Fiber Reinforced Polymer Composites: A Review

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Abstract— *Fibre reinforced polymer (FRP) composites mainly consist of high strength fibres embedded in polymer matrix keeping a distinct interface between them. In this FRP's the individual component keeps their distinct physical and chemical identities but they combine together to produce materials with excellent properties. Low density, high tensile strength and high modulus are the main characteristics of fibre reinforced polymer composites. The main factors that affect load carrying capacity are interfacial bonding between fibre and matrix, alignment of fibre in matrix and the nature of fibres. Here in this review a comparative account of the major synthetic and natural fibre as reinforcement for polymer composites as well as methods for enhancing mechanical properties are discussed.*

Keywords: **Polymer composites, Synthetic fibres, Natural fibres, Mechanical properties, tribological properties**

I. INTRODUCTION

The importance of composite materials is being increasing day by day because of its attractive properties in this fast-growing world. For the past few decades, fibre reinforced polymer (FRP) composite materials are being considered as alternatives for the metallic components in aerospace, defence, automobile, electrical and electronic industries. Compared to metals, FRP composites have low density, higher stiffness and specific strength, improved fatigue performance and higher corrosion resistance and high strength to weight ratio. The performance of these FRPs under various loading conditions; such as torsional, axial and impact loading is very important for the design of the structural components [1]. Actually, the FRP composites are a category under polymer matrix composites (PMC). Generally, PMC consists of two phases namely, the matrix phase and reinforcement phase. Mechanical properties and tribological properties of fibre reinforced polymer composites depend on the fibre, matrix and the interface between them. By modifying the matrix phase, using suitable fillers properties of these fibber reinforced polymer composites can be improved [2]-[3].

This review gives an overview about various kinds of synthetic and natural fibres used in developing polymer matrix composites. Presently the common synthetic fibres used are carbon, Kevlar and glass. Apart from synthetic fibres, reinforcements from natural sources are also used for reinforcing polymer matrices. All these reinforcements are less dense and bind the matrix with high strength and stiffness [4]. The natural polymers reinforced together with the synthetic fibres such as glass fibre, aramid fibres and carbon fibre provide advantages of high stiffness/strength to weight ratio as compared to the conventional materials [5]-[6]. The major natural sources for fibres are Jute, kenaf, coconut, rice husk, sisal and banana [7]. The properties of the matrix had a major influence on the compressive strength of FRP composites. In addition, the interaction between matrix and fibres is much important for designing damage-resistant and damage-tolerant composite structures. In order to improve the compressive strength, damage tolerance and resistance of the composites, the epoxy is modified with various kinds of fillers [8]. One of the traditional way is that, the micron-sized fillers are incorporated into the epoxy resin. However, for such fillers there are some drawbacks, such as reduction in failure strain, impact strength, and sometimes fracture toughness and thermal stability of the epoxy [9]. The problem has been overcome through adding nanoparticles into the epoxy matrix. There are several types of nanoparticles which are commercially available and commonly used for the development of nanoparticle-filled polymer called nanocomposites, such as montmorillonite organoclay, carbon nanotubes, Nano silica and nano fibers. The objectives of adding these nano fillers are to enhance the strength, elastic modulus and toughness without losing the strain to failure and the thermal stability of the epoxy resin [10].

II. CLASSIFICATION OF REINFORCING FIBRES

A. GLASS FIBRES

Glass fibres one of the widely used polymer reinforcements with about, 93% of all FRP are reinforced with glass fibres. Glass fibres are used in the manufacture of printed circuit boards, structural composites and a large range of special-purpose products [11]-[12]. Out of it, the oldest and the most common form is the E-glass or electrical grade glass fibre. Other kinds of glass fibres include A-glass or alkali glass, C-glass or chemical resistant glass, and the high strength R-glass or S-glass. Under laboratory situation glass fibres can withstand tensile stresses of about 7000 N/mm^2. whereas the commercial glass fibres range 2800 to 4800 N/mm^2.

The glass melts are made by fusing silica with minerals, which contains the oxides needed to get a given composition. The molten mass is suddenly cooled to prevent crystallization and then formed into glass fibres by the process known as fiberization [13]. The mechanical behaviours of fibre-reinforced (FR) composites are mainly dependent on their intrinsic abilities to enable stress transfer, which also depends on the matrix strength, fibre strength and the strength of interfacial adhesion between the matrix and the fibre. Glass fibres have been available in various forms such as woven mat, longitudinal, chopped fibre and chopped mats to enhance the tribological and the mechanical properties of the FR composites [14]. The properties of such composites dependent on the orientation and the nature of the fibres laid during specimen preparation.

TABLE I

MECHANICAL AND PHYSICAL PROPERTIES OF GLASS FIBRE

Type	Density (g/cm^3)	Tensile Strength (GPa)	Young's Modulus (GPa)	Elongation (%)
E-glass	2.59	3.446	72.31	4.7
C-glass	2.53	3.32	68.94	4.6
S-glass	2.45	4.88	86.92	5.5
A-glass	2.43	3.30	68.99	4.9
R-glass	2.56	4.133	85.58	4.9
EC-Glass	2.74	3.446	85.57	4.7
AR-glass	2.72	3.242	73.11	4.5

B. Carbon fibres

Out of all the reinforcing fibres, carbon fibres offer the highest specific strength and modulus [15]. Carbon fibre has the ability to maintain its tensile strength even at very high temperatures. Carbon fibres offer high thermal and electrical conductivities with comparatively low coefficient of thermal expansion [16]. These properties of carbon fibre make them ideal for applications in automobile, electronics and aerospace sectors. The carbon fibre provides a maximum strength of 7Gpa, axial compressive strength is 15-60% of its tensile strength. Poly-acrylonitrile (PAN) is the most common precursors used in carbon fibre production, which gives high tensile strength and elastic modulus, mainly applied for structural material composites in sporting/recreational goods and aerospace [17].

Carbon fibres are much versatile, because of their high stiffness to weight and strength to weight ratio. Moreover, they are infusible, chemically inert and electrically conductive. The stiffness and modulus of elasticity of carbon fibbers are also much higher [18].

TABLE II

MECHANICAL AND PHYSICAL PROPERTIES OF CARBON FIBRE

Carbon Fiber Type	Tensile Strength (GPa)	Tensile Modulus (GPa)	Breaking Elongation (%)	Density (g/cm^3)	Carbon Content (wt%)
Low strength	2.5-3.2	245 – 275	1.2-1.5	1.6 -1.9	92 – 94
High strength	3.7 -4.2	245 -275	1.2-1.3	1.6 -1.8	91 -93

Ultra-high strength	4.6 -4.8	251 – 272	1.2-1.45	1.5 -1.9	92 – 95
Intermediate modulus	5.8 -6.1	305	1.21 -1.42	1.8 -1.9	96 -99
high modulus	2.4 -3.0	382 – 405	0.61 -0.73	1.6 -1.8	>99.2
Ultra-high modulus	3.7 -4.1	538 -545	0.31 -0.42	1.8 -2.2	>99.9

C. Kevlar Fibres

Kevlar is the aramid fibre of Poly-para-phenylen terephtalamide (PPTA) with a strong molecular structure [6]. It can be viewed as, nylon with extra benzene rings on the polymer chain to increase its stiffness. It is mainly popular for its tremendous applications in industry and advanced technologies like helicopter blades, ballistic Armour, sporting goods, pneumatic reinforcement, etc [19]. Kevlar are also employed in applications that perform low weight and high strength together with the high impact resistance or penetrations. Compared to the other synthetic fibres, it shows significantly higher tensile strength, lower fibre elongation and higher tensile modulus [20]. Kevlar also exhibits excellent property to high temperature for polymeric materials. Glass transition temperature of Kevlar is around 370°C and do not melt like nylon.

TABLE III

MECHANICAL AND PHYSICAL PROPERTIES OF KEVLAR FIBRE

Fibre	Characteristics	Tensile Modulus (GPa)	Tensile Strength (GPa)	Extension to Break (%)	Relative Density (g/cm^3)
Kevlar 29	Regular	71	2.8	4.5	1.43
Kevlar 49	High modulus	134	2.8	2.9	1.46
Kevlar 129	High strength	98	3.5	3.2	1.46
Kevlar 149	Ultra-high modulus	144	2.4	1.6	1.48

D. Natural fibres

Natural fibres reinforced polymers (NFRP) are being considered as low-cost and lightweight in comparison with the synthetic composites. Natural fibres are normally easier to handle and has good acoustic and thermal insulation properties [21]. There are a wide variety of different natural fibres which can be applied as reinforcement or fillers. The most important types of natural fibres used in composite materials are flax, hemp, jute, kenaf, and sisal due to their properties and easy availability. The major drawback in using natural fibre is the incompatibility between the hydrophilic natural fibres and the hydrophilic thermoplastic matrices during incorporation, which leads to undesirable properties of the resulting composites [22]. Due to low density and satisfactorily high specific properties of natural fibres, the composites based on natural fibres have very good implication in the automotive and transportation industry [23]. All the natural fibres are classified in three categories, mainly based on sources: animals, plant and minerals [24]. Mechanical properties of some of the commonly used natural fibres are [25]-[26] are given in table 4.

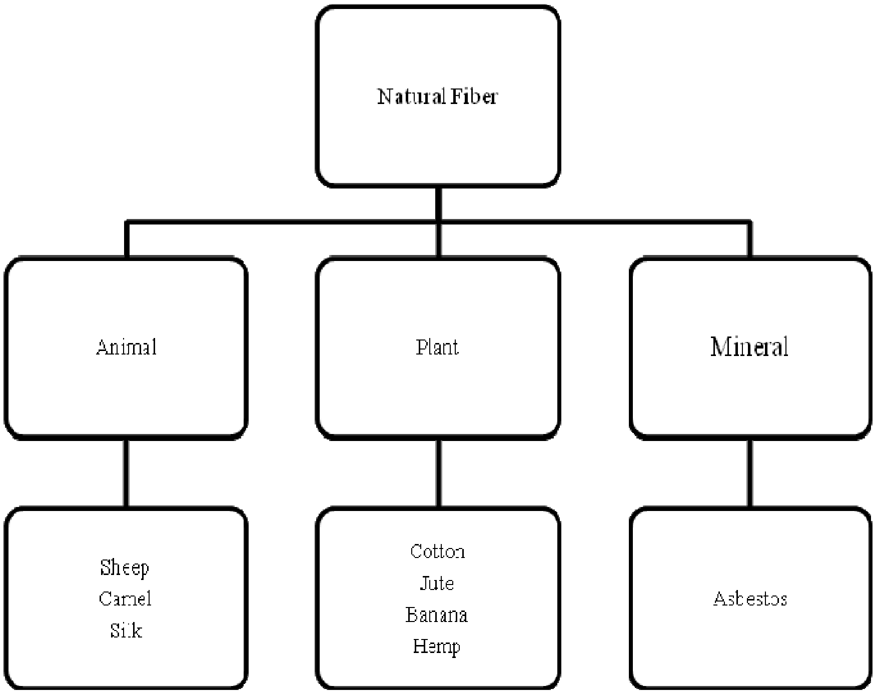

Fig 1: Classification of natural fibres based on the source of origin

TABLE IV

MECHANICAL AND PHYSICAL PROPERTIES OF NATURAL FIBRE

Fibre	Tensile strength (GPa)	Elastic modulus (GPa)	Elongation (%)	Density (g/cm^3)
Cotton	400	5.5-12.6	7.0-8.0	1.5-1.6
Jute	393-700	26.5	1.5-1.8	1.5-1.8
Hemp	690	70	2-4	1.47
Flax	500-1500	27.6	2.7-3.2	2.7-3.2
Kenaf	930	53	1.6	1.45
Sisal	511-635	9.4-22	2-2.5	1.5
Coir	593	4-6	30	1.2

III. CHEMICAL TREATMENT OF FIBRES

Surface treatment of fibres is one of the methods to improve adhesion between the reinforcement and the matrix [27]-[28]. The composites developed with untreated reinforcements have low interlaminar shear strength [29]. These leads to poor bonding and weak adhesion between the matrix and the fibre. This tends to increase in wet ability of reinforcement [30]. Surface treatments of reinforcements are classified into oxidative and non-oxidative treatments [31]. Treatment increases the roughness of fibre material [32]. The increase in roughness increases the overall surface area of the fibre or reinforcement, which leads to greater interaction between both the matrix and reinforcement [33]-[34]. Surface treatment of reinforcement also influences the chemical structure of reinforcement and thus, enhances the chemical bonding with the matrix. In Oxidation treatment method, acidic functional groups are developed on the reinforcement surface. The effect of the treatment in improving the surface properties of reinforcement depends in the concentration of oxidative medium, temperature, treatment time and the reinforcement itself [35]. Generally, the oxidation is achieved with liquids (by nitric acid, hydrochloric acid etc) or by gases (by air, oxygen, ozone etc.) [36]. Oxidation treatments involve gas-phase oxidation, catalytic oxidation and liquid-phase oxidation (chemically or electrochemically). Plasma is an electrically conducting medium consist of positively charged ions, negatively charged electrons and neutral atoms or molecules [37]. The purpose of plasma surface treatment of reinforcements in composite materials is to modify the physical and chemical structures of their surface, reinforcement-matrix bonding strength without influencing their mechanical properties [38]. Different adhesion mechanisms can be carried out by plasma treatments. They are: (a) increase surface energy which improve wetting of the reinforcement by the matrix (b) increase the surface roughness of fibre which leads to mechanical locking of matrix and fibres(c) remove the impurities present in the surface of the reinforcement to increase the contact between fibres and matrix and (d) deposit functional groups for proper chemical interactions between the reinforcement and the matrix [39]. In Gamma treatment, reinforcement is exposed to high-energy laser irradiation or gamma-irradiation which guide to surface roughening and addition of some chemical groups like carbonyl [36]. If the composite materials are exposed to the irradiation, resin hardening will take place, which leads to improved strength and wear behaviour of the product [40]. Properties of the fibre reinforced polymer composites improve when, reinforcement get exposed to radiation. It is because of surface roughening of fibre and improved fibre-matrix adhesion [41].

IV. MECHANICAL AND TRIBOLOGICAL PROPERTIES

Epoxy matrix filled with graphite filler matrix is used for developing carbon fibre composites. Graphite filler is added in the range of 5 to 30wt% of epoxy. The specimen is developed as the ASTM D638-14 standard. After the testing of each specimen the result shows that, the specimen with 7.5, 10 and 11.5 wt%-graphite show the best balance of mechanical (modulus, strength, strain) properties, because the dispersion of graphite platelets is more homogeneous [42]. Fly ash filled epoxy matrix carbon fibre composites were developed. On the basis of tensile testing and flexural testing as per ASTM standards, it is noted that, the specimen with 6 grams of fly ash obtain the maximum tensile strength whereas, the specimen with 8 grams of fly ash shows the maximum tensile modulus of elasticity, and the specimen with 4 grams of fly ash produces maximum flexural strength [43]. The glass fibre reinforced composites are developed using hand-lap method and compressed with 5kg for 24 hrs. Totally five specimens were created and four of the specimens were kept in different temperatures of 600°C, 900°C,1200°C and 1500ºC and heated for one hour. The remaining one specimen is kept as untreated. The tensile test was carried out according to ASTM D 638-01 standard, the impact test according to ASTM D-256 standard and the shear strength according to ASTM D5868 standard. The results show that, heat treatment of the GFRP composite below 1000ºC shows best increase in their different mechanical properties [44]. The tribological properties of fibre reinforced polymer matrix composites (FRPCs) depends on different operating and material parameters. Some of the major parameters responsible for the excessive wear and friction of FRPCs are fibre orientation, Fiber volume fraction, fibre length, surface treatment. Fiber orientation is an important factor in the tribological study of fibre reinforced composites. Many researches are done with different orientations like normal, parallel, anti-parallel and random. All of them concluded that the normal orientation gives minimum wear rate while random orientation gives maximum wear rate [45]-[46]. The load carrying capacity of the composite material mainly depends on the fibre volume fraction. As the fibre volume fraction increases the ability of carrying load also increases. But in core researches it is found that, only up to a particular limit of fibre volume faction the ability of load carrying capacity increases, after that its tends to decrease. This is because of the de-bonding between fibre and resin [47]-[48]. Fiber length has a major role to create interfacial bonding with fibre and matrix. According to theoretical sense short lengths of reinforcement decreases the load carrying capacity of fibre and is responsible for higher wear rate and the excessive length of fibre results in easy pull out of the fibers and develop more wear rate [49]. Since surface treatment increases the surface roughness of the reinforcement which results in good bonding strength between the matrix and fibre, and reduces the wear rate [50]. Even sea water can be used for treating the fibers for enhancing the wear resistance [51].

TABLE V

TRIBOLOGICAL PERFORMANCE OF POLYMER COMPOSITES

Polymer	Fiber	Filler/Treatment	Develop method	Coeff. of friction	Wear rate	Mechanism	Reff:
Polyester	Glass		Molding	Decrease	Decrease	Plastic deformation	[52]
	Al	SiC	Powder		Decrease		[53]

			metallurgy				
PEI	Glass	Graphite, MoS_2, PTFE			Decrease	Adhesion	[54]
Epoxy	Carbon		Resin transfer molding	Decrease	Decrease	Worn surfaces	[55]
Phenolic	Graphite		Compression molding		Increase		[56]
Epoxy	Carbon		Hand lay up		Decrease		[57]
Polyester	Glass		Hand lay up	Decrease	Decrease	Back transfer polymer film	[58]
Epoxy	Rubber dust		Molding		Decrease	Abrasive	[59]
Epoxy	Glass	SiO_2	Cylindrical mold	Decrease	Decrease	Adhesion	[60]
	Al	Red mud	Powder metallurgy	Decrease	Decrease	Adhesion	[61]
Epoxy	Glass	SiC	Hand lay up	Decrease	Decrease	Debonding, fiber breakage	[62]
Epoxy	Glass	Graphite and SiC	Hand lay up		Decrease		[63]
Epoxy	Lantana camara		Molding	Decrease	Decrease	Abrasion	[64]
Epoxy	Kenaf		Molding	Increase	Decrease	Adhesion	[65]
Epoxy	Pin wood dust				Decrease		[66]
Polyester	Betelnut fruit fiber		Hand lay up	Increase	Decrease	cracks, debonding, fiberpullout	[67]
Epoxy	Sugar cane		Hand lay up		Decrease	cutting, ploughing	[68]
Polyester	Linen, jute		Molding	Increase	Decrease	Fiberdebonding	[69]
Polyester	Coir	Alkaline	Hand lay up	Increase	Decrease	Adhesion	[70]
Epoxy	Borassus fruit fiber	Alkaline	Cylindrical mold	Decrease	Decrease	Micro cracks	[71]
Polyester	oil palm	Alkaline	Cylindrical mold	Decrease	Decrease	Debonding	[72]
Epoxy	Bamboo		Hand lay up	Decrease	Decrease	Back film transfer	[73]
Epoxy	Rice husk	Benzolylation	Cylindrical mold		Decrease	Abrasive	[74]
Polyester	Bamboo powder		Cylindrical mold		Decrease	Abrasive	[75]
Epoxy	Coir	Benzolylation	Cylindrical mold		Decrease	Abrasive	[76]
Polyurethane	Kenaf	Alkaline	Hand lay up	Decrease	Decrease	Plastic deformation	[77]
Epoxy	cellulose fiber	Nano SiC, Nano clay			Decrease		[78]

Wear can be defined as a progressive loss of materials from the contacting surfaces due to their relative motion [79]. Actually, wear is an erosion or sideway displacement of particles between two surfaces in contact due to their relative movement [80]. Along with the fatigue and the corrosion, wear is being known as, one of the three important factors which limit the life and the performance of an engineering system or an engineering component [81]. Damages due to wear are of two types. (a) Removal of materials from the contacting areas reduces the overall dimension of the component. This leads to the increase in clearance between the moving parts and gradually leads to high vibration and high noise which reduces the efficiency and results in malfunction of the system [82]. If dynamic loading is applied to thus components, the reduced dimension of the component will result in fatigue failure or fracture [83]. (b) Material removed from the worn surface, commonly known as wear debris, are also harmful. These debris act as abrasive particles which results in increased wear rate similar to three body abrasion wear [84]. These debris can create block sin valves, pipe lines, oil filters or gather together in electrical contacting point which may cause short circuits and thus prevent the normal functioning of the system [85]. The cost of wear is high, so great efforts have been made from the early ages of industries, with focuses to reduce or eliminate wear.

Different forms of wear exist in industry. Different methods are used to categorise wear processes. Wear can be generally classified as: (a) Lubricated wear and unlubricated wear (b) Severe wear and Mild wear (c) Sliding wear, rolling contact wear and impact wear [86]. However, all these wear process involve one or, a combination of different wear mechanisms including adhesion, abrasion, fatigue, oxidation or other tribo-chemical actions etc [87]. To solve a wear problem, it is important to understand or study the different underlying wear mechanisms. If the wear cannot be completely avoided at all, by changing its nature of wear from abrasion or adhesion to oxidation i.e. by the surface engineering of the contacting parts, can be considerably reduces the overall wear rate [88]. Adhesive Wear is the removal of material due to adhesion between two surfaces [89]. It is of two types (a) Mild adhesion: - It is the removal of surface films, such as oxides, at a low rate. (b) Severe adhesion: - It is the removal of metal due to breaking, tearing and melting of metallic joints. This leads to galling or scuffing of the surfaces and even takeover. Abrasive Wear is the cutting of grooves on a surface by hard particles, (for example, sand particles between two contact surfaces, or hard asperities on an opposing surface) [90]. Hard coatings can reduce the abrasive wear. Erosion Wear is the cutting of grooves on a surface by hard particles in a fluid which is travelling at high velocity [91]. Polishing Wear is the continuous removal of surface films, laid down through a chemical reaction from an additive in oil may be a fine hard particle in the lubricant [92]. Polishing wear is characterized by very shiny, smooth, mirror like metal surfaces. Contact fatigue is the cracking, grooving, and spalling of a surface in sequence due to repeated stresses in contact [93]. Contact fatigue is most common in rolling element like bearings, gear teeth, cams etc. Corrosive wear is the removal of corrosion products from a surface by motion, such as the rubbing off the rust from iron surface. Electro-Corrosive wear is the removal of metal by dissolution in a corrosive liquid with the help of electric currents. One source of currents is streaming potential from the high velocity fluids. The oil act as the electrolyte. Fretting wear is a localized wear in lubricated surfaces due to the reciprocating sliding at extremely low amplitude because of vibration. Electrical discharge wear is the removal of the molten metal from the surfaces due to electrical sparks between them. High static voltages, sometimes generated by the large rotating machinery and this static voltage are relieved by sparking to regions of low potential.

Dynamic Mechanical Analysis (DMA) is a method which is commonly used to characterize material's properties as a function of temperature, frequency, atmosphere, time, stressor a combination of these parameters [94]. Dynamic Mechanical Analysis, also known as DMA, is a technique in which a small deformation is being applied to the sample in a cyclic manner. DMA allows the material response to stress, frequency, temperature and other parameters to be studied. DMA is also known as DMTA for Dynamic Mechanical Thermal Analysis [95].

Thermo mechanical Analysis (TMA), provides a constant static force to the material and watch the change in material as temperature or time get varies. It provides the dimensional changes. While, DMA applies an oscillatory force in a constant frequency to the sample and gives the changes in damping and stiffness. DMA data is being used to obtain the modulus information while, the TMA gives the coefficient of thermal (CTE). Both detect transitions, but DMA is more sensitive and accurate [96].

When carbon fibre/epoxy composites with different fibre volume fraction was subjected to different experimental parameters such as frequency, temperature, amplitude and oscillation mode. It is found that, opposed to the storage modulus, the loss modulus is sensitive to all parameters [97]. In fixed multiple frequency mode, the loss modulus increases with oscillation amplitude and decreases with number of tests and frequency [98]. The detection of the interfacial properties is more sensitive in flexural deformation mode than in torsional mode. [99]. In DMA, dynamic heating to attain complete curing gives proof of thermal degradation which leads to diminished final glass transition temperature [100]. Activation energy for glass transition changes by a factor of three from cureless resin to fully cured resin [101].

V. MOISTURE ABSORPTION STUDIES

The study of mechanical properties of fibre reinforced polymeric materials under different environmental conditions is much important. Moisture absorption is one of the main problems for fiber reinforced polymer composites. The presence of the moisture will lead to the degradation of the composite product before its life cycle [102]. The tendency to absorb the moisture is much greater for natural fibers compared to synthetic fibers. Hydrophilic natural fibres are incompatible with hydrophobic thermosetting resins, and it is necessary to improve the adhesion between fibre and matrix, the use of chemical treatments. Natural fibers have been limited by their susceptibility to water absorption, due to their chemical composition being rich in cellulose, hydrophilic in nature. Water absorption results in the swelling of the fibre that could reduce the mechanical and dimensional properties of the composites as a result of the appearance of micro cracks at fibre-matrix space [103]. Many researches are being carried out on the treatment of the natural fibers to increase their mechanical as well as physical and chemical properties. Natural fibers are normally treated with NaOH in different concentrations to improve its physical, chemical and mechanical properties by reducing the presence of moisture content [104-106].

VI. RECYCLING THE FIBRE REINFORCED COMPOSITES

One of the major drawbacks related to polymer composites is its recycling. Today environment legislation is becoming, more confining, it is now mandatory to find industrial scale solution to the problem of recycling these polymer product [107]. Thermolysis and solvolysis are the two-common method used for recycling. The recycling technique should be selected on the basis of the material being recycled and the reuse applications. Thermolysis is appeared to be more appropriate for glass fibre and carbon fibre composites. Thermo-chemical processes are now not used for GFRCs because of the low price of GF and the degraded mechanical properties of the GFs are attained in this technique. These processes are mainly used to recover valuable products from the resin to be used in new resins. Mechanical recycling includes the grinding of materials more finely after initial crushing or cutting into smaller pieces [108]; the rest is same to all the recycling techniques. Thermal processes consist of pyrolysis, fluidised-bed pyrolysis and pyrolysis assisted with microwaves [109]-[112]. These techniques provide the recovery of fibres, fillers and inserts. Developments in recycling are happening in right sense, but bringing the recycled product in commercial reality is still a challenging task.

VII. CONCLUSION

In recent decades large amount of research work in being carried out in the field of fibre reinforced polymer composites. The logical basis for a conducting a review on fiber reinforced polymer composite is to study about the various fibres and its inherent properties. A detailed study about the mechanical and tribological properties of polymer composites reinforced with natural and synthetic fibres were presented here. This paper has reviewed the research works that focuses on the improvement in mechanical and tribological properties. The Mechanism behind the wear phenomena were analysed thoroughly. Improvement in properties can be achieved through proper selection of fibre, extraction, treatment of fibers as well as interfacial engineering.

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