Carbohydrate Polymers 86 (2011) 1–18

Contents lists available at ScienceDirect

Carbohydrate Polymers

journal homepage: www.elsevier.com/locate/carbpol

Review

Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review

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ARTICLE INFO

Article history:
Received 1 March 2011
Received in revised form 19 March 2011
Accepted 18 April 2011
Available online 28 April 2011

Keywords:
Hybrid composites
Cellulosic fibres
Synthetic fibres
Mechanical
Physical
Thermal

ABSTRACT

Present review deals with the recent development of cellulosic/cellulosic and cellulosic/synthetic fibres based reinforced hybrid composites. Hybrid composites made up of two different cellulosic fibres are less common compare to cellulosic/synthetic fibre, but these are also potentially useful materials with respect to environmental concerns. Hybrid composites fabrication by cellulosic fibres is economical and provide another dimension to the versatility of cellulosic fibre reinforced composites. As a consequence, a balance in cost and performance could be achieved through proper material design as per directive of Europe states by 2015. Recent studies relevant to hybrid composites have cited in this review. This work intended to present an outline of main results presented on hybrid composites focusing the attention in terms of processing, mechanical, physical, electrical, thermal and dynamic mechanical properties. Hybrid composites are one of the emerging fields in polymer science that triumph attention for application in various sectors ranging from automobile to the building industry.

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0144-8617/$ – see front matter
doi:10.1016/j.carbpol.2011.04.043

1. Introduction and global scenario

Increased pressure from environmental activists, preservation of natural resources, and attended stringency of laws passed by developing countries leads to the invention and development of natural materials with a focus on renewable raw materials (Anandjiwala & Blouw, 2007; Wittig, 1994). Composite manufacturing industries have to look for plant based natural fibre reinforcements, such as flax, hemp, jute, sisal, kenaf, banana as an alternative material which is going to replace solid wood. Lignocellulosic fibres have the advantage that they are renewable resources and have marketing appeal. Cellulosic fibre reinforced polymer composites have been used for many application such as automotive components, aerospace parts, sporting goods and building industry. Cellulosic fibre reinforced polymer composites have found increased application in bridge and building construction "in recent years". This is due to the advantageous properties of these materials, such as low self-weight, high strength, free formability and substantial resistance to corrosion and fatigue.

Since the 1960s, the use of synthetic fibres has increased dramatically, causing the natural fibre industry to lose much of its market share. In December 2006, the United Nations General Assembly declared 2009 the International Year of Natural Fibres (IYNF). A year-long initiative focused on raising global awareness about natural fibres with particular focus on increasing market demand to help ensure the long-term sustainability for farmers who rely heavily on their production (FAO, 2006). The US market for composites increased from 2.7 billion pounds in 2006 to an estimated 2.8 billion pounds in 2007. It should reach over 3.3 billion by 2012, a compound annual growth rate of 3.3% (Business Communication Company, 2007). The automotive market sector is not the only place that has experienced an increase in natural-fibre usage. The insertion of natural fibres in the industrial, building, and commercial market sectors have experienced a growth rate of 13% compounded over the last 10 years to an annual use of approximately 275 million kilograms (Report, 2004). The fibre-reinforced composites market is now a multibillion-dollar business (Material & Thoughts, 2002).

The combination of biofibres like oil palm, kenaf, industrial hemp, flax, jute, henequen, pineapple leaf fibre, sisal, wood and various grasses with polymer matrices from both non-renewable (petroleum based) and renewable resources to produce composite materials. Biocomposites are competitive with synthetic composites such as glass–polypropylene and glass–epoxies, and gaining attention over the last decade. Hybrid composites reinforced with cellulosic fibres, very often combined with synthetic fibres such as glass fibres, can also demonstrate good mechanical performance (Abu Bakar, Hariharan, & Khalil, 2005; Abdul Khalil, Kang, Khairul, Ridzuan, & Adawi, 2009; De Rosa, Santulli, Sarasini, & Valente, 2009b; Kong, Hejda, Young, & Eichhorn, 2009). Polymer composites with hybrid reinforcement solely constituted of natural fibres are less common, but these are also potentially useful materials with respect to environmental concerns (Athijayamani, Thiruchitrambalam, Natarajan, & Pazhanivel, 2009; Idicula, Joseph, & Thomas, 2010; Khan, Ganster, & Fink, 2009; Saw & Datta, 2009). Cellulosic fibre reinforced composites are initially aimed at the replacement of glass fibre reinforced composites (Joshi, Drzal, Mohanty, & Arora, 2004). Depending on the exact nature of fibre needed, lignocellulosic fibres are in most cases cheaper than glass fibres. Lignocellulosic fibres are also expected to cause less health problems for the people producing the composites compared to glass fibre based composites. Lignocellulosic fibres do not cause skin irritations and they are not suspected of causing lung cancer. This is primarily an issue since the discussion on whether or not very small glass fibres can cause lung cancer, has still not ended. Although flax is known to give off a large amount of dust, this problem exists mainly in the early stages of the flax fibre isolation process and is fairly well under control in the modern flax processing industry (Ghosh & Ganguly, 1993).

2. Lignocellulosic fibres/natural fibres

2.1. Source, classification and applications of lignocellulosic fibres

Lignocellulosic fibres have been used as reinforcing materials for over 3000 years, in combination with polymeric materials. The study of fibre reinforced plastics began in 1908 with cellulose material in phenolics, later extending to urea and melamine and reaching commodity status with glass fibre reinforced plastics. Cotton–polymer composites are reported to be the first fibre reinforced plastics used by the military for radar aircraft (Lubin, 1982; Piggot, 1980). One of the earliest examples (1950) was the East German Trabant car, the frame was constructed from polyester reinforced with cotton fibres. Fibres can be sourced from plants, animals and minerals. A diagram with a classification of the various fibres showed (Fig. 1). There is a wide range of different fibres can be applied as reinforcement or fillers. Lignocellulosic fibres have three main categories depending on the part of the plant from which they extracted.

1. Bast or stem fibres (jute, flax, hemp, ramie, kenaf, etc.);
2. Leaf fibres (sisal, banana, manila hemp, pine apple, etc.);
3. Seed fibres (cotton, coir, oil palm, etc.).

Currently several types of cellulosic fibres reinforced in plastics including flax, hemp, jute, straw, wood fibre, rice husks, wheat, barley, oats, rye, cane (sugar and bamboo), grass, reeds, kenaf, ramie, oil palm empty fruit bunch (EFB) fibres, sisal, hyacinth, pennywort, kapok, paper-mulberry, raphia, banana fibre, pineapple leaf fibre, and papyrus. Lignocellulosic fibres have the advantage that they are renewable resources, low cost, light and have marketing appeal. Many cellulosic fibres such as pineapple leaf fibre are natural waste products, and hence available at minimal cost. Since lignocellulosic fibres are strong, light in weight, abundant, non-abrasive, non-hazardous and inexpensive, they can serve as

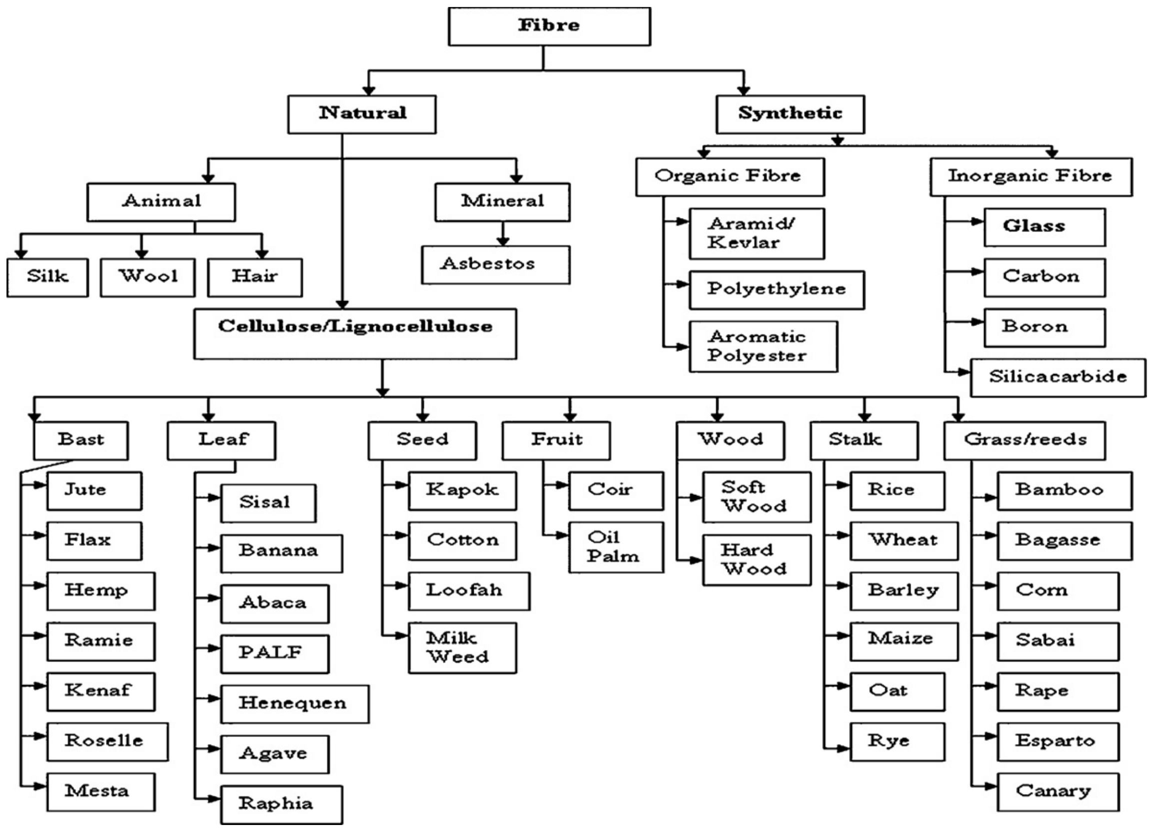

Fig. 1. Classification of natural and synthetic fibres.
Sources: Alexander Bismarck and Thomas (2005), Lilholt and Lawther (2002), and Rowell (2008).

an excellent reinforcing agent for plastics. Several cellulosic products and wastes such as shell flour, wood flour and pulp have been used as fillers in polymers. Lignocellulosic fibres posses moderately high specific strength and stiffness and can be used as reinforcing materials in polymeric matrices to make useful structural composites material. Advantages and disadvantages of lignocellulosic fibres are shown in Table 1 (Sreekumar, 2008). In fact, synthetic fibres such as nylon, rayon, aramid, glass, and carbon are extensively used for the reinforcement of plastics (Erich, Antonios, & Michel, 1984; Lawrence, Russel, & Anron, 1995). Nevertheless, these materials are expensive and are non-renewable resources. Lignocellulosic fibres are renewable materials and have the ability to be recycled. The lignocellulosic fibres leave little residue if they are burned for disposal, returning less carbon dioxide (CO_2) to the atmosphere than is removed during the plant growths. The leading driver for substituting lignocellulosic fibres for glass is that they can be grown with lower cost than glass. The price of glass fibre is around 1200–1800 US$/tonnes, on the other hand, plant fibre costs 200–1000 US$/tonnes (Satyanarayana, Arizaga, & Wypych, 2009). Density of glass fibres are around 2500 kg/m^{3}and plant fibres has a density of 1200–1500 kg/m^3. Because of the uncertainties prevailing in the supply and price of petroleum based products, there is every need to use the naturally occurring alternatives. In many parts of the world, besides the agricultural purposes, different parts of plants and fruits of many crops have been found to be viable sources of raw material for industrial purpose. In many developing countries, proceeds from the sale and export of lignocellulosic fibres contribute significantly to the income and the food security of poor farmers and those working in fibre processing and marketing. For some developing countries, lignocellulosic fibres are of vital economic importance: for example, cotton in some West African countries, jute in Bangladesh and sisal in Tanzania. In other cases, fibres are of less significance at the national level but are of utmost regional importance, as in the case of jute in West Bengal (India) and sisal in "north-east Brazil". In recent years, polymer composites containing cellulosic fibres have received considerable attention both in the literature and industry. Annually, approximately 30 million tonnes of lignocellulosic fibres are produced and used in principal component of clothing, upholstery and other textiles. Many of them also have industrial applications-in packaging, papermaking and composite materials with many uses, including as parts in automobiles, building materials, and sport equipments.

Table 1
Advantage and disadvantages of natural fibres.

Advantages	Disadvantages
Low specific weight results in a higher specific strength and stiffness than glass	Lower strength especially impact strength
Renewable resources, production require little energy and low CO_2 emission	Variable quality, influence by weather
Production with low investment at low cost	Poor moisture resistant which causes swelling of the fibres
Friendly processing, no wear of tools and no skin irritation	Restricted maximum processing temperature
High electrical resistant	Lower durability
Good thermal and acoustic insulating properties	Poor fire resistant
Biodegradable	Poor fibre/matrix adhesion
Thermal recycling is possible	Price fluctuation by harvest results or agricultural politics

Source: Sreekumar (2008) (with permission).

2.2. Chemical composition of lignocellulosic fibres

Chemical composition of different lignocellulosic fibres is displayed in Table 2. Properties of lignocellulosic fibres depend mainly

Table 2
Chemical composition of common lignocellulosic fibres.

Fibre	Cellulose	Hemi-cellulose	Lignin	Extract.	Ash Content	Water soluble	Researchers
Cotton	82.7	5.7	–	6.3	–	1.0	Gassan and Bledzki (1996)
Jute	64.4	12	11.8	0.7	–	1.1	Gassan and Bledzki (1996)
Flax	64.1	16.7	2.0	1.5–3.3	–	3.9	Gassan and Bledzki (1996)
Ramie	68.6	13.1	0.6	1.9–2.2	–	5.5	Gassan and Bledzki (1996)
Sisal	65.8	12.0	9.9	0.8–0.11	–	1.2	Gassan and Bledzki (1996)
Oil palm EFB	65.0	–	19.0	–	2.0	–	Abdul Khalil and Rozman (2004)
Oil palm Frond	56.03	27.51	20.48	4.40	2.4	–	Abdul Khalil and Rozman (2004)
Abaca	56–63	20–25	7–9	3	–	1.40	John and Anandjiwala (2008)
Hemp	74.4	17.9	3.7	0.9–1.7	–	–	Bledzki and Gassan (1996)
Kenaf	53.4	33.9	21.2	–	4.0	–	Abdul Khalil, Yusra, Bhat, and Jawaid (2010)
Coir	32–43	0.15–0.25	40–45	–	–	–	Pillai and Vasudev (2001)
Banana	60–65	19	5–10	4.6	–	–	Reddy and Yang (2005) and Cordeiro, Belgacem, Torres, and Moura (2004)
PALF	81.5	–	12.7	–	–	–	Devi, Bhagawan, and Thomas (1997)
Sun hemp	41–48	8.3–13	22.7	–	–	–	John and Anandjiwala (2008)
Bamboo	73.83	12.49	10.15	3.16	–	–	Wang et al. (2010)
Hardwood	31–64	25–40	14–34	0.1–7.7	<1	–	Tsoumis (1991)
Softwood	30–60	20–30	21–37	0.2–8.5	<1	–	Tsoumis (1991)

on the nature of the plant, locality in which it grows, age of the plant, and the extraction method used. For example, coir is a hard and tough multicellular fibre with a central portion called a "lacuna". Sisal is an important leaf fibre and is exceptionally strong. Pineapple leaf fibre is soft and has "high cellulose content". Oil palm fibres have hard and tough multicellular fibre with a central portion also called a "lacuna". The elementary unit of a cellulose macromolecule is anhydro-D-glucose, which contains three alcohol hydroxyls (–OH) (Bledzki, Reihmane, & Gassan, 1996). These hydroxyls form hydrogen bonds inside the macromolecules (intermolecular) as well as with hydroxyl groups from the air. Therefore, all plant fibres are of a hydrophilic nature, their moisture content reaches 8–13%.

In addition to cellulose and hemi-cellulose, lignocellulosic fibres contain different natural substances. The most prominent of them is lignin. The distinct cells of hard plant fibres are bonded together by lignin, acting like a cementing material. The lignin content of plant fibres influences its structure, properties and morphology. An important characteristic of cellulosic fibre is their degree of polymerization (DP). The cellulose molecules of each fibre differ in their DP and consequently, the fibre is a complex mixture of polymer homologue ($C_6H_{10}O$). Bast fibres commonly show the highest DP among all the plant fibres (~10,000). Cotton, flax and ramie fibres have 7000, 8000, and 6500 DP, respectively (Bledzki & Gassan, 1999). Lignocellulosic fibres can be considered like naturally occurring composites consisting mainly of cellulose fibrils embedded in lignin matrix. These cellulose fibrils are aligned along the length of the fibre, irrespective of its origin, i.e. whether it extracted from stem, leaf or fruit.

2.3. Physical properties of lignocellulosic fibres

The characteristics of individual fibre are according to shapes, sizes, orientations, thickness of the cell walls and other (Satyanarayana, Pai, Sukumaran, & Pillai, 1990). There are some important physical elements must be known about every plantation fibre before it is used to reach at the maximum potential (Han & Rowell, 1997). Knowledge about the length and width of the fibres is important to compare the different plantation fibres. High aspect scale (length/width) is very important in composite based on plantation fibres because it gives us signs about its strength element (Han & Rowell, 1997).

Fibre's strength is an important factor to choose fibre that is specific for certain usage. Table 3 gives data on length and diameter of various cellulosic fibres. The structure, microfibril angle, cell dimensions, defects, and the chemical composition of fibres are the most important variables that determine the overall properties of the fibres (John & Thomas, 2008). The dimensions of individual cells of Lignocellulosic fibres are depending on the species, maturity and location of the fibres in the plant and also on the fibre extraction conditions. Transversally, unit cells in all of the lignocellulosic fibres have a central hollow cavity called the lumen. The shape (round, polygonal or elliptical) and size of the lumen depends on the source of the fibre and thickness of the cell wall (Reddy & Yang, 2005). The presence of the hollow lumen decreases the bulk density of the fibre and acts as an acoustic and thermal insulator. These properties make lignocellulosic fibres preferable for lightweight composites used as noise and thermal insulators in automobiles (Reddy & Yang, 2005).

2.4. Mechanical properties of lignocellulosic and glass fibres

As long as specific modulus of lignocellulosic fibres (modulus per unit specific gravity) is considered, the lignocellulosic fibres show values that are comparable to or even better than glass fibres. Lignocellulosic fibres exhibit significantly better elongation at break which will translate in better composite damage tolerance. Low cost and better damage tolerances make cellulosic fibre attractive for housing construction with "low load" requirements. Wood is the most abundantly used natural cellulose fibre because of its extensive use in pulp and paper industries. However, for better strength and stiffness cellulose fibres like hemp, flax, jute, kenaf and sisal are becoming increasingly important in composites production. Table 4 shows the mechanical properties of commercially important lignocellulosic and glass fibres that could be utilized for composites.

3. Hybrid composites

The word "hybrid" is of Greek–Latin origin and can be found in numerous scientific fields. In the case of polymer composites, hybrid composites are these systems in which one kind of reinforcing material is incorporated in a mixture of different matrices (blends) (Thwe & Liao, 2003a), or two or more reinforcing and filling materials are present in a single matrix (Fu, Xu, & Mai, 2002; Karger-Kocsis, 2000) or both approaches are combined. The incorporation of two or more lignocellulosic fibres into a single matrix has led to development of hybrid composites. The behaviour of hybrid composites is a weighed sum of the individual components in which there is more favourable balance between the inherent advantages

Table 3
Physical properties of lignocellulosic fibres.

Fibre	Length of fibre (mm)	Diameter of fibre (μm)	References
Oil palm EFB	0.89–0.99	19.1–25.0	Law and Jiang (2001) and Mohamad, Zin Zawawi, and Abdul Halim (1985)
Oil palm Frond	1.52–1.59	19.7	Law and Jiang (2001) and Mohamad et al. (1985)
Oil palm trunk	0.96–1.22	29.6–35.3	Khoo and Lee (1985); Mohamad et al. (1985)
Coconut husks	0.3–1.0	100–450	Reddy and Yang (2005)
Banana	0.17	13.16	Ibrahim, Dufresne, El-Zawawy, and Agblevor (2010)
Pineapple leaves	3–9	20–80	Reddy and Yang (2005)
Jute	0.8–6	5–25	Rowell (2008)
Sisal	0.8–8	7–47	Rowell (2008)
Flax	10–65	5–38	Rowell (2008)
Hemp	5–55	10–51	Rowell (2008)
Cotton	15–56	12–35	Rowell (2008)
Henequen	–	8–33	Rowell (2008)
Ramie	40–250	18–80	Rowell (2008)
Kenaf (bast)	1.4–11	12–36	Rowell (2008)
Kenaf (core)	0.4–1.1	18–37	Rowell (2008)
Bagasse	0.8–2.8	10–34	Rowell (2008)
Bamboo	2.7	14	Olesen and Plackett (1997)
Softwood	3.3	33	Olesen and Plackett (1997)
Hardwood	1.0	20	Olesen and Plackett (1997)
E-glass	7	13	Esfandiari (2007)

and disadvantages. While using a hybrid composite that contain two or more types of fibre, the advantages of one type of fibre could complement with what are lacking in the other. As a consequence, a balance in cost and performance could be achieved through proper material design (John & Thomas, 2008). The strength of the hybrid composites is dependent on the properties of fibre, the aspect ratio of fibre content, length of individual fibre, orientation of fibre, extent of intermingling of fibres, fibre to matrix interface bonding and arrangement of both the fibres and also on failure strain of individual fibres. Maximum hybrid results are obtained when the fibres are highly strain compatible (Sreekala, George, Kumaran, & Thomas, 2002).

3.1. Potential and challenges in development of cellulosic fibre hybrid composites

3.1.1. Hybridization of cellulosic fibres

The properties of a hybrid composite depend on the fibre content, fibres length, orientation of fibres, extent of intermingling of fibres, fibre to matrix interface, layering pattern of both fibres and also dependent on the failure strain of individual fibres. Maximum hybrid results are obtained when the fibres are highly strain compatible (Sreekala et al., 2002).

The properties of the hybrid system consisting of two components can be predicted by the rule of mixtures.

$$P_H = P_1 V_1 + P_2 V_2$$ (Thwe & Liao, 2003a)

where P_H is the property to be investigated, P_1 the corresponding property of the first system and P_2 the corresponding property of the second system. V_1 and V_2 are the relative hybrid volume fractions of the first and second system and $V_1 + V_2 = 1$ (Sreekala et al., 2002).

A positive or negative hybrid effect is defined as a positive or negative deviation of a certain mechanical property from the rule of hybrid mixture. The term hybrid effect has been used to describe the phenomenon of an apparent synergistic improvement in the properties of a composite containing two or more types of fibre (Jones, 1994). The selection of the components that make up the hybrid composite is determined by the purpose of hybridization, requirements imposed on the material or the construction being designed. The problem of selecting the type of compatible fibres and the level of their properties is of prime importance when designing and producing hybrid composites (John & Thomas, 2008). Various researchers have tried blending of two fibres in order to achieve the best utilization of the positive attributes of one fibre and to

Table 4
Mechanical properties of commercially important lignocellulosic and glass fibres.

Fibres	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
OPEFB	0.7–1.55	248	3.2	2.5
Flax	1.4	800–1500	60–80	1.2–1.6
Hemp	1.48	550–900	70	1.6
Jute	1.46	400–800	10–30	1.8
Ramie	1.5	500	44	2
Coir	1.25	220	6	15–25
Sisal	1.33	600–700	38	2–3
Abaca	1.5	980	–	–
Cotton	1.51	400	12	3–10
Kenaf (bast)	1.2	295		2.7–6.9
Kenaf (core)	0.21	–	–	–
Bagasse	1.2	20–290	19.7–27.1	1.1
Henequen	1.4	430–580	–	3–4.7
Pineapple	1.5	170–1627	82	1–3
Banana	1.35	355	33.8	5.3
E-glass	2.5	2000–3500	70	2.5
S-glass	2.5	4570	86	2.8

Sources: Abdul Khalil et al. (2010), Bhagawan, Tripathy, and De (1987), Franck (2005), Idicula et al. (2010), Khalil, Alwani, Ridzuan, Kamarudin, and Khairul (2008), Mariatti, Jannah, Bakar, and Khalil, 2008; Rowell (2008), Saechtling (1987), and Satyanarayana and Wypych (2007).

reduce its negative attributes as far as practicable. Some other reasons for blending of one fibre with other natural fibres are to impart fancy effect, reduce cost of the end product, and find out suitable admixture of natural origin to mitigate the gap between demand and supply (Basu & Roy, 2007). Sisal and oil palm fibres appear to be promising materials because of the high tensile strength of sisal fibre and the toughness of oil palm fibre. Therefore, any composite comprised of these two fibres will exhibit the desirable properties of the individual constituents (Jacob, Thomas, & Varughese, 2004a). Mixing natural fibres like hemp and kenaf with thermoplastics put FlexForm Technologies (FlexForm, 2011) on the map and in the door panels of Chrysler's Sebring convertible. FlexForm is also looking to produce vehicle load floors, headliners, seatbacks, instrument panel top covers, knee bolsters, and trunk liners.

3.1.2. Moisture content of cellulosic fibres

In cellulosic fibre based hybrid composites, hybrid arrangement will inhibit the absorption of moisture into the composite and pack arrangement of fibre will filling up the voids which form during the formation of composite. This is because the hydrophilic nature of cellulosic materials, enabling the composites to take up a high amount of moisture from the surrounding environment. The hydrophilic properties of cellulosic materials and the capillary action will cause the intake of water when the samples were soaked into the water and thus increase the dimension of composite. This will cause the swelling of fibre and thus increase the thickness swelling of composites. The moisture content of the fibres varies between 5 and 15%. Moisture content cause dimensional variation in composites and ultimately affects the mechanical properties of the composites. During manufacturing of thermoset based composites, moisture leads to void contents and affects fibre–matrix bonding that lead to decrease in mechanical properties.

3.1.3. Dispersion of the cellulosic fibres in the matrix

Lignocellulosic fibres are hydrophilic in nature and incompatible to hydrophobic polymeric matrices and this causes poor adhesion between fibre and matrices (Rials, Wolcott, & Nassar, 2001), it makes the dispersion of fibres in the polymeric matrices difficult (Gatenholm, Bertilsson, & Mathiasson, 1993; Ishak, Aminullah, Ismail, & Rozman, 1998). Researchers studied composites of cellulosic fibres with polypropylene, polyethylene, and polystyrene, found that the bad dispersion of fibres results in their agglomeration into knotty masses, leading to composites with poor final properties (Gatenholm et al., 1993). Several methods have been reported to improve filler dispersion and interfacial interaction between filler and matrix (Dubois, Alexandre, Hindryckx, & Jerome, 1998; Jones, 1975; Nielsen & Landel, 1994; Zhang, Rodrigue, & AiÌˆt-Kadi, 2004a; Zhang, Rodrigue, & AiÌˆt-Kadi, 2004b).

3.1.4. Fibre–matrix interface

Natural fibres are hydrophilic in nature and poor resistance to moisture and incompatible to hydrophobic polymer matrix. This incompatibility of natural fibres results in poor fibre/matrix interface which in turn leads to reduce mechanical properties of the composites (John & Anandjiwala, 2008). Chemical modification of fibres helps to make it less hydrophilic. They studied surface modification of cellulosic fibres in depth and concluded that most promising approach of chemical modification seemed to be the one that gave rise to continuous covalent bonds between fibre surface and matrix (Belgacem & Gandini, 2005). Surface modification of natural fibres include physical treatments, such as solvent extraction and physico-chemical treatments, like the use of corona and plasma discharges (Morales, Olayo, Cruz, Herrera-Franco, & Olayo, 2006) or laser, γ-ray, and UV bombardment; and chemical modifications, both by direct condensation of the coupling agents onto the cellulose surface and by its grafting by free-radical or ionic polymerizations.It is well known that the fibre–matrix interface is crucial to the stress transfer between the two components (Jones, 1975; Nielsen & Landel, 1994). Reinforcement of hydrophilic natural fibres in to polymeric matrix leads to heterogeneous system whose properties are inferior due to poor fibre–matrix adhesion. Chemical treatment or surface modification of fibres improves adhesion between fibre and matrix which is the critical issue to develop advance composites. The treatment of the fibres may be alkali, acetylation, bleaching, grafting of monomer, and so on. However, plasma surface treatment and plasma polymerization as an alternative coating technique have been mainly used for surface modification of fibres (Cech, Prikryl, Balkova, Vanek, & Grycova, 2003; Li, Ye, & Mai, 1997). Beside surface treatment of fibres, compatibilizer or coupling agents such as silanes, maleated polypropylene (MAPP), and titanates are commonly used to improve fibre–matrix interface (Kalia, Kaith, & Kaur, 2009; Xie, Hill, Xiao, Militz, & Mai, 2010).

3.1.5. Thermal stability

Cellulosic fibres have low thermal stability that results in the exclusion of some manufacturing processes, and also limits the use of the composites to low temperature applications. The low thermal stability increases the possibility of cellulosic degradation and the possibility of emissions of volatile materials that could adversely affect the composite properties. Processing temperatures are thus limited to about 200 °C, although it is possible to use higher temperature for short periods of time.

3.1.6. Biodegradability

Cellulosic fibres degrade easily when exposed to nature. Some methods for degradation include biological, chemical, mechanical, thermal, photochemical and aqueous. The biodegradability of cellulosic fibre is often put forward as a positive advantage justifying the use of these fibres. However, for many outdoor applications it is necessary for the composites to be serviceable for several years. In order to increase their service life, it is necessary to control this natural degradation. One way of preventing or slowing down the natural degradation process is by modifying the cell wall chemistry. Undesirable cellulosic fibre properties such as dimensional instabilities, flammability, biodegradability, and chemical degradation can be eliminated or slowed down in this manner (Rowell, Young, & Rowell, 1997). Chemical treatments can reduce the water uptake in the fibres, and can therefore reduce the amount of fibre swelling and biological degradation by blocking the available –OH group on the fibre surface (Joseph, Joseph, & Thomas, 1999). It is also reported that encasing natural fibres in thermoplastic reduced water uptake.

4. Physical and mechanical properties of hybrid composites

In hybrid composite, the physical and mechanical properties are governed by the fibre content, fibre length, fibre orientation, and arrangement of individual fibres, extend of intermingling of the fibres and the interfacial adhesion between the fibre and matrix (Munikenche Gowda, Naidu, & Chhaya, 1999; Sreekala et al., 2002). Most of the studies on natural fibre hybrid composite involve study of mechanical properties as a function of fibre length, fibre loading, extent of intermingling of fibres, fibre to matrix bonding and arrangement of both the fibres, effect of various chemical treatments of fibres, and use of coupling agents.

4.1. Thermoset hybrid composites

Hybrid composite developed by various researchers, combining fibres with epoxy, polyester, phenolic, poly vinyl ester, poly urethane resins. Reported work on cellulosic/cellulosic and cellulosic/synthetic fibres thermoset hybrid composites are shown in

Table 5
Reported work on natural fibre hybrid thermoset composites.

Hybrid fibre	Matrix polymer	References
Oil palm EFB/jute	Epoxy resin	Jawaid et al., 2010, Jawaid, Abdul Khalil, et al. (2011) and Jawaid, Khalil, et al. (2011)
Oil palm EFB/glass	Epoxy resin	Abu Bakar et al. (2005), Hariharan et al. (2004)
	Polyester	Abdul Khalil et al. (2007), Karina et al. (2008), and Wong et al. (2010)
	Phenol formaldehyde	Sreekala et al. (2002, 2005)
	Vinyl ester	Abdul Khalil et al. (2009)
Jute/glass	Polyester (isothalic)	Ahmed and Vijayarangan (2008), Ahmed, Vijayarangan, and Kumar, (2007), Ahmed, Vijayarangan, and Naidu (2007), Ahmed et al. (2006), and Aquino et al. (2007)
	Unsaturated polyester	Abdullah Al et al. (2006) and De Carvalho et al. (2010)
	Polyester	Akil et al. (2010) and De Rosa et al. (2009a, 2009b)
	Epoxy phenolic resin	Patel et al. (2008)
	Epoxy resin	Koradiya et al. (2010) and Srivastav et al. (2007)
Jute/cotton	Novolac phenolic	De Medeiros et al. (2005)
	Polyester	Alsina et al. (2007) and De Carvalho et al. (2007, 2009)
Jute/bagasse	Epoxy	Saw and Datta (2009)
Cotton/ramie	Polyester	Paiva Júnior et al. (2004)
Kapok/glass	Unsaturated polyester	Venkata Reddy et al. (2007, 2008a, 2008b) and Venkata Reddy, Shobha Rani, et al. (2009)
Sisal/kapok	Unsaturated polyester	Venkata Reddy et al. (2007, 2008a), and Venkata Reddy, Venkata Naidu, et al. (2009)
Sisal/glass	Unsaturated polyester	John and Naidu (2004a, 2004b, 2007) and Ornaghi et al. (2010)
	Polyester	Amico et al. (2010)
	Epoxy resin	Ashok Kumar et al. (2010), Patel and Parsania (2010), and Priya and Rai (2006)
	Phenolic	Mu et al. (2009)
Sisal/cotton	Polyester	Alsina, De Carvalho, Ramos Filho, and D'Almeida (2005), Alsina et al. (2007) and De Carvalho et al. (2009)
Sisal/silk	Unsaturated polyester	Noorunnisa Khanam et al. (2007) and Raghu et al. (2010)
Sisal/roselle	Unsaturated polyester	Athijayamani et al. (2009)
	Polyester	Athijayamani et al. (2010)
Banana/kenaf	Unsaturated polyester	Thiruchitrambalam et al. (2009)
Kenaf/glass	Epoxy resin	Davoodi et al. (2010)
Sisal/banana	Polyester	Idicula et al. (2005a, 2005b, 2009, 2010) and Idicula, Neelakantan, et al. (2005)
Banana/glass	Phenol formaldehyde	Joseph et al. (2006, 2008) and Joseph and Thomas (2008)
	Unsaturated polyester	Pothan et al. (2007, 2010)
Palmyra/glass	Rooflite resin	Velmurugan and Manikandan (2005, 2007)
Bamboo/glass	Unsaturated polyester	Mandal et al. (2010) and Dieu et al. (2004)
	Polyester	Kushwaha and Kumar (2010) and Venkata Subba Reddy et al. (2010)
	Epoxy resin	Kushwaha and Kumar (2010) and Raghavendra Rao et al. (2010)
	Vinyl ester	Mandal et al. (2010)
Biofibre/glass	Polyester	Mishra et al. (2003)
Natural fibre/glass	Epoxy vinyl ester	Cicala et al. (2009)
Coir/glass	Polyester	Wong et al. (2010)
	Phenolic resin	Kumar et al. (2009)
Coir/silk	Unsaturated polyester	Noorunnisa Khanam et al. (2010)
PALF/glass	Polyester	Uma Devi et al. (2010)
Cellulose/glass	Epoxy resin	Kong et al. (2009)
Ridge gourd/glass	Phenolic resin	Varada Rajulu and Devi (2007a, 2007b, 2008)
Jute/biomass	Bisphenol-C-formaldehyde	Mehta and Parsania (2006)

Table 5. Mechanical properties of thermoset biocomposites and effect of glass hybridization on mechanical properties of thermoset biocomposites discuss in details (Ray & Rout, 2005).

4.1.1. *Epoxy based-hybrid composites*

Jawaid, Abdul Khalil, and Abu Bakar (2010), Jawaid, Abdul Khalil, Noorunnisa Khanam, and Abu Bakar (2011), and Jawaid, Khalil, Bakar, and Khanam (2011) reported that physical properties such as water absorption, dimensional stability and density of oil palm EFB composite improved with hybridization of oil palm EFB composites with jute fibres and also studied chemical resistance, void content and mechanical properties of oil palm EFB/jute hybrid composites. The effect of fibre bundle loading and modification of bagasse fibre surface in jute/bagasse hybrid fibre reinforced epoxy composite have been studied. It concluded that fibre surface modification improved fibre/matrix interaction and significantly increased mechanical properties of hybrid composites (Saw & Datta, 2009). It also gives interesting finding of thermomechanical properties and evaluation of fibre/matrix interactions. Hariharan, Abu Bakar, and Abdul Khalil (2004) and Abu Bakar et al. (2005) studied the tensile and impact behaviour of the oil palm EFB-glass fibres reinforced epoxy resin. The hybridization of the oil palm fibres with glass fibres increased the tensile strength, the Young's modulus, and also the elongation at break of the hybrid composites. The impact strength of the hybrid composite increased with the addition of glass fibres. A negative hybrid effect was observed for the tensile strength and Young modulus while a positive hybrid effect was observed for the elongation at break of the hybrid composites.

Mechanical, and water absorption properties of jute/glass fibre reinforced epoxy composites were studied (Koradiya, Patel, & Parsania, 2010). Results indicate that hybrid composites have intermediate mechanical properties than those of jute and glass composites. In this study, they also try to find effect of water absorption in different chemical environments and boiling water. It observed that hybrid composites show improvement in water absorption behaviour compared to jute composite and glass composite. Loading rate behaviour of jute/glass hybrid reinforced epoxy composites examined and reported in this study (Srivastav, Behera, & Ray, 2007). It shows that loading rate insensitivity of hybrid composites in sense of stress at yield, displacement at yield, and interlaminar shear strength (Gatenholm et al., 1993) values at higher loading rate were obtained. Researchers studied the mechanical reinforcement obtained by the introduction of glass fibres in cellulosic fibres (silk fabric)-reinforced epoxy composites (Priya & Rai, 2006). It observed that a relatively small amount of glass fabric to the silk fabric reinforced epoxy matrix enhanced the mechanical properties of the resulting hybrid composites. Hybridization of silk fibres with glass fibre also increased weight fraction of reinforcement and water uptake of hybrid composites was found to be less than that of unhybridized composites. Hardness, impact strength, friction coefficient, and chemical resistance of sisal/glass hybrid composites with and without alkali treatments were studied (Ashok Kumar, Ramachandra Reddy, Siva Bharathi, Venkata Naidu, & Naga Prasad Naidu, 2010). Hybrid composites show optimally improved mechanical properties at 2 cm fibre length compared to 1 and 3 cm fibre lengths. Chemical resistance was also significantly improved for all chemical except sodium carbonates and toluene.

Interfacial stress transfer in a model hybrid composite has been investigated. A Sm3+ doped glass fibre and a high-modulus regenerated cellulose fibre were embedded in close proximity to each other in an epoxy resin matrix dumbbell-shaped model composite (Kong et al., 2009). This study offers a new approach for following the micromechanics of the interfaces within hybrid composite materials, in particular where cellulosic fibres are used to replace glass fibres. Researchers investigate effect of alkali treatment and acrylation of jute fibres on tensile, flexural, electric strength, and volume resistivity of jute/glass bisphenol-C based mixed epoxy phenolic resin composites (Patel, Vasoya, Bhuva, & Parsania, 2008). Similar study on mechanical properties of sisal/glass (treated and untreated) hybrid composites reinforced in blended epoxy and formaldehyde of bisphenol-C were done (Patel & Parsania, 2010). The flexural, compressive properties of bamboo/glass fibre-reinforced epoxy hybrid composites were studied (Raghavendra Rao, Varada Rajulu, Ramachandra Reddy, & Hemachandra Reddy, 2010). Results indicate that alkali treated bamboo fibres hybrid composites shows better properties compared to untreated bamboo fibres composites. Aim of this study to investigate hybridization of glass fibres with natural fibres for application in the piping industry (Cicala et al., 2009). The cellulosic fibres studied were hemp, flax and kenaf. Mechanical properties such as tensile and flexural test of cellulosic/glass fibres reinforced epoxy hybrid composites in the forms of lamina and laminates were determined. Cellulosic/glass fibres based hybrid composite prototype fitting was produced and tested with an experiment simulating the real work conditions. The test confirmed that the proposed fitting can withstand the real work condition. In an interesting work researchers developed passenger car bumper beam from kenaf/glass hybrid composites (Davoodi et al., 2010). The results indicate that developed hybrid composites beam possess similar mechanical properties like typical bumper beam material except impact properties. It concluded that kenaf/glass hybrid may be utilized for making structural components of car.

4.1.2. Phenolic resin based-hybrid composites

Mechanical properties (tensile, flexural, and impact) of novolac type phenolic composites reinforced with jute/cotton hybrid woven fabrics were investigated as a function of fibre orientation and roving/fabric characteristics (De Medeiros, Agnelli, Joseph, De Carvalho, & Mattoso, 2005). Results showed that the composite properties were strongly influenced by test direction and roving/fabric characteristics. Best overall mechanical properties were obtained for the composites tested along the jute roving direction. The hybrid effect of glass fibre and oil palm EFB fibre on the tensile, flexural and impact response of the phenol formaldehyde composite was investigated (Sreekala et al., 2002). The over all performance of the composite was improved by the glass fibre addition. Density and impact strength of the hybrid composite decreases as volume fraction of oil palm EFB fibre increases while hardness of the hybrid composite also showed a slight decrease on an increased volume fraction of oil palm EFB fibre. The maximum impact strength is observed for hybrid composites having a 0.74 volume fraction of the oil palm EFB fibre. Glass/phenolic hybrid composites show better values compared to oil palm composites.

This study explores the merits of combining high-modulus glass fibres with banana fibre in phenolic resoles to develop high-performance, cost-effective, lightweight hybrid composites (Joseph, Sreekala, Koshy, & Thomas, 2008). The tensile strength is 62.9% higher for the intimately mixed composite than for a bilayer composite of both fibres. The water uptake of these composites decreases with the incorporation of glass fibre to banana fibre, and the composites with glass fibre at the periphery and banana fibre at the core have maximum resistance to water absorption They also studied environmental durability properties of banana/glass hybrid composites (Joseph, Oommen, & Thomas, 2006; Joseph & Thomas, 2008). Mechanical properties of Coir based hybrid composites were investigated and result show that tensile properties increase with increasing fibre content (Kumar, Reddy, Naidu, Rani, & Subha, 2009). The effect of alkali treatment of fibres on the mechanical properties was also studied. Significant improvement in coir based composites by alkali-treatment was observed.

Varada Rajulu and Devi (2007a, 2007b, 2008) investigated tensile, compressive and flexural properties of glass/ridge gourd/phenolic hybrid composites. It is observed that by hybridization tensile, compressive and flexural properties of the hybrid composites (with both untreated and alkali treated ridge gourd fabric) in the absence and presence of the two coupling agents is increased several times over that of ridge gourd/PF composites. It also observed that the coupling agent, 3-aminopropyltriethoxysilane improved the mechanical properties more when compared to triethoxymethylsilane. In an interesting study, sisal/glass hybrid phenol formaldehyde (PF) composites of alkali treated sisal fibres were prepared (Mu, Wei, & Feng, 2009). Hybrid composites reinforced in PF resulted in composites having encouraging mechanical and water absorption properties.

4.1.3. Polyester based hybrid composites

Recently, impact behaviour of glass/oil palm hybrid composites have been studied and found that impact strength is improved with increasing number of glass fibre layer and increment in fibre length (Wong, Nirmal, & Lim, 2010). The hybrid effect of glass/oil palm EFB fibre on the tensile, flexural and impact properties of the polyester composites was investigated with increasing loading of both oil palm EFB and glass fibres (Abdul Khalil, Hanida, Kang, & Nik Fuaad, 2007). The mechanical properties of EFB/glass hybrid polyester composite are found to be much higher than those of EFB/polyester composites. All these improvements in the hybrid composite properties are mainly due to the high strength and modulus value of glass fibre compared to EFB fibres. Another researcher also studied physical and mechanical properties of oil palm/glass fibre reinforced polyester composites related to EFB fibre specimen length and fibre loading (Karina, Onggo, Dawam Abdullah, & Syampurwadi, 2008). EFB fibre specimen length showed no significance effect on the flexural strength and density of composites but shorter EFB fibre show higher water absorption and dimensional change compared to longer EFB fibre. Flexural strength and density decrease with increasing EFB fibre, but the addition of 40–70% volume fraction of EFB increases flexural strength of polyester resin by 350%.

De Rosa, Santulli, Sarasini, and Valente (2009a) and De Rosa et al. (2009b) studied post impact properties of jute/glass hybrid composites in relation to layering pattern of glass and jute fibres, E-glass/jute/E-glass hybrid performs better at low impact energies (up to 10 J), which do not damage laminate core. In contrast, jute/E-glass/jute hybrids are better suited to withstand extensive damage produced by higher impact energies (12.5 and 15 J), in that they allow a more effective redistribution of impact damage in the structure. The flexural and indentation behaviour of pultruded jute/glass and kenaf/glass hybrid polyester composites has been monitored using acoustic emission, and compared with that of kenaf fibre composites (Akil, De Rosa, Santulli, & Sarasini, 2010). The water absorption behaviour of sisal/cotton, jute/cotton and ramie/cotton hybrid fabric reinforced composites is evaluated (Alsina, De Carvalho, Filho, & D'Almeida, 2007). The effect of the temperature of immersion, fibre volume fraction, and predrying of the fabrics before their incorporation onto the composites is evaluated. The results obtained show that the hybrid sisal/cotton fabric has a higher water affinity than jute/cotton and ramie/cotton fabrics. Similar study done on jute/cotton and silk/cotton fabrics polymer matrix composites (De Carvalho, Moraes, & D'Almeida, 2009). It observed that tensile properties increases with fibre content, and sisal/cotton hybrid composites were slightly more affected by water exposure than jute/cotton hybrid composites. They also studied tensile behaviours of jute/cotton hybrid composites with three different fabric configurations with varying jute weight ration and five stacking sequences were analyzed (De Carvalho, de Souza, & D'Almeida, 2007). Cotton fibre did not contribute much as reinforcing materials but act as a convenient ancillary fibre aiding at the fabric manufacture.

Researchers investigated tensile strength of ramie–cotton hybrid fibre reinforced polyester composites (Paiva Júnior, De Carvalho, Fonseca, Monteiro, & D'Almeida, 2004). They observed that tensile behaviour was dominated by volume fraction of ramie fibres aligned in the test direction. The fabric and diameter of the thread did not play any role in tensile characteristics. Recently conducted study on the sisal/glass hybrid composites with various stacking sequences, revealed that proper stacking of fibre layer enhance mechanical properties (Amico, Angrizani, & Drummond, 2010). The mechanical performance of short randomly oriented banana and sisal hybrid fibre reinforced polyester composites was investigated (Idicula, Neelakantan, Oommen, Joseph, & Thomas, 2005). A positive hybrid effect is observed in the flexural strength and flexural modulus of the hybrid composites. The tensile strength of the composites showed a positive hybrid effect when the relative volume fraction of the two fibres was varied, and maximum tensile strength was found to be in the hybrid composite having a ratio of banana and sisal 4:1. The impact strength of the composites was increased with increasing volume fraction of sisal, a negative effect is observed for impact properties. They also studied short randomly oriented intimately mixed banana and sisal hybrid fibre-reinforced polyester composites having varying volume fraction of fibre were fabricated by compression molding (CM) and resin transfer molding (RTM) techniques by keeping the volume ratio of banana and sisal, 1:1 (Idicula, Sreekumar, Joseph, & Thomas, 2009). Idicula et al. (2010) also studied mechanical performance of banana/sisal woven fibre and short banana/sisal hybrid fibre reinforced polyester composites.

Mishra et al. (2003) studied mechanical performance of sisal/glass and pineapple/glass fibre reinforced polyester composites. Composites were prepared by varying the concentration of glass fibre and by subjecting the bio-fibres to different chemical treatments. An attempt to study the moisture uptake characteristics of hybrid systems was performed and it observed that water uptake of hybrid composites were less than that of unhybridized composites. Chemical resistance and tensile properties of bamboo/glass fibres reinforced hybrid composites were studied and effect of alkali treatment of the bamboo fibres on these properties was also studied (Venkata Subba Reddy, Varada Rajulu, Hemachandra Reddy, & Ramachandra Reddy, 2010). Hybrid composites are chemical resistant and it was found that alkali treated bamboo fibres based hybrid composites show higher tensile properties. Recently, published work on alkali treated sisal/roselle hybrid polyester composites shows that alkali treated hybrid composites with 10% NaOH show an improvement in strength and stiffness with high toughness (Athijayamani, Thiruchitrambalam, Natarajan, & Pazhanivel, 2010).

4.1.4. Unsaturated polyester based hybrid composites

Jute/glass fibre hybrid reinforced unsaturated polyester composites along with additives and initiator are prepared by hand lay up technique (Abdullah Al, Abedin, Beg, Pickering, & Khan, 2006). Hybrid composite with jute to glass ratio of 1:3 improved mechanical properties such as tensile strength 125%, tensile modulus 49%, bending strength 162%, and bending strength 235% compared to untreated jute composites. Studied water sorption of hybrid composites prepared by compressed molded unsaturated polyester composites reinforced with jute-glass fabric (De Carvalho, Cavalcanti, & De Lima, 2010). In this study they developed mathematical model to predict mass transfer during water absorption.

The hybrid composites were developed using naturally occurring fabrics belonging to the species Ceiba pentandra [kapok]/Agave veracruz [sisal] and kapok/glass with unsaturated polyester resin as a matrix and using the hand lay-up technique (Venkata Reddy, Noorunnisa Khanam, & Shobha Rani, 2007). The kapok/glass hybrid composites showed better chemical resistance than the kapok/sisal hybrid composites. They also studied impact properties of kapok based unsaturated polyester hybrid composites (Venkata Reddy, Venkata Naidu, & Shobha Rani, 2008a). Compression, chemical resistance, and thermal properties of the kapok/sisal-unsaturated polyester hybrid composites are investigated as a function of fabric/fibre content and different volume ratios of fabrics (Venkata Reddy, Shobha Rani, Chowdoji Rao, & Venkata Naidu, 2009; Venkata Reddy, Venkata Naidu, Shobha Rani, & Subha, 2009). The addition of small amount of sisal fibres to kapok reinforced polymer composite enhancing the compressive properties of the resulting hybrid composites. Alkali-treated kapok/sisal hybrid composites (5 vol%) improve the compression strength and modulus over that of untreated kapok/sisal hybrid composite by 8.8 and 10.6%, respectively, containing 50:50 volume ratios of kapok and sisal. Among all the resultant hybrid composites those with fabrics ratio of 1:3 demonstrate improved compressive properties. They also studied mechanical properties of kapok/glass hybrid composites and found values higher than un-hybridized composites at all fibre loading (Venkata Reddy, Shobha Rani, et al., 2009; Venkata Reddy, Venkata Naidu, et al., 2009; Venkata Reddy, Venkata Naidu, & Shobha Rani, 2008b). A significant improvement was observed in tensile and hardness properties of these composites by alkali treatment. Flexural, compressive, and interlaminar shear strength properties increase with increase in glass fibre loading in composite. The kapok/glass hybrid composites exhibited higher flexural and compressive values than sisal/glass and kapok/sisal composites. They investigated effect of glass fibre loading on flexural and tensile properties of sisal/glass fibre hybrid composite and it observed that hybrid composite show lower flexural properties and higher tensile strength than the matrix (John & Naidu, 2004a, 2004b). The effect of alkali and trimethoxy silane (coupling agent) treatment of fibres on the flexural and tensile properties have been studied and observed that silane treatment has no significance effect on the flexural properties and significant improvement in tensile strength of the sisal–glass hybrid composites has been observed by these treatments. Studied chemical resistance properties of the treated and untreated sisal/glass and silk/sisal hybrid composites and observed that the developed hybrid composites are resistant to all the tested chemicals except carbon tetrachloride (John & Naidu, 2007; Raghu, Noorunnisa Khanam, & Venkata Naidu, 2010). Recently done work to evaluate the mechanical performance (flexural and impact) of glass/sisal hybrid composite with different fibre loadings and different volume ratios of sisal and glass fibres (Ornaghi, Bolner, Fiorio, Zattera, & Amico, 2010).

Mechanical properties such as tensile, flexural, and compressive strengths of sisal/silk and coir/silk unsaturated polyester based hybrid composites with different fibre lengths have been studied (Noorunnisa Khanam, Mohan Reddy, Raghu, John, & Venkata Naidu, 2007; Noorunnisa Khanam, Ramachandra Reddy, Raghu, & Venkata Naidu, 2010). Significant improvement in tensile, flexural, and compressive strengths of the coir/silk hybrid composites has been observed by alkali treatments. Researcher investigated the variation of mechanical properties such as tensile, flexural, and impact strengths of roselle and sisal fibres hybrid polyester composite at dry and wet conditions (Athijayamani et al., 2009). In an interesting research, researcher tries to investigate effect of alkali and sodium lauryl sulphate (SLS) on mechanical properties of banana/kenaf hybrid composites and woven hybrid composites (Thiruchitrambalam, Alavudeen, Athijayamani, Venkateshwaran, & Perumal, 2009). SLS treatment has show better improvement in tensile, flexural and impact strength of both non woven and woven hybrid composites compared to alkali treated composites.

Glass/bamboo fibre hybrid bulk molding compounds (BMC) laminates were fabricated by compression molding, and their physio-mechanical properties were investigated (Dieu, Liem, Mai, & Tung, 2004). Hybrid composites with fibre/matrix ratio 25:75 wt% (25% bamboo and 75% glass fibres) showed better physio-mechanical properties than other combination. In an interesting study, research worked on effect of layering pattern on water absorption of banana/glass hybrid composites (Pothan, Cherian, Anandakutty, & Thomas, 2007). They tried to analysis water absorption behaviour through thermodynamics parameters such as sorption coefficient, diffusion coefficient and concluded that layering pattern plays an important role in water absorption of hybrid composites.

4.1.5. Polyester (isothalic) based hybrid composites

Hybridization of jute fibre composite with glass fibre enhances the mechanical properties of hybrid composites and stacking sequence effect the flexural and interlaminar shear strength but for the same relative weight fraction of jute and glass fibres, layering sequence has little effect on tensile properties (Ahmed & Vijayarangan, 2008). The effect of hybridization of glass fibres on water absorption behaviour of woven jute fabric-reinforced isothalic polyester composites is also studied (Ahmed, Vijayarangan, & Rajput, 2006). The addition of 16 wt% of glass fibre results in maximum flexural and interlaminar shear strength (Gatenholm et al., 1993). Further addition of glass does not show any improvement in these properties. Jute laminates have poor damage resistance and tolerance capability which can be enhanced by effective hybridization. A linear increasing trend in damage area was noticed with the increase in impact energy for all types of laminates. The rate of increase in damage area is greater for all jute laminates, indicating their poor damage resistance capability than hybrid laminates (Ahmed, Vijayarangan, & Kumar, 2007). The young modulus in warp and weft direction increases whereas the Poisson's ratio decreases with increase in glass fibre content. This indicate that, jute composite undergo more transverse strain and less longitudinal strain than jute-glass hybrid composite. The characteristics dimension of point stress criterion increases with increase in the hole size. Jute composites have higher notch sensitivity than jute–glass hybrid composites. The empirical relations and correlations developed for prediction of notch sensitivity of synthetic fibre composites also holds good for jute and jute–glass hybrid composites (Ahmed, Vijayarangan, & Naidu, 2007). This indicates that, jute fibres offer same reinforcing effect in matrix as synthetic fibre. Aquino et al. investigated moisture absorption effect on the mechanical properties of a jute/glass hybrid composite formed by orthophthalic polyester resin. The maximum moisture absorption of the hybrid composite was 7.64% after eleven months of water immersion. It observed that the moisture absorption caused decrease in mechanical properties of the hybrid composite for both loading types, tensile and bending (Aquino, Sarmento, Oliveira, & Silva, 2007).

4.1.6. Vinyl ester based hybrid composites

The mechanical and physical properties of the vinyl ester reinforced with oil palm EFB laminated at different layer arrangements with glass fibres composites were investigated (Abdul Khalil et al., 2009). The mechanical properties (tensile, flexural and impact) of EFB/glass fibre with vinyl ester hybrid composites were found higher than that of mechanical and chemical board. Different layers of arrangement of fibres (oil palm EFB and glass fibres) showed different properties of composites. Water absorption and thickness swelling properties of the hybrid composites at various layer arrangements were decrease by the incorporation of glass fibre compared to mechanical and chemical board.

4.1.7. Rooflite resin based hybrid composites

Velmurugan and Manikandan (2005) investigated the hybridization of palmyra fibre waste with glass fibre in polyester matrix. Hybrid composites containing higher amount of waste palmyra fibre showed good reinforcement effect compared to composites reinforced with higher amount of glass fibre. They also studied mechanical properties of randomly mixed palmyra/glass fibre hybrid composites (Velmurugan & Manikandan, 2007). It is observed that the composites containing 50 mm length fibre and 55 wt% fibre have maximum mechanical properties. The studies are carried out for both skin core and dispersed type hybrid composites. The mechanical properties of fibre skin core construction are higher than the dispersed fibre construction.

In an interesting study, Mandal, Alam, Varma, and Maiti (2010) investigated effect of weight fraction and length of short bamboo/glass fibres on flexural strength and inter-laminar shear strength (Gatenholm et al., 1993) of vinyl ester resin and unsaturated polyester (USP) resins based composites. It observed that flexural properties of glass/bamboo fibre reinforced vinyl ester resins were higher than those based on USP resins. Replacement of 25 wt% of glass fibres did not affect the flexural modulus and a marginal increase in ILSS was observed. However, replacement of 75% glass fibres by bamboo fibres resulted in a significant decrease in flexural strength, modulus and ILSS. Similar study conducted on mechanical and water absorption behaviour of bamboo/glass mat (strand and woven) reinforced epoxy and polyester laminate composites (Kushwaha & Kumar, 2010). Hybridization with glass mat enhanced mechanical and water absorption properties of hybrid composites and woven glass mat reinforced hybrid composites show better properties compared to the strand mat. It also indicated effect of layering pattern and glass fibre loading for both the epoxy and polyester matrix composites.

4.2. Thermoplastic hybrid composites

Thermoplastic hybrid composite developed by various researchers, combining fibres with polypropylene, polystyrene, polyethylene (low and high density), poly vinyl chloride, polycarbonate, natural rubber. Reported work on cellulosic/cellulosic and cellulosic/synthetic fibres reinforced thermoplastic hybrid composites are shown in Table 6.

4.2.1. Polypropylene (PP) based-hybrid composites

Hybrid composite was made using oil palm EFB and glass fibres (Law and Jiang, 2001) as reinforcing agents in polypropylene (PP)

Table 6
Reported work on natural fibre hybrid thermoplastic polymer composites.

Hybrid fibre	Matrix polymer	References
Oil palm EFB/glass	Polypropylene (PP)	Rozman et al. (2001a)
Jute/glass	Polypropylene (PP)	Esfandiari (2007)
Sisal/glass	Polypropylene (PP)	Jarukumjorn and Suppakarn (2009), Nayak and Mohanty (2010), Nayak et al. (2009), and Schmidt et al. (2009)
	Polyethylene (PE)	Kalaprasad et al. (2004)
Banana/glass	Polypropylene (PP)	Nayak et al. (2010b) and Samal et al. (2009a)
	Polystyrene	Haneefa et al. (2008)
Bamboo/glass	Polypropylene (PP)	Nayak et al. (2009, 2010a), Samal et al. (2009b), and Thwe and Liao, (2002, 2003a, 2003b)
Hemp/glass	Polypropylene (PP)	Panthapulakkal and Sain (2007) and Reis et al. (2007)
Flax/glass	Polypropylene (PP)	Arbelaiz et al. (2005)
Cotton/flax	Polyethylene (PE)	Foulk et al. (2006)
Wood flour/glass	Poly vinyl chloride (PVC)	Jiang et al. (2003)
Cotton/waste silk	Polycarbonate (PC)	Tasdemir et al. (2008)
Coir/sisal	Natural rubber	Haseena et al. (2004, 2005, 2007)
Oil palm EFB/glass	Natural rubber	Anuar et al. (2006)
Kenaf/glass	Natural rubber	Wan Busu et al. (2010)
Sisal/oil palm	Natural rubber	Jacob, Francis, et al. (2006), Jacob, Jose, et al. (2006), Jacob, Varughese, et al. (2006), Jacob et al. (2004a, 2004b, 2005, 2007), and John et al. (2008)

matrix (Rozman et al., 2001a, 2001b). Studies demonstrate that effect of oil extraction of oil palm EFB fibre on the flexural and tensile properties of composites incorporated with various coupling agents. Extraction of the oil palm EFB fibres has show significant improvement in flexural and tensile strength and toughness, with slight increase in the flexural and tensile modulus and elongation at break. A preliminary study on oil palm EFB/glass hybrid composites indicated that the incorporation of both fibres into PP matrix resulted in the reduction of tensile and flexural strength. Objective of this study is not the comparison between natural fibre and glass fibre composites but the development of advanced statistical tools to describe the mechanical properties of these materials (Esfandiari, 2007). It was observed that theoretical elastic modulus predicted was close to the experimental value. The relatively small difference between the expected values of modulus was attributed to imperfections, in terms of fibre/matrix adhesion and voids, in the analyzed composite.

This study aimed to investigate the effect of glass fibre hybridization on the physico-mechanical properties of sisal–polypropylene composites (Jarukumjorn & Suppakarn, 2009). Incorporating glass fibre into the sisal polypropylene composites enhanced tensile, flexural, and impact strength without having significant effect on tensile and flexural moduli. Incorporation of glass fibre with sisal fibre in PP decreased the water absorption of the composites and as the glass fibre content increased the water absorption decreased. Recently one researcher also worked on permeability and mechanical properties of sisal/glass hybrid composites prepared by resin transfer molding technique (Schmidt, Goss, Amico, & Lekakou, 2009). Reinforcement of sisal fibre mat as flow medium increased the permeability of hybrid reinforcement and also significantly improved mechanical properties. Fabricated hybrid composites of polypropylene reinforced with intimately mixed short banana and glass fibres using Haake twin screw extruder followed by compression molding with and without maleic anhydride grafted polypropylene (MAPP) as a coupling agent (Samal, Mohanty, & Nayak, 2009a). Water absorption of hybrid composite decreases due to the presence of glass fibre and coupling agents. Incorporation of both the fibres into PP matrix resulted in an increase in tensile, flexural and impact strength with an increasing level of fibre content up to 30 wt% at banana:glass fibre ratio of 15:15 wt% and 2 wt% of MAPP. Sanjay et al. also studied polypropylene–bamboo/glass fibre reinforced hybrid composites (BGRP) using an intermeshing counter rotating twin screw extruder followed by injection molding (Nayak, Mohanty, & Samal, 2009). In an interesting study, Moe et al. investigated hydrothermal aging and fatigue behaviour of bamboo–glass fibre reinforced polypropylene hybrid composite (BGRP) (Thwe & Liao, 2003a). Tensile strength and elastic modulus of BGRP samples have shown moderate reduction after aging at 25 °C after 6 months, however, they were reduced considerably after aging at 75 °C for 3 months. Moisture absorption and tensile strength degradation are suppressed using MAPP as a coupling agent in composite systems. The hybrid approach of blending more durable glass fibre with bamboo fibre is an effective way to improve the durability of natural fibre composite under environmental aging. They also investigated the effects of environmental aging and accelerated aging on tensile and flexural behaviour of bamboo-glass fibre reinforced polypropylene hybrid composite (BGRP), all with a 30% (by mass) fibre content, were studied by exposing the samples in water at 25 °C for up to 1600 h and at 75 °C for up to 600 h (Thwe & Liao, 2003b). Replacing bamboo with glass fibre results in reduced moisture sorption of the composite since moisture uptake is negligible for the latter. Compared to those aged at 25 °C, mass gain is lower when aged at 75 °C after about 600 h, caused by the dissolution of components of the bamboo fibre (e.g. lignin) and the PP matrix, which is visually evident under scanning electronic microscope. Tensile and flexural strength and stiffness of BGRP decreased after aging in water at 25 and 75 °C for prolonged period. The extent of strength and stiffness loss depends on the aging time and temperature. In this study, the effect of fibre content, fibre length, bamboo to glass fibre ratio, and coupling agent (MAPP) on tensile and flexural properties of short bamboo–glass fibre reinforced PP hybrid composites (BGRP) were examined (Thwe & Liao, 2002). Sorption behaviour and retention in mechanical properties of the composites after aging were also studied. By incorporating up to 20% (by mass) glass fibre, the tensile and flexural modulus of BGRP were increased by 12.5% and 10%, respectively; and tensile and flexural strength were increased by 7% and 25%, respectively. Increased bamboo fibre length shows drop in tensile strength and tensile modulus has increased by small amount. Flexural strength and modulus of longer bamboo fibre composites are 25% and 35% higher than those of shorter.

Reis, Ferreira, Antunes, and Costa (2007) studied the flexural behaviour of hand manufactured hybrid laminated composites with a hemp fibre/polypropylene core and two glass fibres/polypropylene surface layers at each side of the specimen. When compared with glass fibres reinforced polypropylene laminates, the hybrid composites have economical, ecological and recycling advantages and also specific fatigue strength benefits. The major finding is that laminate composites (LC) present an ultimate strength about 4% higher than the hybrid composites (HLC), while the Young's modulus was about 3.8% higher. The specific flexural strength and flexural stiffness are around 22% higher in HLC composites than in LC laminates. In this case the rupture of the fibres also occurs in tension region. Panthapulakkal and Sain (2007) investigated mechanical, water absorption, and thermal properties of short hemp/glass fibre-reinforced hybrid PP composites prepared by injection molding. Hybridization with glass fibre improves the mechanical properties of short hemp fibre composites. Researchers develop hybrid composite by combination of flax and glass fibres in polypropylene matrix (Arbelaiz et al., 2005). Hybrid composites with 30 wt% glass fibre loading show higher mechanical properties than those for flax fibre bundle/PP and modified by MAPP, it showed higher modulus than unmodified hybrid composites.

4.2.2. Polystyrene based hybrid composites

Studied the influence of fibre content, fibre loading and hybrid effect on the mechanical properties such as tensile strength, young modulus, elongation at break and flexural properties of the banana/glass hybrid fibre reinforced polystyrene composite (Haneefa, Bindu, Aravind, & Thomas, 2008). The effect of interface modification on the mechanical properties of the hybrid composite was investigated, chemical modification such as alkali, benzoyl chloride and polystyrene maleic anhydrites treatment improved the tensile properties of the composites. Modification resulted in enhanced fibre dispersion in the composite, reduced hydrophilicity of banana fibre and improved fibre/matrix compatibility through mechanical anchoring, physical and chemical bonding.

4.2.3. Polyethylene (PE) based-hybrid composites

An effort was made to evaluate the tensile properties of intimately mixed short sisal/glass hybrid fibre reinforced low density polyethylene (LDPE) as a function of fibre length and various surface chemical modifications on the fibre as well as the matrix (Kalaprasad et al., 2004). It is seen that the fibre breakage during processing of the composite is more in the case of glass fibre due to its brittle nature than that of sisal fibre. The results clearly indicate that the tensile properties of intimately mixed sisal/glass hybrid composites are highly dependent on the length of sisal fibre. Treatments with different chemicals improved the tensile properties of hybrid composites. Among the various chemical modifications, composites containing benzyl peroxide treated fibres show highest tensile strength and modulus. Cost/performance ratio analysis shows that acetylation is more efficient than other treatments used in this study. Composites made with cotton and flax-containing commercial fabrics and recycled high-density polyethylene (HDPE) were evaluated for physical and mechanical properties (Foulk, Chao, Akin, Dodd, & Layton, 2006). Incorporation of cotton and flax fibres into recycled HDPE composite increased the composites water absorption and swelling behaviour. Fabrics were treated with maleic anhydride, silane, enzyme, or adding maleic anhydride grafted polyethylene (MAA-PE; MDEX 102-1, ExxelorVA 1840) to promote interactions between polymer and fibres. With the exception of the silane treatment, the treated denim fabric tensile strength values decreased with respect to untreated fabrics.

4.2.4. Poly vinyl chloride (PVC) and polycarbonate (PC) based-hybrid composites

They studied mechanical properties of poly (vinyl chloride)/wood flour/glass fibre hybrid composites (Jiang, Kamdem, Bezubic, & Ruede, 2003). By adding L glass fibre, unnotched and notched impact strength of hybrid composites increased significantly without losing flexural properties while there was no such improvement when using type S glass fibre. The significant improvement in impact strength of hybrid composites was attributed to the formation of the three-dimensional network glass fibre architecture between type L glass fibres and wood flour. Waste silk and cotton and recycled polycarbonate (PC) polymer were mixed and as a result composite structures were obtained (Tasdemir, Kocak, Usta, Akalin, & Merdan, 2008). Upon increasing the length of silk in polycarbonate, yield strength, tensile strength, % elongation and Izod impact strength decreases, while hardness, elasticity modulus and melt flow index (MFI) increases. Heat deflection temperature (HDT) and vicat softening values are not changed. On the another hand, with increase in length of cotton in PC, yield strength, tensile strength, elasticity modulus, and hardness decrease while % elongation, Izod impact strength, MFI, HDT and vicat softening values increase.

4.2.5. Natural rubber based hybrid composites

Researchers have developed novel hybrid biocomposites by reinforcement of a fruit (coir) and leave (sisal) fibre in natural rubber. The researchers also used the swelling technique to estimate interfacial adhesion of sisal/coir fibre reinforced natural rubber composites (Haseena, Dasan, Namitha, Unnikrishna, & Thomas, 2004). The addition of sisal and coir fibres offered good reinforcement in natural rubber and resulted in improvement of properties (Haseena, Dasan, Unnikrishnan, & Thomas, 2005). Anuar, Ahmad, Rasid, and Nik Daud (2006) reported work on tensile and impact properties of thermoplastic natural rubber hybrid composite with short glass fibre and oil palm empty fruit bunch fibre. The study also focused on the effect of fibre (glass and oil palm EFB) treatment with coupling agent. Results show that composite containing 10% oil palm EFB and 10% glass fibre gave an optimum tensile and impact strength for treated and untreated hybrid composites.

In an intensive study, researchers design hybrid biocomposites by unique combination of sisal and oil palm fibres in natural rubber and studied mechanical and physical properties. It observed that increasing the concentration of fibres reduced tensile and tear strength, but enhanced modulus of the composites (Jacob et al., 2004a; Jacob, Thomas, & Varughese, 2004b). It also seen that chemical modification of both sisal and oil palm fibres was imperative for increased interfacial adhesion and resulted in enhanced properties. Researchers also studied water sorption and stress relaxation characteristics of the hybrid biofibres composites with reference to fibre loading and chemical modification (Jacob, Francis, Thomas, & Varughese, 2006; Jacob, Jose, Thomas, & Varughese, 2006; Jacob, Varughese, & Thomas, 2006; Jacob, Varughese, & Thomas, 2005). It found that water sorption dependent on the properties of the biofibres and chemical modification was seen to decrease the water uptake in the composites. Chemical modification of the fibre surface was found to affect the degree of adhesion and exhibited lower rate of stress relaxation. Biodegradation (Jacob, Thomas, & Varughese, 2007) characteristics of sisal/oil palm hybrid composites also studied by them.

The effects of chemical modification of fibre surface in sisal–oil palm reinforced natural rubber green composites have been studied (John, Francis, Varughese, & Thomas, 2008). The fibre reinforcing efficiency of the chemically treated biocomposites was better compared to untreated composites. All the observations show that the chemical treatment of sisal and oil palm fibres result in superior tensile properties due to better interaction between fibre and rubber matrix. Recently kenaf/glass fibres reinforced natural rubber hybrid composites were compounded by melt blending method (Wan Busu, Anuar, Ahmad, Rasid, & Jamal, 2010). Hybrid composite prepared with fibre content (5, 10, 15, and 20 vol% of fibre) and found that hybrid composite kenaf/glass (3:1) give better properties.

5. Electrical properties of hybrid composites

It is clear from the literature review that very limited research has been reported on the electrical properties of hybrid composites. Electrical properties of banana/glass hybrid fibre reinforced composites with varying hybrid ratios and layering patterns were analyzed (Joseph & Thomas, 2008). Researchers investigated dielectric characteristics and volume resistivity of sisal–oil palm hybrid biocomposites. It seen that dielectric constant increases with fibre loading at all frequencies and volume resistivity decreases with frequency and fibre loading, this implies that the conductivity increases upon the addition of lignocellulosic fibres (Jacob, Francis, et al., 2006; Jacob, Jose, et al., 2006; Jacob, Varughese, et al., 2006). Chemical modification of fibres resulted in decrease in dielectric constant and increase in volume resistivity. The dissipation factor was seen to increase with fibre loading which indicates that the electrical charges can be retained over a longer period of time. Electrical properties of jute/glass fibre reinforced epoxy composites were studied (Koradiya et al., 2010). Results indicate that hybrid composites have intermediate electrical properties than those of jute and glass composites. Similar study on electrical properties of sisal/glass (treated and untreated) hybrid composites reinforced in blended epoxy and formaldehyde of bisphenol-C were done (Patel & Parsania, 2010).

Electrical strength and volume resistivity of jute-biomass based hybrid composites have been evaluated and compared with those of jute–bisphenol-C-formaldehyde (BCF) composites. No much difference in dielectric breakdown strength between hybrid composites (1.21–2.11 kV/mm) and BCF–jute (1.41 kV/mm) composite is observed but volume resistivity of hybrid composites especially for BCF–jute–wheat husk and BCF–jute–jamun flower husk has increased by 197–437% (Mehta & Parsania, 2006). In an interesting work, researchers studied electrical properties such as dielectric constant, volume resistivity and dielectric loss factor of sisal/coir hybrid fibre reinforced natural rubber composites in relation to fibre loading, fibre ratio, frequency, chemical modification of fibres and the presence of a bonding agent (Haseena, Unnikrishnan, & Kalaprasad, 2007). Dielectric constant and volume resistivity values of sisal/coir hybrid show same behaviour as reported in relation to fibre loading and frequency (Jacob, Francis, et al., 2006; Jacob, Jose, et al., 2006; Jacob, Varughese, et al., 2006). The dielectric constant values of chemical treated fibres composites decrease due to the increased hydrophobicity of fibres. The addition of a two-component dry bonding agent consisting of hexamethylene tetramine and resorcinol, used for the improvement of interfacial adhesion between the matrix and fibres, reduced the dielectric constant of the composites.

6. Thermal properties of natural fibre hybrid composites

Researchers studied thermal properties of banana/glass hybrid composites, they observed that MAPP treated Banana/glass hybrid composites (BSGRP) shows higher thermal stability compare to banana fibre reinforced polymer composite (Samal et al., 2009a). It may be due to SiO groups in glass fibre which interlinks with anhydride group of MAPP, providing synergism between glass and banana fibres. Thermal analysis also confirms the enhancement in melting point, crystallization temperature and onset thermal degradation temperature of hybrid composites. Similar study carried out through differential scanning calorimetry and thermogravimetric analysis, reveals that MAPP treated banana and glass fibre enhanced cryrstallization temperature and thermal stability of polypropylene (Nayak, Mohanty, & Samal, 2010b). Thermal properties of sisal/glass hybrid PP investigated by Kasama et al., it observed that the addition of glass fibre improved thermal properties of sisal/PP composites (Jarukumjorn & Suppakarn, 2009). PP/10sisal/20GF/PP-g-MA composite provided the highest T_{d5} (temperature at which 5% weight loss) and T_{d50} (temperature at which 50% weight loss) while the PP/sisal composite gave the lowest T_{d5} and T_{d50}. Further enhancement of heat distortion temperature (HDT) was found when the glass fibres were added into sisal–PP composites. Thermal properties of sisal/glass hybrid composites also studied by Nayak and Mohanty (2010) and it also confirm higher thermal stability in the case of hybrid composites. Crystallization temperature (Mongkollapkit, Kositchaiyong, Rosarpitak, & Sombatsompop, 2010) of 2 wt% MAPP-treated sisal/glass hybrid is found to be more than composites without MAPP, which indicates a further enhancement in the nucleation process in the presence of compatibilizer.

Differential scanning calorimeter (DSC) and thermo gravimetric analysis (TGA) indicates an increase in thermal stability of the matrix polymer with incorporation of bamboo and glass fibres, confirming the effect of hybridization and efficient fibre matrix interfacial adhesion (Nayak et al., 2009). It also observed that the addition of bamboo fibre, glass fibre and MAPP does not significantly influence the melting temperature of PP matrix. However, introduction of fibres and MAPP interrupts the linear crystallizable sequence of PP matrix and lowers the degree of crystallization. They done similar study and reported that thermal stability of polymer matrix increases with incorporation of bamboo and glass fibres, it may be due to better fibre/matrix adhesion (Nayak, Mohanty, & Samal, 2010a). Incorporation of glass fibres results in considerable increase in the thermal stability of both the composite systems which is possibly due to the higher thermal stability of glass fibre than bamboo fibre (Lee & Wang, 2006). Furthermore, the bamboo/glass hybrid composites system also exhibited maximum charred residue indicating higher flame retardancy of the systems. Samal, Mohanty, and Nayak (2009b) also studied thermal properties such as crystallization, melting behaviour and thermal stability of bamboo/glass hybrid composites. TGA showed an increase in thermal stability of the matrix polymer with incorporation of bamboo and glass fibres, confirming the effect of hybridization and efficient fibre matrix interfacial adhesion.

Thermal properties of the hemp fibre composites were improved by hybridization with glass fibres (Panthapulakkal & Sain, 2007). Both hemp and hybrid fibre composites showed a two-step degradation and it observed that hybridization of hemp fibre composite with glass fibre shifts the temperature of degradation to a higher value, indicating an increased thermal stability of the hybrid composites. In an interesting study thermal properties of sisal/oil palm hybrid fibre reinforced natural rubber composites was performed (Jacob, Francis, et al., 2006; Jacob, Jose, et al., 2006; Jacob, Varughese, et al., 2006) and thermal stability of the composites was seen to increase upon fibre loading and chemical modification. A thermal property of kapok/sisal hybrid composites with and without alkali treatment was analyzed by differential scanning calorimetry (Venkata Reddy, Shobha Rani, et al., 2009; Venkata Reddy, Venkata Naidu, et al., 2009). Results indicate that treated kapok/sisal hybrid composite show slightly improvement in melting temperature compared to untreated hybrid composites.

7. Dynamic mechanical properties of natural fibre hybrid composites

Dynamic mechanical analysis (DMA) is one of the most powerful tools to study the behaviour of polymer composite materials and it allows for a quick and easy measurement of material properties (Swaminathan & Shivakumar, 2009). The dynamic properties of randomly oriented intimately mixed short banana/sisal hybrid fibre reinforced polyester composites were determined (Idicula, Malhotra, Joseph, & Thomas, 2005a). Dynamic properties such as the storage modulus (E'), damping behaviour ($\tan\delta$) were investigated as a function of total fibre volume fraction and the relative volume fraction of the two fibres. Hybrid composites having volume ratio of banana and sisal as 3:1, which has the lowest $\tan\delta$ value and the highest E' value at T_g. They also studied effect of layering pattern on storage modulus (E'), damping behaviour ($\tan\delta$), and loss modulus (E'') of bilayer (banana/sisal), trilayer (banana/sisal/banana and sisal/banana/sisal), and intimate mix composites by keeping the relative volume fraction of banana and sisal 1:1 and the total fibre loading to a 0.40 volume fraction as a function of temperature and frequency (Idicula, Malhotra, Joseph, & Thomas, 2005b). Bilayer composite showed high damping property while intimately mixed and banana/sisal/banana composites showed increased stiffness compared to the other pattern. The activation energy of the intimately mixed composite was found to be the highest.

Natural rubber was reinforced with sisal and oil palm fibres and was subjected to dynamic mechanical analysis to determine the dynamic properties as a function of temperature (Jacob, Francis, et al., 2006; Jacob, Jose, et al., 2006; Jacob, Varughese, et al., 2006). The storage modulus (E') was found to increase with weight fraction of fibre due to the increased stiffness imparted by the natural fibres, E'' increased with loading while the tan δ was found to decrease. 2% NaOH treated natural fibre hybrid composites exhibits the maximum E'' and 4% NaOH exhibited maximum E'. It is obvious that chemically treated composites have decreased tan δ value than untreated composites.

The dynamic mechanical properties of randomly oriented intimately mixed glass/pineapple leaf fibres (PALF) (glass/PALF/glass) and (PALF/glass/PALF) hybrid composites based on PALF and glass fibres in unsaturated polyester matrix were investigated (Uma Devi, Bhagawan, & Thomas, 2010). Intimately mixed and trilayer (glass/PALF/glass) hybrid polyester composites gave higher storage modulus values compared with PALF/glass/PALF composite. Tan δ of polyester resin was drastically reduced on incorporation of PALF and glass fibre. Glass/banana hybrid polyester composites are subjected to dynamic mechanical analysis over a range of temperature and three different frequencies (Pothan, George, John, & Thomas, 2010). E' values of hybrid composite decrease above T_g temperature where glass is the core material. It observed that layering pattern of the composite shows a significant effect on the dynamic properties of the composite and intimately mixed composite displays the highest E' values in all compositions. The DMA results show that the storage modulus and loss modulus of MAPP treated banana/glass hybrid composites improved over the whole temperature range, indicating better adhesion between fibre/matrix (Samal et al., 2009a).

Samal et al. (2009b) and Nayak et al. (2009) studied dynamic mechanical properties of bamboo/glass fibre hybrid composites and they observed that increase in storage modulus indicating higher stiffness in case of hybrid composites as compared to untreated composites and pure matrix. It concluded from results that storage modulus increases with the addition of fibres and MAPP as well as hybridization with glass while damping properties of the composites decreased with the addition of fibres and MAPP. They also studied the effect of MAPP on dynamic mechanical properties of sisal/glass hybrid composite and observed maximum improvement in storage modulus of sisal/glass reinforced PP hybrid composites after treatment with MAPP (Nayak & Mohanty, 2010). Similar work on DMA of sisal/glass hybrid composites reported increase in storage and loss modulus with hybridization of sisal/polyester with glass fibres (Ornaghi et al., 2010). In an interesting study, researchers worked on dynamic mechanical properties of oil palm/glass hybrid reinforced phenol formaldehyde (PF) composites (Sreekala, Thomas, & Groeninckx, 2005). Hybrid composites show higher value of damping factor and lower value of storage modulus compared to unhybridized oil palm fibre/PF composite.

8. Application of natural fibre reinforced hybrid composites

Several researchers explore application of natural fibre based composites in automobile industry (Bledzki, Faruk, & Sperber, 2006; Davoodi et al., 2010; Mohanty, Misra, & Hinrichsen, 2000; Puglia, Biagiotti, & Kenny, 2004). Mercedes-Benz introduced jute-based door panels into its A-Class vehicles as long as eight years ago. Virtually, all the major car manufacturers in Germany (Daimler Chrysler, Mercedes, Volkswagen, Audi Group, BMW, Ford and Opel) now use natural fibres composites in various applications (Suddell & Evans, 2005). In Germany, after authorisation of hemp cultivation led to development of flax/hemp (50:50) needle felt for high-segment cars. A landmark agreement between automobile giant Ford automobiles supplier Visteon Automotive system and Kafus biocomposites enhanced natural fibre composites applications in interior panels, linings and fittings. Even though natural fibre/matrix composite might be half as strong as a glass composite but this is possible to suffice by appropriate technology. In 2000, Audi launched the A2 midrange car in which door trim panels were made of polyurethane reinforced with mixed flax/sisal mat (Suddell & Evans, 2005). Researcher has developed, manufactured and assembled a small prototype car with all body panels made from jute fibre reinforced composite and hybrid composite as illustrated in Fig. 2 (Al-Qureshi, 2001). Door panels of E-Class Mercedes-Benz (Fig. 3) were made out of a mixture of flax and sisal fibres in an epoxy matrix shown remarkable weight reduction of about 20% (Schuh, 2004). It is an important step towards higher performance of hybrid composites in automobiles applications. It is reported that presently, 27 components of a Mercedes S class are manufactured from natural fibre based composites with total weight of 43 kg (Sreekumar, 2008). The end of life vehicle (ELV) directive in Europe states that by 2015, vehicles must be constructed of 95% recyclable materials, with 85% recoverable through reuse or mechanical recycling (Peijs, 2003). The fuel-cost

Fig. 2. A car made from jute fibre reinforced composite and hybrid composite in Brazil (with permission).

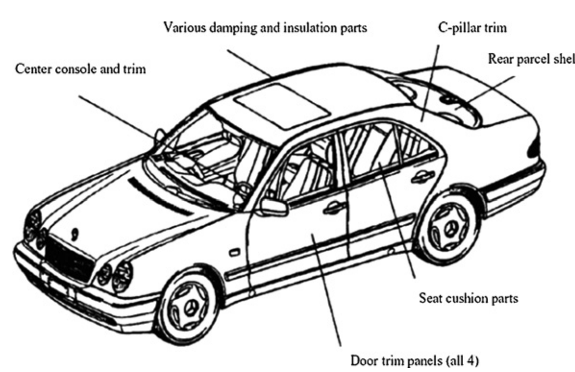

Fig. 3. Plant fibre application in the current E-Class Mercedes-Benz (Schuh, 2004).

scare was good news for the development of hybrid and electric vehicles, which were in abundance at the 2009 North American International Auto Show in Detroit, USA. During composite Europe 2009, BioConcept-Car, the world's first racing car whose body was made entirely of natural fibre reinforced plastics granted the "Composite Poineer award 2009" for its pioneering role in the field of natural fibre-reinforced plastics. The existing wood substitute building materials available in market are unable to fulfil industrial demands. Natural fibre based hybrid composites can provide suitable alternatives for making table top laminates, door panels, shutters, roofings, etc., possess desired properties. Sisal/jute door panels are developed and tested as per Indian standard speciation and performance is satisfactory (Singh & Gupta, 2005). Replacement of asbestos sheet by natural fibres in roofing is also seen as one of the suitable options. The potential applications of the hybrid composites in automobiles and building industry are going to increase in near future.

9. Conclusions

The utilization of natural fibres in industrial application provides challenges for researcher to development suitable techniques to obtain good quality fibres for use as reinforcement for polymer composites. Hybrid composites are cost effective, recyclable, and biodegradable and may replace or reduce utilization of synthetic fibres in different applications. It is required to understand the basic structural components of cellulosic fibres and their effect on the physical, mechanical, electrical and thermal properties of hybrid composites. However, there are number of issues which could constrain the utilization of these fibres as reinforcement in hybrid composites. This review paper attempts to give overview of study going on physical, mechanical, electrical, thermal and dynamic mechanical properties of cellulosic/cellulosic and cellulosic/synthetic hybrid composites. It would appear that a wide variety of work is being conducted worldwide with some cross over of ideas and focus on physical and mechanical properties of hybrid composites but still not explore about electrical, thermal and dynamic mechanical properties of hybrid composites. Several researchers developed hybrid composites by chemical modification of fibres or used coupling agents to improve fibre/matrix interface in hybrid composites.

Future research on hybrid composites not only driven by its automotive applications but it needs to explore its application in other areas such as aircraft components, building industry, rural areas and biomedical. There is need for more analysis of different properties of hybrid composites by modern equipment such as fragmentation test/single fibre composite test, X-ray photoelectron spectroscopy (XPS), atomic force microscopy (AFM), contact angle, zeta potential measurement, and stress relaxation in the most of the areas covered in this review. Challenges still exist in the suitable analytical modelling work on most of the published results and it will not only help in interpreting the experimental results but also optimizing specific applications in many sectors such as building industry, constructive components in aeroplane and automobiles, and rural areas.

Acknowledgements

The researchers would like to thank the Universiti Sains Malaysia, Penang for providing the USM fellowship and research grant 1001/PTEKIND/841020 that has made this work possible.

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