhesion between them. The adhesion between the fiber and the resin is depending on the nature of the fiber and its contents such as lignin, cellulose, and hemi-cellulose. the bonding between the fiber and the resin can be enhanced by treating the fiber with some suitable coupling agents. Poor adhesion and interaction between the constituents causes nonuniform stress distribution in the composite. Hence, to obtain the better properties, treating the fiber with chemical agents are necessary [32]. Hydroxyl group, which is present in the natural fiber, makes the fibers as hydrophilic. Therefore, the combination of resin with hydrophobic nature should be necessary to obtain the good material, which in turn will enhance the interfacial bond between the fiber and the matrix [33].

Surface modification of fiber/filler plays a vital role in enhancing the properties. The presence of the lignin, cellulose, hemi-cellulose etc., in the plant fiber will increase the water absorption rate, which in turn degrade the properties of the composites. In order to avoid the wettability of the fiber and to increase the bond strength between other constituents of the composites, surface modification of the fiber is must. Surface modification will be done using the chemical agents. Alamgir *et al*. [34] tested raw and modified jute fiber-PP composites by differing weight fractions of jute fiber. The mechanical properties of composites were determined. Tests revealed that the increase of tensile strength, flexural strength, and Charpy impact strength were found to be exceptionally high for the composites with treated fiber. They compared the results obtained from the combination of raw jute fiber-PP and alkali treated jute fiber-PP composites and showed that the treated fiber composites excel in mechanical properties compare to other set of composites. Govardhan and Rao [35] evaluated the effect of fiber surface modification of roystonea regia/ epoxy composites by alkali and silane treatments. Dry fibers were treated with 5% solution of NaOH for 2 h to remove the unwanted soluble cellulose, hemicelluloses, pectin, lignin, etc., from the fiber. The fiber to solution weight ratio was maintained at 1:25. After 2 h, the fiber were washed thoroughly in distill water to remove excess of NaOH and dried at 60°C for 24 h for conducting silane treatment, the coupling agent 3-ameno profile triethoxy silane as diluted to 1% (v/v) in acetone and dry fibers were dipped in diluted coupling agent solutions for 3 h fibers were then washed and kept in air for 3 days then dried in an woven at 80°C for 12 h. Finally, alkali treatment proved to be more effective on dynamic mechanical properties as compared to silane treatment. Raghu *et al*. [36] developed the natural fiber composites of untreated and alkali-treated silk-sisal unsaturated polyester (USP)-based hybrid composites by using hand lay-up technique. USP resin supplied from Allied Marketing Co., Sikandarabad, was used as matrix. Methyl ethyl ketone peroxide and cobalt naphthenate were of commercial grade used as a catalyst and accelerator. The effect of some acids, alkalis, and solvents were used on the matrix and hybrid composites were studied according to ASTM standards and found that silk-sisal hybrid composites are strongly resistant to almost all chemicals except carbon tetrachloride. They also suggested that these hybrid composites can be used for making water and chemical storage tasks. Manikandan *et al*. [37] developed NaOH and H_2SO_4 treated basalt fiber reinforced USP composites and studied the effect of surface modifications of fiber on mechanical properties. Their study proved that the surface modification of the fiber improved fiber-matrix adhesion, resulting the mechanical properties superior to glass fiber reinforced polymer composites.

2.5. Loading Fiber/Filler

Inclusion of fiber/filler to the polymer will increase the strength of the composites, but if the polymer is loaded with higher volume/weight percentage of filler/fiber, composite will not yield good properties. It is mainly due to the bond between the fiber and the matrix. In this case, fiber cannot be fully wetted with the polymer matrix. This will result in poor interaction phase between the fiber and the matrix. Maleque *et al*. [19] prepared the pseudo-stem banana woven fabric reinforced epoxy composite by the hand layup method and compared the mechanical properties of the composites with the pure epoxy composite. The results revealed that mechanical properties of the banana woven fabric reinforced epoxy material showed better results compared to pure epoxy composites. Lu and Shubhashini [38] prepared hemp reinforced composites using both recycled high density polyethylene (rHDPE) under virgin HDPE and studied the effects of fiber loading and the different types of matrix on the composites' mechanical properties. The result revealed that fiber loading of hemp-rHDPE with 40% volume fraction has achieved the better tensile and flexural strength. Further with 30% fiber loading demonstrated the best impact strength. Zhong *et al*. [39] investigated the mechanical properties and wear resistance of alkali-treated sisal fibers (SF) reinforced urea-formaldehyde composites by varying wt.% of SF content. Composite with 50 wt.% SF has the optimal impact strength of 9.42 kl/m^2 whereas for 30%, it was less by 62.98% compared to 50% fiber loading. Flexural strength for 50 wt.% has given the result of 58.58 MPa and proved to be excellent in composite with 30 wt.% SF by their superior bonding and adhesion between fiber and matrix compared to other composites.

2.6. Size Fiber/Filler

The use of short fiber, micro and nanoparticles in polymers for performance enhancement started around mid-1990s and this area has become quite promising for the future as newer materials are being economically and routinely fabricated. In most of the cases, a polymer composite relies for its better mechanical properties on the extremely high interface area between the filler and the matrix. High interface leads to better bonding between the two phases and hence better strength and toughness properties over unfilled polymer or polymer composites. Composites of PP and snail shell size ranging as 0, 0.15, 0.30, and 0.42 μm was prepared by Genevive *et al*. [40]. Mechanical test results revealed that the incorporation of snail shell powder improved the properties of the fabricated composites. Results also showed the increasing properties trend with increase in the filler content and decrease in the filler particle size.

2.7. Orientation of the Fiber

Dai *et al*. [41] prepared woven carbon-fiber/epoxy composites and performed study on the tensile, compressive, and flexural behavior of the composites. They told that the properties of the material depends on the distribution of the resin and the weaving pattern of the fiber. Alavudeen *et al*. [42] found the effect of weaving patterns and random orientation on the mechanical properties of banana, kenaf, and banana/kenaf fiber-reinforced hybrid polyester composites. They prepared composites using hand lay-up method with two different weaving patterns, namely plain and twill type. The plain weaving pattern showed higher strength compare to twill type, and random orientation composites. This proved that the higher strength is due to the uniform load transferring ability and better inter-locking capability between the constituents in plain type composites.

3. APPLICATION

Applications of the NFC are finding wide way mainly in industrial sector, automotive field, aerospace, sports and marine systems due to their advantages such as low density, high strength to weight ratio, corrosion resistance behavior, and bio-degradability. As these bio-composites giving good esthetic look, they have been used in construction fields such as interior and exterior products such as windows, door panels etc. In present days, most of the car companies such as BMW, Audi Group, Ford, Opel, Volkswagen, Daimler Chrysler, and Mercedes using the greener material for producing various automobile parts such as seat backs, parcel shelves, boot linens, front and rear door linens, truck linens, and door-trim panels [43].

NFC are also best suited for high-hand applications such as exterior auto body components, such as the middle section between the headlights above the fender of a passenger bus apart from the interior parts of the automotives [44]. Coconut fibers rubber latex composite have been using by German auto companies for producing the automotive parts such as seats of the Mercedes Benz A-class model, and, flax-SF mat reinforced epoxy composites fabricating the door panels of Mercedes Benz E-class model [45]. Door trim panels of Audi Company getting manufactured using flax/sisal mat reinforced polyurethane composites [46]. Ford is using kenaf reinforced PP composites in "Mondeo" model for making door panels and kenaf reinforced PP in floor trays [47]. BMW group has used about 10,000 tonnes of natural fiber to produce automotive parts. [48]. Darshil *et al*. [49] showed that the flax can replace E-glass through their research. They fabricated composite rotor blades (suitable for 11 kW turbines) built from flax/polyester and E-glass/polyester. The resin transfer molded flax blade is 10% lighter (fiber mass saving of 45%) than the identical construction E-glass blade. They conducted Static flap-bending tests and confirmed that the flax blade satisfies the structural integrity requirements. It is proved that the flax is a potential structural material for replacing E-glass material.

4. CONCLUSION

Natural fiber reinforced thermoset composites are the best alternative materials for the synthetic fiber reinforced composites due to their properties such as low density, less expensive, high flexibility, abundant availability, and eco-friendly nature. Even though natural fibers are with many advantages, it will be of no use if the composites are not fabricated without surface modification of the fibers, good selection of fiber, and the matrix and proper combination of the constituents such as weight fraction, size, and orientation of the fibers. Using natural fibers as reinforcement in the thermosets will introduce the positive effect on the mechanical properties of the thermosets. Composites with the higher mechanical properties are suitable chosen and used in automobile sector, industries, aerospace, sports, and also in medical fields for making the components required.

5. REFERENCES

1. A. K. Kaw, (2006) ***Mechanics of Composite Materials,*** 2nd ed. Boca Raton, FL, USA: Taylor & Francis, LLC.
2. G. Gubin, (1982) ***Hand Book of Composites,*** New York: Van Nastrand Reinhold Co.
3. B. Harris, (1986) ***Engineering Composite Materials,*** London: The Institute of Metals.
4. L. J. Broutman, R. H. Krock, (1974) ***Composite Materials,*** Vol. 1. New York: Academic Publishers.
5. F. C. Campbell, (2004) ***Manufacturing Process for Advanced Composites,*** The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK: Elsevier Ltd.
6. D. Hull, T. W. Clyne, (1996) ***An Introduction to Composite Materials,*** 2nd ed. Cambridge: Cambridge University Press.
7. ASM International Materials Park, (1992) ***American Society for Metals Handbook,*** Ohio, USA: ASM International Materials Park.
8. A. Bismarck, (2008) Are hierarchical composite structures the way forward to improve the properties of truly green composites, ***Express Polymer Letters,*** **2(10):** 687.
9. J. J. Blaker, K. Y. Lee, A. Bismarck, (2011) Hierarchical composites made entirely from renewable resources, ***Journal of Biobased Materials and Bioenergy,*** **5:** 1-16.
10. A. Bismarck, S. Mishra, T. Lampke, (2005) Plant fibers as reinforcement for green composites. In: A. K. Mohanty, M. Misra, L. Drzal, (Eds.), ***Natural Fibers, Biopolymers and Biocomposites,*** Boca Raton: CRC Press.
11. A. K. Mohanty, M. Misra, G. Hinrichsen, (2000) Biofibres, biodegradable polymers and biocomposites: An overview, ***Macromolecular Materials and Engineering,*** **276(3-4):** 1-24.
12. B. C. Suddell, J. E. Williams, (2005) Natural fiber composites in automotive applications. In: A. K. Mohanty, M. Misra, L. Drzal, (Eds.), ***Natural Fibers, Biopolymers & Biocomposites,*** Boca Raton: CRC Press.
13. D. NabiSaheb, J. P. Jog, (1999) Natural fiber polymer composites: Review. ***Advances in Polymer Technology,*** **18(4):** 351-363.
14. K. Ilomaki, (2012) ***Dissertation on Adhesion Between Natural Fibers and Thermosets,*** Tampere University of Technology.
15. K. K. Chawla, (1987) ***Composite Materials, Science and Engineering,*** New York: Springer-Verlag.
16. S. Rimdusit, S. Damrongsakkul, P. Wongmanit, D. Sramas, S. Tiptikorn, (2011) Characterization of coconut fiber-filled polyvinyl chloride/ acrylonitrile styrene acrylate blends, ***Journal of Reinforced Plastics and Composites,*** **30:** 1691-1702.
17. F. Z. Arrakhiz, M. Malha, R. Bouhfid, K. Benmoussa, A. Qaiss, (2013) Tensile, flexural and torsional properties of chemically treated alfa, coir and bagasse reinforced polypropylene, ***Composites Part B: Engineering*****, 47:** 35-41.
18. K. Begum, M. A. Islam, (2013) Natural fiber as a substitute to synthetic fiber in polymer composites: A review. ***Research Journal of Engineering Sciences,*** **2(3):** 46-53.
19. M. A. Maleque, F. Y. Belal, S. M. Saupam, (2007) Mechanical properties study of pseudo-stem banana fiber reinforced epoxy composites, ***Arabian Journal for Science and Engineering,*** **32(2B):** 359-364.
20. P. J. Roe, M. P. Ansell, (1985) Jute reinforced polyester composites, ***Journal of Materials Science*****, 20:** 4015-4020.
21. L. Bing, H. Yuhui, C. Guangmin, (1997) Influence of modified wood fibers on mechanical properties of wood fiber reinforced polyethylene, ***Journal of Applied Polymer Science,*** **66:** 1561-1568.
22. N. Srinivasababu, M. R. K. Murali, K. J. Suresh, (2009) Tensile properties characterization of Okara woven fiber reinforced polyester composites, ***International Journal of Engineering,*** **3(4):** 403-412.
23. P. V. Joseph, J. Kuruvilla, S. Thomas, (1997) Effect of processing variables on the mechanical properties of sisal-fiber reinforced polypropylene composites, ***Composites Science and Technology,*** **59:** 1625-1640.
24. M. Thejvidi, M. M. Shekaraby, N. Motiee, S. K. Najafi, (2006) Effect of chemical reagents on the mechanical properties of natural fiber polypropelene composites, ***Journal of Polymer Science Part A,*** **27(5):** 563-569.
25. U. Hujuri, S. K. Chattopadhay, R. Uppaluri, A. K. Goshal, (2008) Effect of maleic anhydride grafted polypropelene on the mechanical and morphological properties of chemically modified short pineapple leaf fiber reinforced polypropelene composites, ***Journal of Applied Polymer Science,*** **107:** 1507-1516.
26. S. K. Chattopadhay, R. K Khandal, R. Uppaluri, A. K. Goshal, (2011) Bamboo fiber reinforced polypropelene composites and their mechanical, thermal and morphological properties, ***Journal of Applied Polymer Science,*** **119:** 1619-1626.
27. G. Kalaprasad, K. Joseph, S. Thomas, (1999) Theoretical modeling of tensile properties of short sisal fiber reinforced low density polyethylene composites, ***Journal of Materials Science,*** **32:** 4261-4267.
28. K. Okubo, T. Fujii, Y. Yarnamoko, (2004) Development of bamboo-based polymer composites and their mechanical properties,

***Composites Part A: Applied Science and Manufacturing,* 35:** 377-383.

29. T. M. Osman, D. E. Rordan, L. B. Friedman, L. F. Vega, (2006) The commercialization of nanomaterials: Today and tomorrow, ***Journal of Materials,* 58:** 21-24.
30. M. Idicula, K. Joseph, S. Thomas, (2010) Mechanical performance of short banana/sisal hybrid fiber reinforced polyester composites, ***Journal of Reinforced Plastics and Composites,* 29:** 12-29.
31. M. Ramesh, K. Palanikumar, K. Hemachandra Reddy, (2013) Mechanical property evaluation of sisal-jute-glass fiber reinforced polyester composites, ***Composites Part B: Engineering*, 48:** 1-9.
32. M. A. NorulIzani, M. T. Paridah, U. M. K. Anwar, M. Y. Mohd Nor, P. S. H'Ng, (2013) Effects of fiber treatment on morphology, tensile and thermogravimetric analysis of oil palm empty fruit bunches fibers, ***Composites Part B: Engineering,* 45(1):** 1251-1257.
33. S. M. A. Tawakkal, M. J. Cran, S. W. Bigger, (2014) Effect of kenaf fibre loading and thymol concentration on the mechanical and thermal properties of PLA/kenaf/thymol composites, ***Industrial Crops and Products,* 61:** 74-83.
34. M. A. Kabir, M. M. Huque, M. R. Islam, A. K. Bledzki, (2010) Mechanical properties of jute fiber reinforced polypropylene composites: Effect of chemical treatment by benzene diazonium salt in alkaline medium, ***Bio Resources,* 5(3):** 1618-1625.
35. G. Goud, R. N. Rao, (2012) Effect of surface modification and hybridization on dynamic mechanical properties of Roystonearegia/glass-epoxy composites, ***Bulletin of Materials Science,* 35(7):** 1143-1149.
36. K. Raghu, P. N. Khanam, S. V. Naidu, (2010) Chemical resistance studies of silk/sisal fiber – Reinforced unsaturated polyester-based hybrid composites, ***Journal of Reinforced Plastics and Composites,* 29:** 343-345.
37. V. Manikandan, J. T. W. Jappes, S. M. Suresh Kumar, P. Amuthakkannan, (2012) Investigation of the effect of surface modifications on the mechanical properties of basalt fibre reinforced polymer composites, ***Composites Part B: Engineering,* 43:** 812-818.
38. N. Lu, S. Oza, (2013) A comparative study of mechanical properties of hemp fiber with virgin and recycled high density polyethylene matrix, ***Composites Part B: Engineering*, 45:** 1651-1656.
39. J. B. Zhong, J. Lv, C. Wei, (2007) Mechanical properties of sisal fiber reinforced urea-formaldehyde resin composites, ***Express Polymer Letters,* 10:** 681-687.
40. G. C. Onuegbu, I. O. Igwe, (2011) The effects of filler contents and particle sizes on the mechanical and end-use properties of snail shell powder filled polypropylene, ***Materials Sciences and Application,* 2:** 811-817.
41. S. Dai, P. R. Cunningham, S. Marshall, C. Silva, (2015) Influence of fibre architecture on the tensile, compressive and flexural behaviour of 3D woven composites, ***Composites Part A: Applied Science and Manufacturing,* 69:** 195-207.
42. A. Alavudeen, N. Rajini, S. Karthikeyan, M. Thiruchitrambalam, N. Venkateshwaren, (2015) Mechanical properties of banana/kenaf fiber-reinforced hybrid polyester composites: Effect of woven fabric and random orientation, ***Materials and Design*, 66:** 246-257.
43. B. Suddel, (2009) Industrial fibers: Recent and current developments, Proceedings of the Symposium on Natural Fibres, p71-82.
44. N. Graupner, A. S. Herrmann, J. Müssig, (2009) Natural and man-made cellulose fibre-reinforced poly (lactic acid) composites: An overview about mechanical characteristics and application areas, ***Composites Part A: Applied Science and Manufacturing,* 40(6-7):** 810-821.
45. S. Shinoj, R. Visvanathan, S. Panigrahi, M. Kochubabu, (2011) Oil palm fiber and its composites: A review, ***Indusial Crops and Products,* 33(1):** 7-22.
46. T. Sen, H. N. Reddy, (2011) Various industrial applications of hemp, kinaf, flax and ramie natural fibres, ***International Journal of Innovation, Management and Technology,* 2:** 192-198.
47. U. S. Bongarde, V. D. Shinde, (2014) Review on natural fiber reinforcement polymer composite, ***International Journal of Engineering Science and Innovative Technology,* 3(2):** 431-436.
48. R. Kakroodi, Y. Kazemi, D. Rodrigue, (2013) Mechanical, rheological, morphological and water absorption properties of maleated polyethylene/ hemp composites: Effect of ground tire rubber addition, ***Composites Part B: Engineering,* 51:** 337-344.
49. D. U. Shah, P. J. Schubel, M. J. Clifford, (2013) Can flax replace E-glass in structural composites? A small wind turbine blade case study, ***Composites Part B: Engineering*, 52:** 172-181.

***Bibliographical Sketch**

B Suresha is a Professor of the Department of Mechanical Engineering, The National Institute of Engineering, Mysuru since 1990 and is currently the Dean, Research & Development, Head, Centre for Composite Materials Research. He obtained a Diploma (1983) in ME from CPC Polytechnic, and obtained his B.E from NIE, Mysuru (1987) affiliated to UoM Mysuru, M. Tech in Machine Dynamics (1995) from IIT Madras and PhD (2007) from PSG College of Technology, affiliated to Anna University, Chennai. Research Interest includes Materials science, Microstructure-property relationships, Light weight PMCs, Natural fibers -Composites, Fracture toughness, Wear, Abrasion, Erosion, Manufacturing Techniques-High Performance Composites, Design with Composites, Nanocomposites.