J. Mater. Environ. Sci. 6 (4) (2015) 902-917
ISSN: 2028-2508
CODEN: JMESCN

Surface Morphology & Mechanical properties of some unique Natural Fiber Reinforced Polymer Composites- A Review

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Received January 2014, Revised 29 Oct 2014, Accepted 29 Oct 2014
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Abstract
Natural fiber reinforced polymer composites (NFRPCs) have gained a worldwide acceptance as a potential substitute for glass filled composites over past few years especially in the automotive sector. As natural fibers are lesser in weight, easier to handle, non abrasive & cost effective, composites made from them are also sustainable & economical. Every natural fiber has its own surface morphology which decides the interfacial matrix-fiber adhesion. Some natural fibers like piassava have fine protrusions containing silica on their surface which enhances interlocking at the fiber-matrix interface and thereby improving mechanical properties of the composites. Hydrophilic nature of natural fibers creates wetting issues with the resin matrix which are mostly improved by chemical, radiation & corona treatments. The mechanical properties of natural fiber composites generally increases with volume fraction of fibers up to an optimum level, and then tend to decrease. In this review, we have given special emphasis to surface morphology of some unique natural fibers & its effect on mechanical properties of the composites. Apart from automotive sector, new horizons for application of natural fiber composites are also discussed.

Keywords: Natural fiber composites, Surface morphology, Mechanical properties, Applications.

1. Introduction
Natural fibers have made a remarkable impact as a potential substitute for conventional synthetic fibers like aramid & glass fiber over a past few decades. Owing to their mechanical properties, good thermal insulation properties, low density, nonabrasive nature, easy availability from replenishable sources, cheaper prices & recyclability of natural fiber reinforced polymer composites[1] have attracted the composite industry, both for structural & nonstructural applications. Glass fibers being non-degradable pose serious health and environment hazards. They can't be easily thermally recycled as they melt at very high temperatures and remain as a residue which can damage the furnace and are quite abrasive in nature. However the main focus of this review is to realize the potential of some unique natural fibers as a replacement for glass fibers, a key component in the automobile & structural composites.
Nowadays ecological concerns have initiated the use of natural fibers in various composites that enter the market. Environmental legislations and consumers urge towards greener technologies have drawn a margin to the use of non-renewable sources. Engineering composites reinforced with various natural fibers based on ligno-cellulose such as sisal, flax, jute, hemp[2] have been reported earlier. The initial works on natural fiber reinforced composites were based on thermoset matrices, mostly phenolic & unsaturated polyester resins with sisal and jute[3-4], & later were switched to thermoplastic matrix composites[5-11]. Natural fiber reinforced composites are most widely used in automobile components particularly because of their low cost & low density. Ford *Montageträger has* made use of hemp-polypropylene composite for its front end grills. The underbody of an A-class Diamler chrysler was reported to be made from compression molded flax polypropylene composite. John Deere tractors make use of soy-resin body panels reinforced with natural fibers.

1.1 Classification of Natural fibers.

Natural fibers, especially plant fibres are grouped into six main categories viz, bast, leaf, seed, fruit, grasses/reeds, & wood fibers. A hierarchical representation of various fibers and their families are given in Fig 1[12-13].

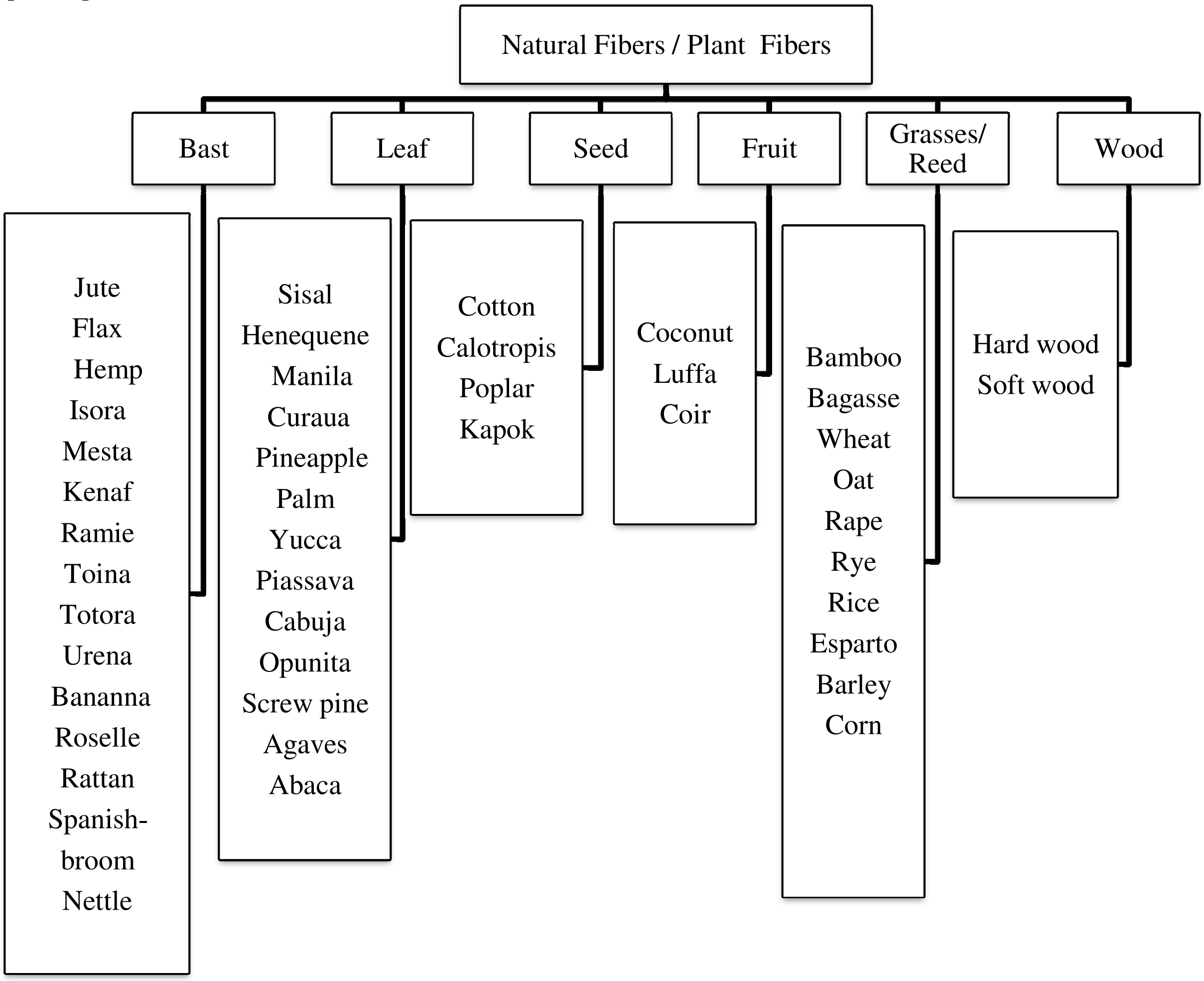

Fig 1. Classification of some selected Natural/Plant fibers.

However all these fibers cannot be used for composite applications due to their poor strength and wetting characteristics with polymer in the composites. All natural fibers have different surface morphologies and mechanical/physical properties (see Table 1)[14-16]. Some natural fibers have complex surface morphologies like piassava fiber (contains silicon rich spiny protrusions on its surface) & curaua fiber (cylindrical shaped filaments) which show different bonding characteristics at the polymer-fiber interface. Dimensions of natural fibers also vary with climatic & growing conditions. Hemp & flax fibers have higher aspect ratios (see Table 2) [17].

Natural fiber reinforced composites have excellent specific strength & high modulus with products made from them having reduced density than from glass fiber reinforced composites. Natural fiber does not pose any serious health hazards while processing them as particulate glass fibers do. When glass fibers are heated or incinerated they emit toxic fumes which cause dermal or respiratory irritations. Natural fibers being environmental friendly have no such concerns. Composites made from natural fibers have much lower costs & density than glass fiber composites which makes them more engrossed with automotive manufactures.

Table 1. Mechanical & Physical properties of selected natural and manmade fibres.

Fiber	Density (g/cc)	Moisture Content (%)	Tensile strength (MPa)	Youngs Modulus (GPa)	Elongation (%)
					2.7-
					3.2
					2-4
Flax	1.5	10.0	500-1500	27.6	1.6
Hemp	1.47	10.8	690	70	30
Kenaf	1.45	-	930	53	2-
Coir	1.2	8.0	593	4-6	2.5
Sisal	1.5	11.0	510-635	9-22	1.5-
Jute	1.3	12.6	393-773	26.5	1.8
Cotton	1.5-1.6	-	400	5.5-12.6	7-8
Banana	1.35	-	529-579	8-20	1-
Bamboo	0.8	-	391-1000	48-89	3.5
Pineapple	1.52-1.56	11.8	413-1627	34.5-82.5	-
Henequen	1.49	-	430-580	10.1-16.3	1.6
Bagasse	0.55-1.25	-	20-290	2.7-17.0	3-5
E-glass	2.5	-	2000-3500	70	0.9
S-glass	2.5	-	4570	86	0.5
Aramid	1.4	-	3000-3150	63-67	2.8
Carbon	1.4	-	4000	230-240	3.3-
					3.7
					1.4-
					1.8

Table 2. Dimensions of some Natural fibers.

Fiber	Diameter (μm)	Length (mm)
Jute	15-35	2-5
Luffa	20-50	-
Kenaf	14-33	2-6
Abaca	10-30	-
Hemp	10-51	5-55
Isora	10-17	-
Sisal	15-30	-
Pineapple	25-34	-
Flax	15-22	9-70
Cotton	11-21	10-60

1.2. Chemical Composition of Natural fibers.

Mostly natural fibers are ligno-cellulosic in nature, but also contain other components like hemicellulose, pectin, ash, silica, oils, waxes & other water solubles. It is very much necessary to know the individual concentration of these components while fabricating natural fiber composites. Cellulose is a semicrystalline polysaccharide while hemicellulose is a highly branched amorphous polymer. For better adhesion of fibers in the matrix, the ash content & the wax content should be minimal. Wax decreases the interfacial adhesion & results in delamination of composites. The hydroxyl groups of the cellulose in natural fibers imparts the hydrophilic nature, which reduces the interfacial bonding & make them more susceptible to moisture absorption. Table 3 shows the chemical composition of some selected plant fibers [18-20].

2. Kapok reinforced Epoxy composites.

Kapok fiber (*Cieba pentandra)* is one of the lightest nautral fibres and is eight times lighter than cotton. Kapok fibers have wax content on their surface which may affect the fiber matrix interfacial bonding. Hence these fibres are dewaxed for removing the wax and other impurities from the fibre surface prior to its use in composites. Dewaxing of fibers is often done by stirring the fibres in solvents like toluene or ethanol, followed by washing fibers with distilled water. The crystallinity of raw kapok fiber is 54% and that of dewaxed fiber is roughly around 63%. However dewaxed kapok fibres had shown an increased percentage in crystallinity due to the regular arrangement attained by removal of wax & other impurities. SEM images of the cross section of kapok fiber shows that these fibers are hollow in nature (see Fig 2(a),(b)).

Table 3. Chemical composition of some selected Natural/Plant fibers

Fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash content (%)	Pectin (%)	Silica (%)
Jute	45-71.5	13.6-21	12-26	0.5-2	0.2	0.5-2
Ramie	68.6-91	5-16.7	0.6-0.7	-	1.9	-
Kenaf	31-57	21.5-23	15-19	2-5	-	2.2
Abaca	56-63	15-17	7-9	3	-	1.1
Hemp	57-77	14-22.4	3.7-13	0.8	0.9	-
Henequen	77.8	4-8	13	-	-	-
Sisal	47-78	10-24	7-11	0.5-1	10	0.5
Pineapple	73.4	7.1	10.5	2	-	-
Banana	44.2	12.1	32.8	2.2	-	-

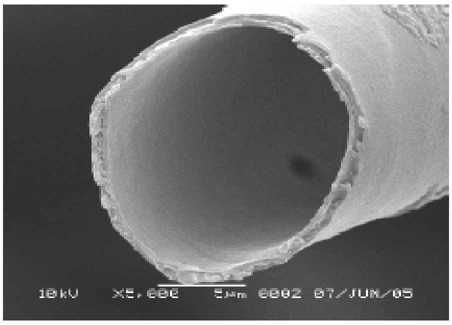

Fig 2(a). Body of Kapok fiber [21]

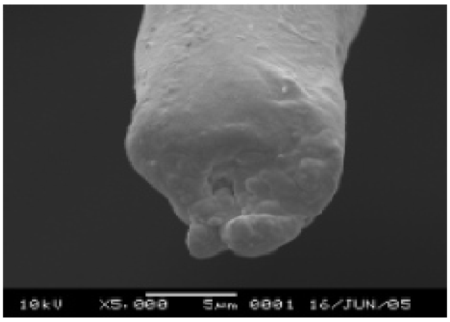

Fig 2(b). Tail of Kapok fiber [21]

Surface morphology of raw & dewaxed kapok fiber composites show that there is more uniformity & homogeneity in dewaxed fiber composites than raw fiber reinforced Epoxy composites (10 wt% fiber). SEM micrographs shown in Fig 3 (a),(b).

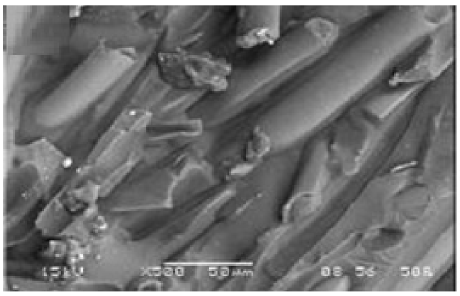

Fig 3(a). Raw fiber composite [22]

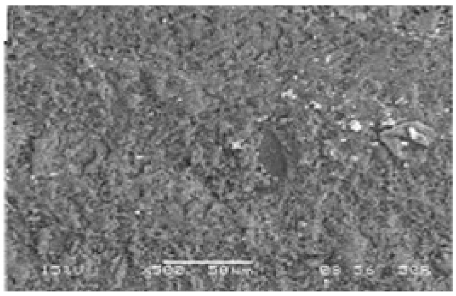

Fig 3(b). Dewaxed fiber composite [22]

3. Screw pine reinforced Unsaturated Polyester composites.

Screw pine (*Pandanus Odoratissimus)* plant leaf fiber from the *pandanaceae* family have fairly good mechanical properties when compared to that of pineapple leaf fiber, and hence were used in making traditional products like mats, baskets, hats & toys. Uses of this natural fiber in polymer composites are gaining importance especially with thermoset matrices. Screw pine reinforced unsaturated polyester (UPR) composites with mercerized fiber has better flexural strength and modulus when compared to raw fiber at different loadings. Mercerized screw pine fiber reinforced unsaturated polyester composites has flexural strength of more than 130 MPa at 30% loading[15]. However the tensile strength of this composite is lesser than 15 MPa. NaOH treated screwpine fiber with unsaturated polyester resin shows a rougher surface morphology (see Fig 4).

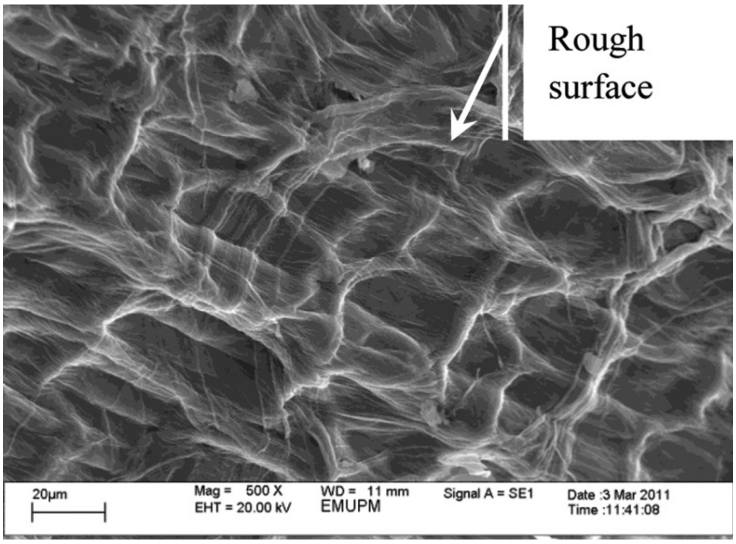

Fig 4. Rough Surface of treated Screw Pine fiber UPR composite [23]

Chemical treatments are applied to natural fibers so as to reduce the hydrophilic nature and to enhance the interfacial bonding with the polymer matrix. They interact with the hydroxyl groups of fibers and form new moieties that are capable of forming bonds with the reactive functional groups in the polymers. Surfactant treatment also increases the dispersion of natural fiber in the resin. Various chemical treatments for natural fibers are reported in the literature and a few of them are given in Table 4 [24].

4. Hybrid Natural fiber reinforced polymer composites.

Every natural fiber has mechanical properties different to other fibers and their composites respond to applied stresses in different ways. Hybrid fiber systems with two or more fibers combined have been studied so as to get a synergy of different properties of fibers .This synergy would then reflect upon the composites made out of such combinations. Some fibers may possess good flexural strength but poorer tensile properties hence they are judiciously made into a hybrid fiber system with fibers having higher tensile strength so that the resulting composite would possess both the desired property. Reinforced composites made out of such a system would give better mechanical properties and paves way for its use in structural applications.

Some of the hybrid systems such as sisal & banana hybrid, roselle & banana hybrid, roselle & sisal hybrid are fabricated with bio based epoxy resin[25], kenaf & ramie hybrid system are being used as automotive liners[26]. Plant/glass fiber hybrid reinforced polymer laminates are also being studied for their impact properties. A 30:20 wt% of flax & glass fiber in PP has reported an impact strength of 43.2 KJ/m^2[27]. Even at relatively lower loadings of 6:8 wt% of jute & glass fiber with unsaturated polyester has an impact strength of around 44 KJ/m^2[28].

Table 4. Some Chemical treatments applied for Natural/Plant fibers

Fiber Treatment	Chemicals Used
Mercerization/Alkali	Sodium Hydroxide
Acetylation	Acetic Anhydride
Benzoylation	Benzoyl Peroxide
Acrylation	Acrylic acid
Acrylonitrile Grafting	Acrylonitrile
Peroxide	Benzoyl peroxide
Permanganate	Pottasium permanganate
Isocyanate	Toulene diisocynate
Silane coupling	Alkoxy silanes, Amino silanes.
Maleated Coupling	Maleic anhydride grafted PP

5. Spanish broom reinforced Polypropylene composites.

Spanish broom (*Spartium junceum)* (SJ) fibers are widely being used with commodity plastics like PE,PP to form reinforced composites. Studies reveal that only an optimum range of 10-20 wt% of these fibers with PP enhances the tensile strength of the composites. As the fiber concentration increases, the hydrophobic polymer finds it difficult to wet the hydrophilic fibres. Its when the coupling agents like zirconates, titanates, & silanes play their roles. They act as a bridge between the polymer & the fiber by forming covalent bonds & improving their compacatability. Most of the alkoxy silane/titanate/zirconate coupling agents can be represented by a general formula given below

$$R\text{-}(CH_2)\text{-}X\text{-}(OR')_m \text{ , where } X = Si, Ti, \text{ or } Zr, \text{ and } m=0\text{–}3.$$

Where OR´ is a hydrolysable alkoxy group, and R and R´ are the functional organic groups. In most of the coupling agents the alkoxy groups are first hydrolysed to form silanol containing species. These silanols then form hydrogen bonded structure with the hydroxyl groups of the natural fibers. Finally during drying/curing, covalent bonds (-Si-O-) are formed with concomitant elimination of water. The various steps involved in the silane functionalization of natural bio-fiber is shown below (fig 5).

Radiation treatment of fibers has also been used to remove excessive hydroxyl groups from the fiber surface to promote wetting with polymer matrix. The tensile strength of spanish broom fiber reinforced PP ranges between 25-35 MPa at the optimum range. As the fiber loading increases there is a steep decrease in the tensile strength & coupling agents show no considerable effects[30]. However the young's modulus of the composite has higher values with increasing weight percent of fibers. SEM images of fracture surfaces of PP/SJ composites (80/20) with untreated & 2% silane treated fibres is shown in Fig 6(a),(b).

SEM micrograph of fractured surfaces shows the interfacial adhesion of fibres & PP matrix in silane treated fiber composites. As in treated composites, fiber & matrix shows more compactness than raw fiber composites due to the bonding between coupling agent, hydrophilic natural fibres & hydrophobic polymer matrix.

6. *Grewia optiva* fiber reinforced Phenol Formaldehyde composites.

Grewia Optiva (GO) plants fibers belong to *Tiliaceae/Sparrmanniaceae* class of plants which are mostly cultivated in the subtropical climatic conditions of the Himalayas. India being an agricultural country is home to numerous varieties of flora. Such unique fibers with thermoplastic or thermosets may bring about quiet interesting composites which can be used in automobile interiors, building constructions, floor coverings & many more. Studies with varying particulate GO fiber loadings (10,20,30,40 wt%) with PF resin has shown that an optimum range of mechanical properties increased upto 30 wt% fiber loading & then decrease [31].

At higher loadings agglomeration of fibers caused poorer transfer of load & stresses by fiber agglomerates to matrix which decreased the mechanical properties of composites. These results were obtained without any surface treatments and hence more improvements can be brought about with chemical modification of GO fibers. Tensile & flexural properties of GO fiber reinforced PF composites are shown in Table 5. Similar studies with other phenoplasts matrices like Resorsinol-Formaldehyde (RF) resin reinforced with *Grewia Optiva* fibers have also been reported [32].

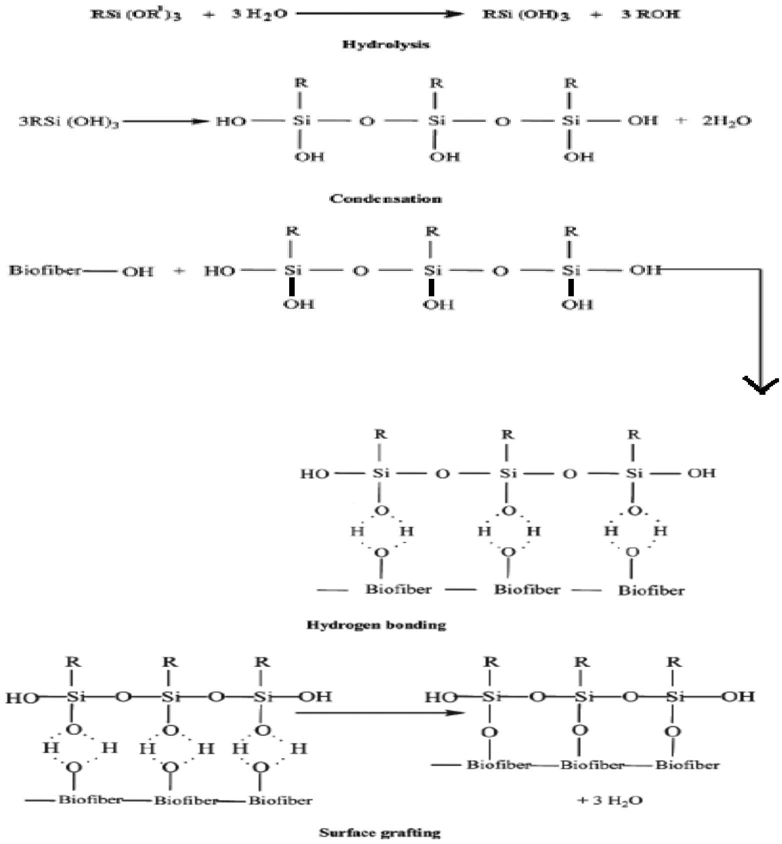

Fig 5. Various steps during Silane Functionalization of natural fibers[29].

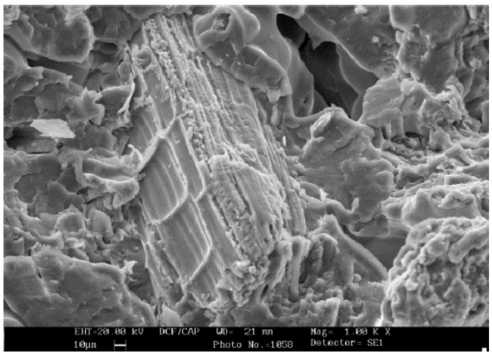

Fig 6(a). PP/SJ with untreated fibers [30].

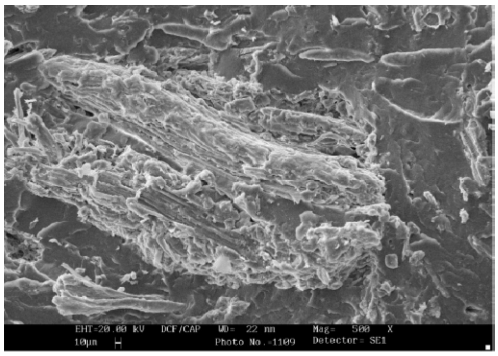

Fig 6(b). PP/SJ with 2% silane treated fibers [30]

Table 5. Mechanical properties of *Grewia Optiva*/ PF composites at different fiber loadings[31].

Fiber Loading (%)	Tensile strength (Mpa)	Flexural stress (Mpa)	Youngs Modulus (Mpa)	Flexural Modulus (MPa)
10	27.74	321.4	590	9423
20	32.38	402	682	11035
30	37.86	491.22	801	12921
40	35.74	458.4	762	11851

7. Isora reinforced Unsaturated Polyester composites.

Isora fibers are obtained from the bark of the *Helicteres isora* plant by a process known as retting. Raw isora & treated isora fibers have a considerable difference in their morphology. On chemical treatments, the pores become cleaner & reduces the fiber diameter, thereby increasing the fiber aspect ratio. This must have occurred due to the leaching out of soluble components like waxes, fatty acids, lignin & other components from the fibers. It also roughens the fiber surfaces which enhances interlocking at the resin fiber interface. But during mercerization or any alkaline treatments, -OH groups are produced by breakage of the crosslinks between cellulose & lignin or cellulose & hemicelluloses. After NaOH treatment, hydrolysis occurs due to the breakage of ether & ester bonds. This helps in removal of soluble lignin or hemicelluloses from the fiber, thereby creating more free hydroxyl groups[33] (see Fig 7).For instance the spectra of untreated & treated betel palm, kenaf fibers shows predominant peaks at 3200-3400 cm^{-1} & 1033.63 cm^{-1} which indicate the stretching vibrations of O-H & C-O respectively[34]. But with treated fibers, intense broad peaks appeared at 3200-3400 cm^{-1}, which indicated more –OH groups after alkaline treatment.

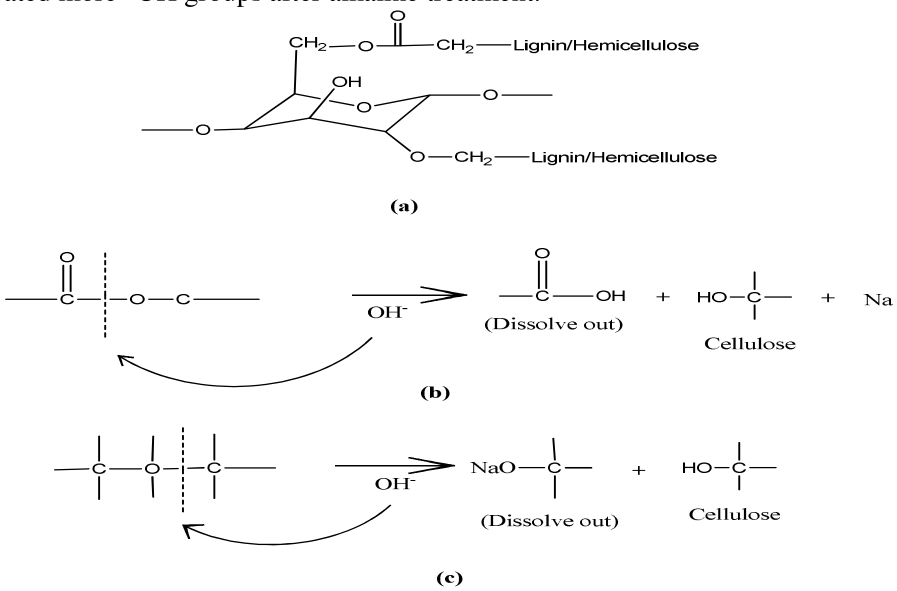

Fig 7(a) Possible crosslink network between cellulose & hemicelluloses or cellulose & lignin. Mechanism of breaking down of (b) ester bond (c) ether bond[33].

SEM micrographs of raw & surfactant treated (triton-x-100, isooctylphenoxypolyethoxyethanol) isora fibers are shown in Fig 8(a),(b) which clearly shows thinner fibers formed by triton treatment. Mechanical properties of triton treated isora reinforced USP composites are highest among other chemically modified isora composites[35]. Surfactant treated isora fibers has good dispersability in resin matrices which brings about higher mechanical properties. Raw isora fiber reinforced USP composites fails mostly by fiber pull out from the resin matrix which indicates a poor interfacial bonding between the resin & fiber.

8. Roselle reinforced Aminoplast/Phenoplast composites.

Roselle (*Hibiscus sabdarifa)* plant is a species from the *Hibiscus* family. These fibers are readily available in the Himalayan region. A very few work on roselle fiber reinforced composites suitable for applications have been reported earlier [36]. More emphasis on unique bast fibers is required for developing newer composites, replacing glass fibers. Particulate roselle reinforced RF (Resorcinol-Formaldehyde) composites show better mechanical properties than short & long fiber reinforced RF composites. However the main drawbacks of these composites are that they are sensitive to moisture & have poor chemical resistance. Improvement of these properties can be achieved by reducing the hydrophilic character of roselle fibers through chemical modifications. Roselle fibers have also been studied with other thermoset matrices like UF (Urea-

Formaldehyde) resins with varying fiber loadings. Mechanical properties were found to increase upto 30 wt% loadings & then decrease [36]. But when compared to *Grewia Optiva*/PF composites, chopped roselle short fiber/UF composites have low tensile strength of about 9.2 MPa & flexural strength of 52 MPa at 30 wt% loading. Table 6 shows the tensile & flexural properties of roselle/UF composites at various loadings.

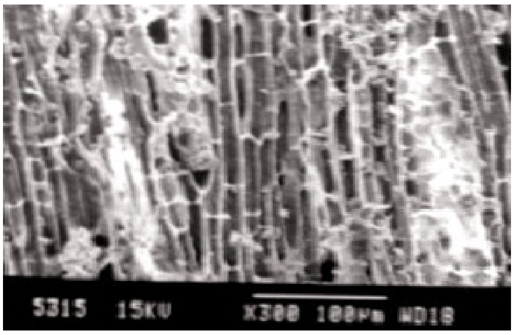

Fig 8(a). Raw Isora fiber [35].

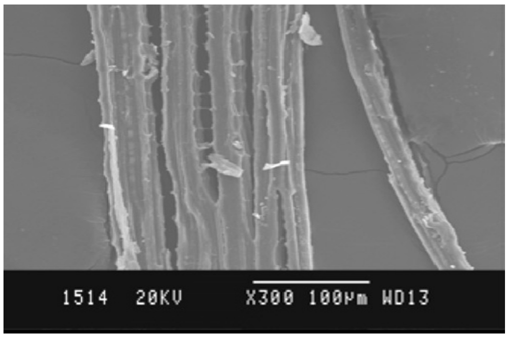

Fig 8(b). Surfactant treated Isora fibers [35].

Table 6. Mechanical properties of *Hibiscus sabdarifa* / UF composites [36].

Fiber Loading (%)	Tensile strength (Mpa)	Flexural stress (Mpa)	Youngs Modulus (Mpa)	Flexural Modulus (MPa)
10	6.15	33.15	155.24	2368
20	8.02	36.90	199.38	2702
30	9.20	51.90	233.54	3578
40	8.70	44.70	207.64	3171

9. *Arenga pinnata* fiber reinforced Epoxy composites.

Arenga pinnata *(Arenga saccharifer)* plant belongs to *Arecaceae* family. They are commonly known as Black fiber palm, Kaong, Irok or Gomuti palm. Studies reveal that kaong fiber reinforced epoxy composites with an increasing fiber content from 0-15 wt% shows an increase in tensile strength from 37.5 MPa to 49.6 MPa. Beyond this limit it affects the tensile strength adversely. At 15 wt% this fiber improves the rigidity & stiffness of the epoxy resin markedly. A woven roving of 10 wt% of kaong fiber with epoxy resin shows even better tensile strength & young's modulus than 15 wt% short or long fiber reinforced composites[37]. At 20 wt% voids on the surfaces are also quiet visible. Voids arise due to the entrapped air pockets in the matrix during composite processing. As natural fibers are hygroscopic in nature, proper drying of fibers are necessary before composite fabrication, failing for which reduces the interfacial bonding and life span of the composite

10. *Typha angustifolia* reinforced Unsaturated Polyester composites.

Typha angustifolia (TA) plants belong to the *Typhaceae* family. They are mostly found in regions where there is plenty of water. These fibers are also capable of absorbing harmful water from the chemical effluents discharged by the industries. Mechanical properties of *Typha angustifolia* fiber reinforced unsaturated polyester are fairly good enough to be used for composite applications. The tensile strength & impact strength of these composites were found to be 49 MPa & 115 J/m (vol fraction of fiber,V_f - 0.355) respectively[38]. *Typha angustifolia* fibers have low densities and interestingly the composite density of *Typha angustifolia* /UPR decreased with increasing volume fraction of fibers without compromising on the mechanical properties. Fig 9 (a),(b). shows the variation of tensile strength & impact strength of *Typha angustifolia*/UPR composites at different V_f . Lighter weight, better mechanical & insulating properties makes these newly developed composites suitable for applications such as electronic packages, insulation boards, automobile parts, building constructions.

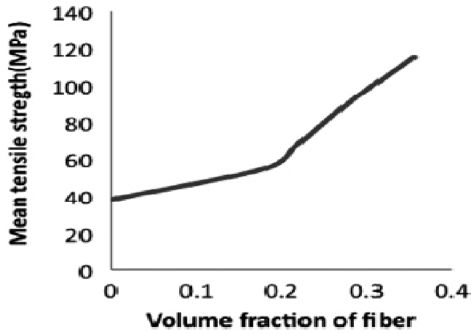

Fig 9(a). Tensile strength v/s V_f [38]

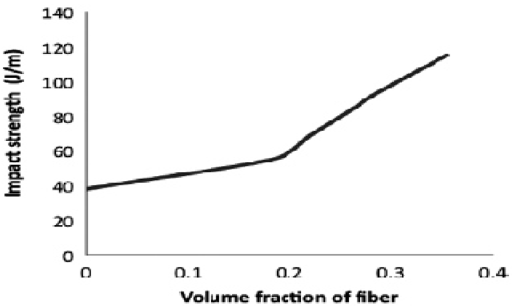

Fig 9(b). Impact strength v/s V_f [38]

11. Golden cane reinforced Unsaturated Polyester composites

Golden cane palms (*Chrysalidocarpus lutescens*) also know as royal palm, areca palm, or butterfly palm belongs to the *Arecaceae* family. They grow as an ornamental plant in tropical & subtropical regions. The source of the fiber are the leaves of the plant which falls on the ground after ripening followed by the retting process to make fibers suitable for composite reinforcements. Tensile strength & tensile modulus of golden cane reinforced UPR composites are 67.12 Mpa (at V_f - 0.43) & 1.428 GPa at the same volume fraction. Impact strength is fairly good enough & ranges to 358 J/m, even higher than *Typha angustifolia* fiber/UPR composites. The flexural strength of golden cane/USP composites is 22.7% and 31.2% more than that of sisal and banana-polyester composites, respectively (at V_f – 0.39). A similar increase of 44% & 75% in flexural modulus of golden cane/UPR composites was observed than sisal and banana-polyester composites[39]. Interestingly, this composite fits into the category of tough engineering composites because they can shift the crack propagation site from the edge of the notch. Considering all the mechanical properties, good impact strength & flexural modulus they can find applications as building/construction materials.

12. Piassava fiber reinforced composites.

Piassava fibers fall under the Brazilian *Palm* family, and are available in plenty in the amazons. These fibers are cheaper and were traditionally used for making brooms, brushes, cables & roofing of houses. Among them there are many varieties and most common are *Leopoldinia piassaba* & *Attalea funifera* piassavas. The surface of piassava is arranged with an ordered array of silica rich spiny protrusions, & reentrant cells which can interact with the polymer matrix in a composite. Energy Dispersive Spectroscopy (EDS) analysis of piassava fibers confirms silica in these protrusions[40]. Its postulated that these spiny protrusions acts as anchors and enhances the mechanical interlocking at the fiber matrix interface. SEM micrographs of *Leopoldinia piassaba* & *Attalea funifera* piassavas having silica rich spiny protrusions is shown in Fig 10(a)(b).

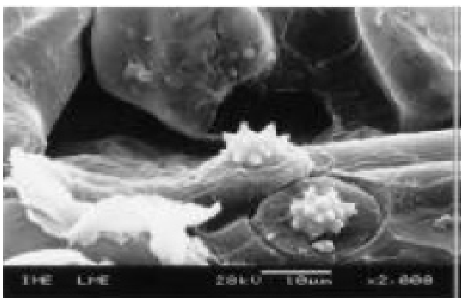
Fig 10(a). *Leopoldinia piassaba*[40]

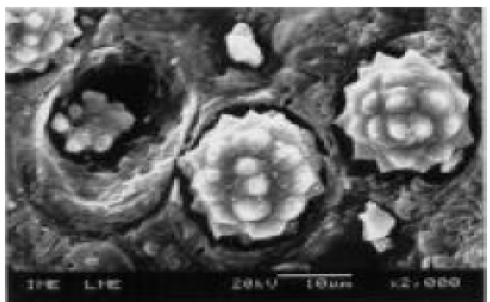
Fig 10(b). *Attalea funifera*[40]

Despite having unique surface characteristics a very few work has been reported in the literature on piassava as a reinforcing material for composites[40-41]. Interfacial shear strength of piassava/polyester composites were found to be similar to that of glass fiber/ phenolic composites[42-43]. Piassava fiber also has good interfacial interaction especially with orthophtalic polyesters, without any surface or chemical treatements. Hence piassava reinforced composites can be strong contestants for replacing glass fibers from structural composites.

13. Curaua fiber reinforced composites

Curaua (*Ananas erectifolius*) fibers extracted from leaves of the plant are one among the strongest & flexible fibers. Its strength can be correlated with the surface morphology. Each curaua fiber has a filamentary structure consisting of more than 50 cylindrically shaped filaments (see Fig 11). When a load is applied, these filaments tend to slide past one another. So the tensile stress levels required for complete rupture of these fibers falls in very high range(~1,000 MPa)[44]. Such unique fibers hence can contribute remarkably in developing engineering composites for high end applications. . Table 7 gives a comparison of mechanical properties of some NFCs with GFCs, where we can observe that NFCs have good tensile strength at higher volume fraction of natural fibers.

Table 7. Comparison of mechanical properties of glass fiber & some natural fiber reinforced composites.

Polymer/Fiber	Fiber loading (wt %)	Tensile strength (Mpa)	Tensile modulus (Gpa)	Flexural strength (Mpa)	Flexural modulus (Gpa)	Impact strength (J/m)	Elongation @ break (%)	Ref
Polyester/ Glass fiber (virgin)	20	36.2	2.6	-	-	227	2.8	[47,48]
	30	41.9	2.5	140	7.2	464.3	3.1	
	40	64.4	7.2	-	-	645.1	1.8	
	50	**6.8**	**0.1**	**210**	**10.3**	**811.3**	**13.5**	
	60	9.5	0.1	-	-	809.9	17.9	
Polyester/ Glass fiber (waste)	20	20.1	1.9	-	-	86.7	1.8	[47]
	30	26.2	1.9	-	-	122.9	1.9	
	40	27.9	2.0	-	-	159.6	1.8	
	50	**3.2**	**0.1**	-	-	**385.8**	**8.6**	
	60	3.2	0.1	-	-	229.3	9.0	
Polyester/ Buriti Petiole fiber	10	53.7	0.59	-	-	-	4.8	[49]
	20	72.2	0.95	-	-	-	9.4	
	30	96.9	0.96	-	-	-	6.7	
	40	**100.1**	**1.66**	-	-	-	5.4	
PP/ Pineapple leaf fiber	**50**	**42.17**	**3.42**	**31.01**	**2.32**	-	-	[50-51]
	60	48.73	3.12	21.77	2.23	-	-	
PP/ Curaua fiber	**50**	**46.38**	**3.78**	**33.10**	**2.51**	-	-	[52-53]
	60	50.75	3.34	24.97	2.53	-	-	

Impact strength of continuous & aligned curaua fiber composites were found to increase with fiber loading. Impact energy of curaua fiber reinforced polyester & epoxy were found to increase linearly upto 20-30% volume fractions. However mercerized curaua fiber reinforced orthophtalic polyester composites had shown adverse effects on impact energy, apparently by deterioration of curaua fibers after treatment

[45].Interestingly it was observed that in failed composites, owing to the curaua fiber flexibility total rupture of samples was prohibited. In a comparative study of unidirectional curaua & glass fiber reinforced polyester laminates for orientation angles greater than 90°, the mechanical properties of glass fiber laminates was obvious to be superior but were considered to be similar with curaua fiber reinforced laminates[46]. These indications reveal the fact that curaua fibers can go at par with glass fibers as a reinforcing materials in composites

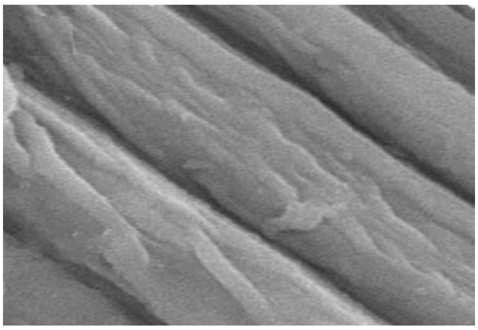

Fig 11. Filamentary structure of Curaua fibers(2000×).[44]

14. Greener composites from Natural fiber reinforced biopolymers.

Biodegradable polymers like polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch, cellulose esters, chitosan, and chitin are being reinforced with naturally occurring fibers to form fully degradable green composites. However to gain a worldwide acceptance their technical constraints should be addressed before the scientific & technical community. Most of the works centers around PLA, a brittle thermoplastic polymer which is being produced over 1,40,000 tonnes annually[54]. Studies on mechanical properties of PLA reinforced with natural fibers like flax, kenaf, jute, basalt, sweet sorghum have already been reported[55-59]. Both PLA & natural fibers are hygroscopic in nature and was assumed to show better interfacial adhesion. Earlier speculations of poor debonding characteristics of composites at the interface was that lack of adhesion resulted most probably during mechanical testing or due to rough handling at the time of composite production. More conclusions on this can be drawn only by further research using strong analytical tools. PLA/Kenaf composites are reported to be used for making mobile phone casings by NEC (Model no- FOMA(R), N701iECO)[60]. Greener composites from sugarcane bagasse reinforced corn-starch based resin(a blend polycaprolactone & starch) were studied for their mechanical properties at different volume fractions. Flexural properties were higher for fiber lengths 9.1 & 16.1 mm but decreased for 1.6 & 3.2 mm due to the fact that its lesser than the critical fiber length of bagasse(3.75 mm). Optimum flexural properties were obtained at 65 vol% of bagasse[61]. The surface morphology of bagasse is unique as it has a cellular structure in its raw form. After compression the void fraction of the fiber decreases & the cellular structure of the bagasse becomes denser thereby enhancing the mechanical properties of the composite. Raw bagasse has about 75-80% porous structure as evident from the SEM micrograph (Fig 12). Upon compression of bagasse, it's estimated that the mechanical properties would increase about four times or even more. Microphotographs of tensile fracture sample of bagasse/corn-starch resin composite clearly shows collapsed bagasse fibers (see Fig 13). Mercerized bagasse reinforced composites shows even better flexural properties than raw fiber composites.

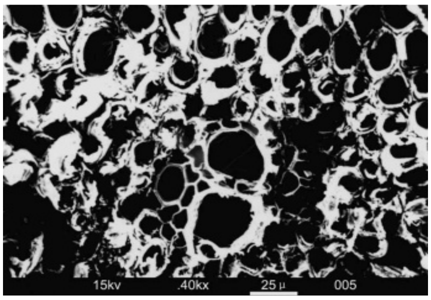

Fig 12. Raw Bagasse fiber with voids[61]

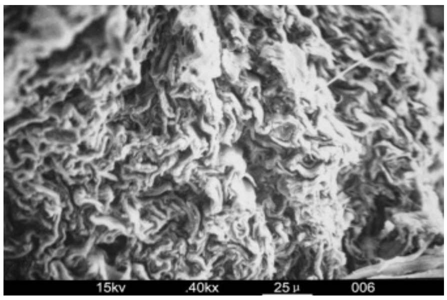

Fig 13. Fracture surface of bagasse/starch composite[61]

Poly(hydroxy alkanoates)(PHAs) forms another class of biodegradable polyesters for developing green composites, but however their applications has been less due to their high prices. Incorporating natural fibers in PHAs like poly(hydroxybutyrate-co-valerate)(PHBV) with pineapple leaf fibers, recycled cellulose fibers & bamboo pulp fibers[62-64] also shows better mechanical properties than pure PHBV resin. However such fully biodegradable composites can be used in biomedical applications where biodegradability & biocompactability are of much importance. Similarly other green composites like ramie/soy resin composites [65], epoxidized soybean oil/flax fiber composites [66] have also shown better mechanical properties with increasing natural fiber content.

15. Applications of Natural fiber reinforced polymer composites.

Natural Fiber Composites (NFCs) has competitive mechanical properties & reduced costs which made a wide spread use of them in varied fields. With the advent of newer methodologies for processing & treatments of natural fibers, NFCs have become more popular especially with automobile industry. Several products like mobile phone cases, laptop cases, toys, snowboards, tennis rackets, building/construction materials, musical instrument parts, furniture and may more have already developed from NFCs apart from automotive exterior & interior components.

Racing bicycles with NFCs have also been developed by Museeuw, with flax-carbon-epoxy prepegs[67]. Museeuw, a Belgium based bicycle company claims that the flax content in the bicycle frames were upto 80%. Carbon-flax prepreg laminates have good stiffness & reduced vibration damping characteristics suiting them for dynamic applications. Deckings, Railing systems, window frames and fencings are also made from wood, flax, rice husk & bagasse reinforced composites. Even though NFCs find applications in vast diverse fields, amongst all the automotive industry makes the most judicious use of them. In 1941, Henry Ford designed & built a car from compression molded NFCs with 70% cellulosic fibers (including hemp) with a resinous binder. Now companies like Volkswagen, Audi, BMW, Daimler Chrysler, Opel, Peugeot, & Renault have already replaced many of their interior & exterior components with natural fiber reinforced composites. They have replaced door panels, side panels, headliners, dashboard parts, back side of seats and many more with NFCs. Natural fiber based composites are used in building/construction sector, especially with components that have more aesthetic value than the structural value. As they can't take up large loads, parts which require more strength cannot be fabricated from natural fiber composites.

Table 8 shows some applications of NFCs in various sectors with emphasis to the fibers used & processing techniques employed.

Table 8. Applications of Natural Fiber Composites (NFC) in various sectors (Source: Lucintel).

Sector	Parts made from NFC	Processing techniques	Fibers used
Automobile	Door panels Seat backs Head liners Dash boards Truck liners	Injection moulding Compression moulding	Kenaf, Hemp, Abaca, Wood fiber
Electrical & Electronics	Mobile cases Laptop cases	Injection moulding	Kenaf
Sports Goods	Tennis racket Bicycle frames Snowboards	Oven cure	Flax, Hemp
Building/ Construction	Decking Railing Door Panels Window frames	Extrusion Injection moulding Compression moulding	Bagasse, Flax,Wood, Coir, Stalk, Rice husk

But however their impact strengths are worth commendable. NFCs have good thermal & acoustic insulation properties which suites them for many applications such as roofings, flame retardant boards and floor coverings etc. For instance the HRR (Heat Release Rate) of PE/Flax composite is less than that of PE, which infers the flame retardency behavior of these composites. The major potential of these composites lies in the building/construction sector, where glass fibers can be replaced from non-load bearing composites

16. Processing limitations of Natural fiber composites.

The major drawback of Natural fibers is that they cannot be processed at higher temperatures for longer periods. Thermo Gravimetric Analysis (TGA) analysis of Jute fibers shows that they start degrading around 240° C[68].Processing temperatures are hence restricted below 220°C, as fibers start to degrade & volatile emissions occur at higher temperatures[69]. This limits the type of thermoplastics that can be used with natural fibers to commodity plastics such as PE, PP, PVC, and PS. Conventional processing techniques like Extrusion (short fiber), Injection Molding (short & long fiber) and Compression molding (short, long, continuous, matt & fabric) are used to make natural fiber reinforced composites.

Some additives like Calcium oxide (CaO) are added to wood composites, while processing as it neutralizes the acidity of wood and also absorbs humidity and minimizes degradation risks during processing. Presence of CaO also gives an increase in the modulus of the composites. Natural fibers are hygroscopic in nature and should be dried properly before mixing with the polymer matrix as chances of air being entrapped in the composites are high. Polymers are hydrophobic & natural fibers being of opposite nature, dispersion of fibers becomes difficult with the matrix. As the fiber loading increases, agglomeration occurs which deteriorates the mechanical properties of the composites. Hence the fiber loading should be optimal to achieve the desired mechanical property. Compactibilizers like Maleated PP, acrylic acid grafted PP are being used with natural fibers to prevent agglomeration & proper blending of fibers in the composites. Processing of natural fiber with thermosets are mostly done by hand-layup, pressure bag molding, compression molding and resin transfer molding. Thermoset reinforced products like insulating panels, snowboards, and tennis rackets are generally fabricated by hand layup process followed by oven curing.

17. Summary & Conclusion.

Natural fiber composites (NFCs) have their own advantages and technical drawbacks. Hydrophilicity of natural fibers is of great concern, as it increases the moisture absorption thereby reducing the dimensional stability of the composites. As some natural fibers are hollow in nature their composites show better thermal and acoustic insulation properties. But most of NFCs are not applicable for load bearing applications as they have low tensile strengths when compared to glass fiber composites (GFCs). Natural fibers have excellent vibration damping property which can be made use in vehicle parts where there is excessive vibration and noise. These fibers absorb the waves and dampen it much faster than their synthetic counterparts. Hence they are used in conjunction with carbon and aramid fibers so as to get both strength and damping effects. Potential areas of applications include underbodies of heavy trucks, cars, trains, bicycle frames and many more. In the building/construction sector, there lies a major potential for NFCs in the years ahead. As they have good thermal & acoustic insulating properties they can be used in the interiors as well as in exterior applications where aesthetics have more importance. However further studies on newer and existing natural fibers have to be promoted to discern the hidden potential of novel natural fiber composites.

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