Mechanical properties of hybrid polymer composite

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Chapter Outline

4.1 Introduction

Fiber-reinforced composites have received great attention from researchers and scientists worldwide due to their attractive material characteristics. They have been widely used for various applications such as aerospace, automobile, civil infrastructure, and marine. Fibers (in the forms of roving, yarn, woven, etc.) reinforced with polymer matrix are known to result in enhanced mechanical properties of the composites. There are two basic types of fibers including natural and man-made fibers (a.k.a. synthetic or artificial fibers). Natural fibers such as flax, jute, and sisal have low densities compared to synthetic counterparts. They have acceptable specific strength/stiffness and relatively high elongations at breaking. The advantages of natural-fiber composites (a.k.a. green or fully-biocomposites) over synthetic fiber-based composites include low cost, light weight, abundantly available from renewable resources, environmentally friendly, biodegradability, recyclability, and renewability. On the other hand, synthetic fibers such as aramid, basalt, carbon, glass, and nylon are more durable and stronger than most natural fibers. Synthetic-fiber composites have thus been used in high-performance applications such as automobile and aircraft industries (Ramamoorthy et al., 2015). The major disadvantages of synthetic-fiber composites (synthetic fibers

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are mostly derived from petroleum) are their low melting temperature, high cost, and nondegradable, while those of natural-fiber composites (natural fibers are made from plants, animals, and mineral sources) are their poor fiber-matrix adhesion and relatively high moisture sorption. The combined use of natural and synthetic fibers in polymer hybrid composites may take advantages of both fibers while minimizing their shortcomings. This chapter reviews the most recent studies on natural fiber-based hybrid composites with the main emphasis on their mechanical properties.

4.2 Polymer matrix composites (PMCs)

4.2.1 Reinforcing fibers

4.2.1.1 Natural fibers

Natural fibers have numerous advantages over traditional reinforcing synthetic fibers (e.g., glass and carbon) such as low density, low cost, high toughness, acceptable specific strength, renewability, biodegradability, ease of separation, lower energy requirements for processing, and worldwide availability (Saw et al., 2012; Lee and Wang, 2006). All fibers which come from natural sources (plants, animals, etc.) and do not require fiber formation or reformation are defined as natural fibers (Needles, 2001; Jacob et al., 2004). There are three basic types of natural fibers according to their origin. They are classified as the following:

- Plant fibers (referred to as cellulosic or lignocellulosic fibers): Plant fibers are categorized into six types including:
  - Bast or stem fibers (e.g., flax, hemp, isora, jute, kenaf, kudzu, mesta, nettle, okra, paper mulberry, roselle hemp, ramie, rattan, urena, wisteria)
  - Leaf fibers (e.g., abaca, agave, banana, cantala, caroa, curaua, date palm, fique, henequen, istle, Mauritius hemp, piassava, pineapple, phormium, raphia, sansevieria, sisal)
  - Seed/fruit fibers (e.g., coconut, coir, cotton, kapok, milkweed hairs, loofah, oil palm, sponge gourd)
  - Wood fibers (softwood and hardwood)
  - Stalk fibers (derived from stalks of barley, maize, oat, rice, wheat, and other crops)
  - Cane, grass, and reed fibers (e.g., albardine, bamboo, bagasse, canary, corn, esparto, rape, papyrus, sabai).
- Animal fibers: Animal fibers generally compose of proteins such as collagen, keratin, and fibroin. They are classified as animal wool or hairs (e.g., alpaca, angora wool, bison, camel, cashmere, mohair, goat hair, horse hair, lamb's wool, qiviut, yak wool, etc.), silk fibers (e.g., mulberry silk cocoons, tussah silkmoths, spider silk), and keratin fiber (e.g., bird and chicken feathers).
- Mineral fibers: Mineral fibers include the asbestos group (chrysotile, amosite, crocidolite, tremolite, anthophyllite, and actinolite), fibrous brucite, and wollastonite.

4.2.1.2 Man-made fibers

Man-made fibers are fibers in which either the basic chemical units have been formed by chemical synthesis followed by fiber formation or the polymers from natural sources have been dissolved and regenerated after passage through a spinneret to form fibers. Those fibers made by chemical synthesis are often called synthetic fibers, while fibers regenerated from natural polymer sources are called regenerated fibers or natural polymer fibers (Needles, 2001). The regenerated fibers include viscose/cuprammonium rayon (the fiber is mainly cellulose), cellulose ester, protein, and miscellaneous natural polymer fibers. Synthetic fibers can be classified according to their chemical structure as follows: polyamides, polyesters, polyvinyl derivatives, polyolefins, polyurethanes, and miscellaneous synthetic fibers (Gordon Cook, 1984).

4.2.1.3 Nanofillers

Nanofillers are defined as nano-objects with one, two, or three external dimensions in the size range from approximately 1—100 nm (i.e., nanoscale). According to the International Organization for Standardization (ISO) technical specification ISO/TS 80004-2:2015, nanofillers can be classified as three different types: (1) nanoplate (a nano-object with one external dimension at the nanoscale); (2) nanofiber (a nano-object with two external dimensions at the nanoscale) [e.g., hollow nanofiber—nanotube; rigid nanofiber—nanorod; and electrically conducting nanofiber—nanowire]; and (3) nanoparticle (a nano-object with three external dimensions in the nanoscale). Nanofillers play important role in modifying and improving physical, mechanical, optical, electrical, and thermal properties of polymer-based composites (Saba et al., 2014). The most commonly used nanofillers are nanoclays (morphology of layered silicate), nano-oxides, carbon nanotubes (CNT), polyhedral oligomeric sislesquioxanes (POSS), expanded graphite, carbon black, and fullerenes (Tables 4.1 and 4.2).

4.2.2 Polymer matrices

The important functions of polymer matrices are to bond fibers together and to transfer loads to the fibers. The polymer matrices can also provide a good surface finish quality of the composites and protect reinforcing fibers against chemical attack. They are classified as either thermosetting or thermoplastic resins.

4.2.2.1 Thermosetting resins

Thermosetting resins undergo chemical reactions (curing process) that crosslink the polymer chains and thus connect the entire matrix together in a three-dimensional network. Once cured, they cannot be remelted or reformed. Thermosetting resins tend to have high dimensional stability, high-temperature resistance, and good resistance to solvents because of their three-dimensional cross-linked structure (U.S. Congress, Office of Technology Assessment, June 1988). The most frequently used thermosetting resins are polyesters, vinylesters, epoxies, phenolics, polyamides (PA), and bismaleimides (BMI).

Table 4.1 Chemical composition of some important natural fibers (Mohanty et al., 2000; Jawaid and Abdul Khalil, 2011; Faruk et al., 2012)

Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Pectin (wt%)
Bast				
Flax	71	18.6–20.6	2.2	2.3
Hemp	70.2–74.4	17.9–22.4	3.7–5.7	0.9
Jute	61–71.5	13.6–20.4	12–13	0.2
Kenaf	31–39	21.5	15–19	–
Ramie	68.6–76.2	13.1–16.7	0.6–0.7	1.9
Leaf				
Abaca	56–63	20–25	7–9	–
Banana	60–65	19	5–10	–
Curaua	73.6	9.9	7.5	–
Henequen	77.6	4–8	13.1	–
PALF	70–82	–	5–12	–
Sisal	67–78	10.0–14.2	8.0–11.0	10.0
Seed				
Cotton	82.7	5.7	–	–
Fruit				
Coir	36–43	0.15–0.25	41–45	3–4
Oil palm	65	–	29	–
Wood				
Hardwood	31–64	25–40	14–34	–
Softwood	30–60	20–30	21–37	–
Stalk				
Wheat straw	38–45	15–31	12–20	–
Rice husk	35–45	19–25	20	–
Rice straw	41–57	33	8–19	–
Cane/grass				
Bagasse	55.2	16.8	25.3	–
Bamboo	26–43	30	21–31	–

Table 4.2 **Mechanical properties of natural and man-made fibers (Ramamoorthy et al., 2015; Mohanty et al., 2000; Jawaid and Abdul Khalil, 2011; Hyer, 2009)**

Fiber	**Density (g cm^{-3})**	**Diameter (μm)**	**Elongation (%)**	**Tensile strength (MPa)**	**Young's modulus (GPa)**
Bast					
Flax	1.4–1.5	5–38	1.2–3.2	345–1500	27.6–80
Hemp	1.48	10–51	1.6	550–900	70
Jute	1.3–1.46	5–25	1.5–1.8	393–800	10–30
Kenaf	1.2	12–36	2.7–6.9	295	–
Ramie	1.5	18–80	2.0–3.8	220–938	44–128
Leaf					
Abaca	1.5	–	3.0–10	400	12
Banana	1.35	13.16	5.3	355	33.8
Curaua	1.4	–	3.7–4.3	500–1150	11.8
Henequen	1.4	–	3–4.7	430–580	–
PALF	1.5	20–80	1–3	170–1627	82
Sisal	1.33–1.5	7–47	2.0–3.0	400–700	9–38
Seed					
Cotton	1.5–1.6	12–35	3.0–10.0	287–597	5.5–12.6
Fruit					
Coir	1.2	–	15.0–30.0	175–220	4–6
Oil palm EFB	0.7–1.55	19.1–25.0	2.5	248	3.2
Wood					
Softwood kraft pulp	1.5	33	4.4	1000	40
Cane/glass					
Bagasse	1.2	10–34	1.1	20–290	19.7–27.1
Bamboo	0.6–1.1	–	–	140–230	11–17
Man-made					
PAN-based Carbon (IM)	1.78–1.82	8–9	1.0	2410–2930	228–276
PAN-based Carbon (HM)	1.67–1.9	7–10	0.5	2070–2900	331–400
PAN-based Carbon (UHM)	1.86	7–10	0.3–0.4	1720	517

(*Continued*)

Table 4.2 (Continued)

Fiber	Density (g cm^{-3})	Diameter (μm)	Elongation (%)	Tensile strength (MPa)	Young's modulus (GPa)
Rayon	1.53–1.66	6.5	1.5–2.5	620–2200	41–393
E-glass	2.54	8–14	1.8–3.2	3450	72.4
S-glass	2.49	10	5.7	4590	85.5
Aramid (Kevlar-29)	1.44	12	3–4	2760	62
Aramid (Kevlar-49)	1.48	12	2.2–2.8	2800–3792	131

Note: EFB, empty-fruit bunches; PALF, pineapple leaf fiber; PAN, polyacrylonitrile; IM, intermediate modulus; HM, high modulus; UHM, ultra-high modulus.

4.2.2.2 Thermoplastic resins

Unlike thermosetting resins, thermoplastic molecules do not crosslink and they can be melted by heating and solidified by cooling, which render them capable of repeated reshaping and reforming. They are, in general, ductile and tougher than thermosetting resins and are widely used for nonstructural applications without reinforcements and fillers (Mallick, 2007). Thermoplastic resins offer attractive mechanical properties such as excellent tensile strength and stiffness, good compression and fatigue strength, high dimensional stability, and excellent durability and damage tolerance. In addition, they have good wear-resistant and flame-retardant characteristics, which are suitable for various applications especially aerospace (McKague, 2001). Typical thermoplastic resins include polypropylene (PP), polyvinylidene fluoride (PVDF), polymethyl methacrylate (PMMA, also known as acrylic), polyphenylene sulfide (PPS), polyether etherketone (PEEK), polyetherimide (PEI), and polyetherketone ketone (PEKK). Comparisons on qualitative characteristics of thermoplastic and thermosetting resins are shown in Table 4.3.

4.2.3 Manufacturing processes for PMCs

Manufacturing processes of PMCs can be grouped into three categories: short-fiber suspension methods; squeeze flow methods; and porous media methods (Astrom, 2001). Short-fiber suspension methods involve the transport of fibers (usually short discontinuous fibers) and resin (either thermosetting or thermoplastic) as a suspension into a mold or through a die to form the composite. Injection molding, compression molding, and extrusion processes are included in this category. Squeeze flow methods include fibers (usually continuous or long discontinuous fibers) partially or fully preimpregnated with thermoplastic resin. Pultrusion, thermoforming (thermoplastic sheet forming), and tape winding processes fall under

Table 4.3 Qualitative comparisons of thermoplastic and thermosetting resins (McKague, 2001)

Characteristic	Thermoplastics	Thermosets
Tensile properties	Excellent	Excellent
Stiffness properties	Excellent	Excellent
Compression properties	Good	Excellent
Compression strength after impact	Good to excellent	Fair to excellent
Bolted joint properties	Fair	Good
Fatigue resistance	Good	Excellent
Damage tolerance	Excellent	Fair to excellent
Durability	Excellent	Good to excellent
Maintainability	Fair to poor	Good
Service temperature	Good	Good
Dielectric properties	Good to excellent	Fair to good
Environmental weakness	None, or hydraulic fluid	Moisture
NBS smoke test performance	Good to excellent	Fair to good
Processing temperature, °C (°F)	343–427 (650–800)	121–315 (250–600)
Processing pressure, MPa (psi)	1.38–2.07 (200–300)	0.59–0.69 (85–100)
Lay-up characteristics	Dry, boardy, difficult	Tack, drape, easy
Debulking, fusing, or heat tacking	Every ply if part is not flat	Typically every 3 or more plies
In-process joining options	Co-fusion	Co-cure, co-bond
Post-process joining options	Fastening, bonding, fusion	Fastening, bonding
Manufacturing scrap rates	Low	Low
Ease of prepregging	Fair to poor	Good to excellent
Volatile-free prepreg	Excellent	Excellent
Prepreg shelf life and out time	Excellent	Good
Health/safety	Excellent	Excellent

Note: NBS, National Bureau of Standards.

this category. Porous media methods compose continuous fibers impregnated with thermosetting resin (due to its low viscosity) to form the composite in an open or a closed mold. Liquid composite molding, thermoset pultrusion, filament winding, and autoclave processes are belonging to this category. Fig. 4.1 shows an overview of manufacturing processes for PMCs.

4.3 Hybrid composites and their mechanical properties

4.3.1 Introduction

Hybrid composites are defined as composite materials consisting of two or more different reinforcing fibers impregnated in the same matrix. The purpose of

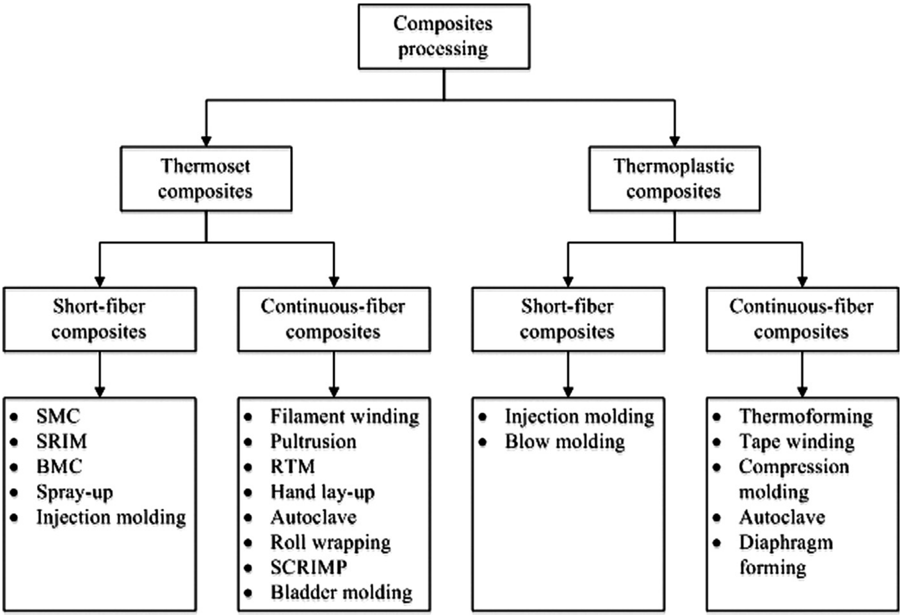

Figure 4.1 Manufacturing Processes for PMCs (Mazumdar, 2001).

hybridization is to achieve tailor-made properties of polymer composites and to take advantages of constituent materials in the composites. There are several types of hybrid composites depending on the way the constituent materials are mixed (Chamis and Lark, 1977; Fukuda, 1984; Pegoretti et al., 2004; Wang et al., 2008). According to Chamis and Lark (1977), there are four general categories of hybrid composites including: (1) interply hybrids; (2) intraply hybrids; (3) interply/intraply hybrids; and (4) superhybrids. The interply hybrids consist of plies from two or more unidirectional composites stacked in a specified sequence. Intraply hybrids include two or more different fibers mixed in the same ply. Interply/intraply hybrids compose of plies of intraply and interply hybrids stacked in a specified sequence. Superhybrids compose of metal foils or metal composite plies stacked in a specified sequence. The term "hybrid" or "synergistic" effect is usually used to imply that the initial failure strain of a hybrid composite (corresponding to the failure of low-elongation fibers in a hybrid) is greater than failure strain of a low-elongation, non-hybrid composite (Fukuda, 1984). Brittle inorganic fibers and ductile organic fibers are often combined to make hybrid composites such as aramid/glass, palm/glass, mineral fiber/glass, etc. (Wang et al., 2008). Hybrid biocomposites are defined as the combination of two or more different natural fibers (biofibers) in a matrix or a combination of biofibers and synthetic fibers in a matrix. Glass fibers are generally used to improve the mechanical properties of natural-fiber composites. The following sections discuss mechanical properties of various hybrid natural/synthetic fiber composites.

4.3.2 Hybrid natural fiber-reinforced composites

4.3.2.1 Hybrid bagasse/jute fiber-reinforced composites

Jute is one of the most well-known plant (vegetable) fibers, largely found in Asian countries like Bangladesh, China, India, Nepal, and Thailand (they produce about 95% of the global production of jute fibers) (Alves et al., 2010). It is a lignocellulosic bast fiber having inherent advantages such as renewable nature, biodegradability (associated with environmentally friendly), high strength and initial modulus over other fibers (Saw et al., 2012). Sugar-cane bagasse (generally called "bagasse") is one of the largest cellulosic agro-industrial byproducts. It is a lingo-cellulosic residue (byproduct) of the sugar industry and is major used by the sugar factories as fuel for the boilers. Bagasse offers many advantages over other crop residues (e.g., rice and wheat straw) and agricultural residues because of its low ash contents (Pandey et al., 2000). It is typically found in tropical countries such as Brazil, India, China, and Thailand (Table 4.4).

Saw and Datta (2009) studied mechanical properties of hybrid polymer composites reinforced with short bagasse fiber (BF) and short jute fiber (JF) bundles. Epoxidized phenolic novolac (EPN) was used as the resin matrix. Different fiber ratios and fiber surface treatments were investigated. JF bundles were treated by alkali solution (a.k.a. sodium hydroxide—NaOH) while BF bundles were either untreated or modified by chlorine dioxide (ClO_2) and furfuryl alcohol ($C_5H_6O_2$). The purpose of fiber surface modification was to create quinones in the lignin portions of BF bundles. The quinones reacted with the furfuryl alcohol to improve adhesion ability of the modified BF bundles. The results showed that the hybridization of the modified BF and alkali-treated JF bundles in the EPN resin matrix resulted in higher tensile, flexural, and impact properties in comparison to those of the unmodified BF bundles. The optimal mechanical properties were obtained when the BF/JF ratio was 50:50 (Table 4.5).

4.3.2.2 Hybrid bamboo fiber-reinforced composites

Bamboo is known as one of the most attractive biofibers because it has several advantages such as small environmental load, renewability, rapid growth, and relatively high strength compared to other natural fibers (e.g., jute and cotton) (Takagi and Ichihara, 2004). Asian countries such as China and India produce over 80% of the worldwide availability of bamboo fiber (Han et al., 2008).

Okubo et al. (2009) developed novel hybrid biocomposites consisting of a biodegradable poly-lactic acid (PLA) matrix reinforced with bamboo fiber bundles and microfibrillated cellulose (MFC). MFC is a cellulosic material with expanded high-volume cellulose and usually consists of aggregates of cellulose microfibrils. Its diameter is in the range of 20−60 nm and it has a length of several micrometers (Lavoine et al., 2012). Various terms are used to describe MFC in the literature including microfibril, microfibril aggregates, microfibrillar cellulose, nanofibril, nanofiber, nanofibrillar cellulose, and fibril aggregates (Siró and Plackett, 2010). Okubo et al. (2009) investigated the influence of MFC dispersion on the properties

Table 4.4 Hybrid biocomposites and their manufacturing processes

Hybrid biocomposites	Resin	Chemical treatments	Manufacturing processes	References	Year
All natural fibers					
Bagasse/jute	EPN	Chlorine dioxide and furfuryl alcohol (bagasse); Alkali (jute)	Hand lay-up and compression molding	Saw and Datta (2009)	2009
Bamboo/MFC	PLA	Alkali (bamboo)	Injection molding	Okubo et al. (2009)	2009
Banana/kenaf	UP	Alkali or sodium lauryl sulfate (SLS)	Compression molding	Thiruchitrambalam et al. (2009)	2009
Banana/sisal	Epoxy	Untreated	Hand lay-up	Venkateshwaran et al. (2011)	2011
Coconut/cork	HDPE	Untreated	Twin-screw extrusion and compression molding	Fernandes et al. (2013)	2013
Coir/silk	UP	Alkali treatment	Hand lay-up	Khanam et al. (2009)	2009
Corn husk/kenaf	PLA	Untreated	Injection molding	Kwon et al. (2014)	2014
Cotton/jute	Phenolic novolac	Untreated	Compression molding	De Medeiros et al. (2005)	2005
Cotton/kapok	UP	Alkali treatment	Hydraulic compression molding	Mwaikambo and Bisanda (1999)	1999
Cotton/ramie	UP	Untreated	Compression molding	Paiva Júnior et al. (2004)	2004
Jute/oil palm EFB	Epoxy	Untreated	Compression molding	Jawaid et al. (2011)	2011
Kenaf/PALF	HDPE	Untreated	Compression molding	Aji et al. (2011)	2011
Roselle/sisal	UP	Untreated	Hydraulic compression molding	Athijayamani et al. (2009)	2009
Silk/sisal	UP	Alkali treatment	Hand lay-up	Khanam et al. (2007)	2007
Synthetic/natural fibers					
Aramid/coir	Epoxy	Untreated	Hand lay-up	Rashid et al. (2011)	2011
Aramid/kenaf	Epoxy	Untreated	Hand lay-up	Yahaya et al. (2016)	2016
Aramid/sisal	Phenolic	Untreated	Hot press	Zhong et al. (2011)	2011

Basalt/flax-hemp	Epoxy	Untreated	Vacuum infusion	Petrucci et al. (2013)	2013
Basalt/flax-glass	Epoxy	Untreated	Vacuum infusion	Petrucci et al. (2013)	2013
Basalt/glass-hemp	Epoxy	Untreated	Vacuum infusion	Petrucci et al. (2013)	2013
Carbon/basalt-flax	Epoxy	Untreated	Hand lay-up and vacuum bagging	Nisini et al. (2016)	2016
Carbon/flax	Epoxy	Others	Vacuum bagging	Fiore et al. (2012)	2012
Carbon/sisal	UP	Alkali treatment	Hand lay-up	Khanam et al. (2010)	2010
Glass/abaca	Orthophthalic	Untreated	Hand lay-up	Venkatasubramanian and Raghuraman (2015)	2015
Glass/abaca-banana	Orthophthalic	Untreated	Hand lay-up	Venkatasubramanian and Raghuraman (2015)	2015
Glass/banana	Orthophthalic	Untreated	Hand lay-up	Venkatasubramanian and Raghuraman (2015)	2015
Glass/bamboo	PP	MAPP	Injection molding	Thwe and Liao (2003)	2003
Glass/coir	UP	PVA	Hand lay-up	Jayabal et al. (2011)	2011
Glass/curaua	UP	AAP	Hydraulic press	Almeida Júnior et al. (2012)	2012
Glass/jute	Polyester	Untreated	Hand lay-up	Ahmed Sabeel and Vijayarangan (2008)	2008
Glass/kapok	Polyester	Alkali treatment	Hand lay-up	Venkata Reddy et al. (2008)	2008
Glass/kenaf	Epoxy	Untreated	Modified SMC	Davoodi et al. (2010)	2010
Glass/PALF	Polyester	Untreated	Hydraulic press	Mishra et al. (2003)	2003
Glass/palmyra	Rooflite	Untreated	Hydraulic compression molding	Velmurugan and Manikandan (2007)	2007
Glass/silk	Epoxy	Untreated	Hand lay-up	Priya and Rai (2006)	2006
Glass/sisal	Polyester	Alkali, cyanoethylation, and acetylation treatments	Hydraulic press	Mishra et al. (2003)	2003

Note: EFB, empty-fruit bunches; PLA, poly-lactic acid; UP, unsaturated polyester; HDPE, high-density polyethylene; PALF, pineapple leaf fiber; MFC, microfibrillated cellulose; EPN, epoxidized phenolic novolac; PP, Polypropylene; MAPP, maleic anhydride polypropylene; PVA, polyvinyl acetate; AAP, acetyl acetone peroxide; SMC, sheet molding compound.

Table 4.5 **Mechanical properties of hybrid biocomposites**

Hybrid biocomposites	Fiber ratio (by weight or volume)	Flexural modulus (GPa)	Flexural strength (MPa)	Tensile modulus (GPa)	Tensile strength (MPa)	Impact strengt (kJ m^{-2})	References
Natural fibers							
Bagasse/jute	Bagasse fiber bundles (untreated) and jute fiber bundles (treated)						Saw and Datta (2009)
	0:100	0.645	31.15	0.302	11.45	6.90	
	20:80	0.789	36.46	0.356	16.02	7.46	
	35:65	1.101	45.32	0.420	19.45	9.53	
	50:50	1.480	55.63	0.492	23.07	10.66	
	65:35	1.311	51.19	0.399	21.15	8.33	
	100:0	0.502	26.78	0.227	9.87	6.67	
	Bagasse fiber bundles (treated) and jute fiber bundles (treated)						
	20:80	1.178	42.72	0.526	18.72	10.00	
	35:65	1.484	54.57	0.635	22.57	13.33	
	50:50	1.748	65.22	0.753	26.77	15.93	
	65:35	1.518	60.12	0.704	23.54	10.93	
	100:0	0.632	30.78	0.286	11.20	8.66	
Bamboo/MFC	MFC/PLA composites (milled to 5 μm)						Okubo et al. (2009)
	1 wt% of MFC	–	–	4.61 ± 0.27	45.9 ± 4.1	–	
	2 wt% of MFC	–	–	3.95 ± 0.14	51.7 ± 2.3	–	
Banana/kenaf	50:50, nonwoven hybrid						Thiruchitrambalam et al. (2009)
	10% NaOH treatment	–	57.2	–	44	13	
	10% SLS treatment		60.8		50	16	
	50:50, woven hybrid						
	10% NaOH treatment	–	62.0	–	50	18	
	10% SLS treatment		68.0		54	21	

Banana/sisal	100:0	8.920	57.33	0.642	16.12	13.25	Venkateshwaran et al. (2011)
	75:25	9.025	58.51	0.662	17.39	15.57	
	50:50	9.130	59.69	0.682	18.66	17.90	
	25:75	9.235	60.87	0.703	19.93	20.22	
	0:100	9.340	62.04	0.723	21.20	22.54	
Coconut/cork	10:44:44:2 (wt% of coconut/cork/HDPE/ coupling agent)	–	–	0.599 ± 0.02	20.4 ± 0.3	–	Fernandes et al. (2013)
Coir/silk	Alkali treatment						Khanam et al. (2009)
	10 mm fiber	–	39.53	–	15.01	–	
	20 mm fiber	–	45.07	–	17.24	–	
	30 mm fiber	–	42.02	–	16.14	–	
Corn husk/kenaf	0:30 (PLA 70 wt%)	–	–	2.117	–	–	Kwon et al. (2014)
	15:15 (PLA 70 wt%)	–	–	1.547	–	–	
	30:0 (PLA 70 wt%)	–	–	1.221	–	–	
Cotton/jute	23.7:76.3 (jute fabric type III)						De Medeiros et al. (2005)
	Test angle, 0°	9.9 ± 0.8	136.7 ± 4.0	7.1 ± 0.3	59.4 ± 1.7	9.3 ± 0.9	
	Test angle, 45°	8.4 ± 0.7	84.6 ± 4.7	4.6 ± 0.1	21.1 ± 1.4	7.5 ± 1.0	
	Test angle, 90°	7.2 ± 0.7	58.3 ± 5.4	4.1 ± 0.1	14.6 ± 0.5	5.5 ± 1.0	

(*Continued*)

Table 4.5 **(Continued)**

Hybrid biocomposites	Fiber ratio (by weight or volume)	Flexural modulus (GPa)	Flexural strength (MPa)	Tensile modulus (GPa)	Tensile strength (MPa)	Impact strengt (kJ m^{-2})	References
Cotton/kapok	3:2						Mwaikambo and Bisanda (1999)
	Untreated ($V_f = 60\%$)	–	–	0.884	55.70	110.53	
	Alkali treatment ($V_f = 43\%$)	–	–	1.635	52.87	119.25	
	Non-accelerated weather condition ($V_f = 46.6$ %)	0.709	52.40	–	–	–	
	Accelerated weather condition (V_f=46.6 %)	0.703	39.55	–	–	–	
Cotton/ramie (ramie fibers placed longitudinally to the mould length)	10.8:41.1 (0° composite)	–	–	–	90.9 ± 12.7	–	Paiva Júnior et al. (2004)
	11.9:45.5 (0° composite)	–	–	–	117.3 ± 13.3	–	
	11.9:45.1 (0° composite)	–	–	–	118.0 ± 6.5	–	
Jute/OPEFB	1:4						Jawaid et al. (2011)
	OPEFB/Jute/OPEFB	–	–	2.39	25.53	–	
	Jute/OPEFB/Jute	–	–	2.59	27.41	–	
	Pure OPEFB	–	–	2.23	22.61		
	Pure jute	–	–	3.89	45.55		

Kenaf/PALF	1:1 (At 0.25 mm fiber length and 60% fiber loading)	4.114	34.01	0.874	32.24	6.167	Aji et al. (2011)
Roselle/sisal	1:1						Athijayamani et al. (2009)
	Dry condition, fiber length = 15 cm	–	76.5	–	58.7	1.30	
	Wet condition, fiber length = 15 cm	–	62.9	–	44.9	1.28	
Silk/sisal	1:1, fiber length = 20 mm						Khanam et al. (2007)
	Untreated	–	46.18	–	18.95	–	
	Alkali treatment	–	54.74	–	23.61	–	
Natural/synthetic fibers							
Aramid/coir	Coir (warp) + Kevlar (weft)	–	16.70	–	–	66.82	Azrin Hani Abdul et al. (2011)
	Kevlar (warp) + Coir (weft)	–	25.16	–	–	61.12	
Aramid/kenaf	Fiber volume fraction ratio						Yahaya et al. (2016)
	21.2:10.46 (woven)	–	94.21	3.337	145.8	51.41	
	16.78:16.51 (unidirectional)	–	100.30	2.368	115.36	41.24	
	21.39:9.57 (mat)	–	35.82	1.888	101.56	24.64	
Aramid/sisal	20:80 (Degree of surface microfibrillation of sisal fiber = 32 SR)	–	–	–	26.9	–	Zhong et al. (2011)
Basalt/flax-hemp	7.85:5.57:9.11 (V_f ratio)	7.45 ± 0.67	128.46 ± 29.14	7.69 ± 0.63	115.97 ± 3.77	–	Petrucci et al. (2013)
Basalt/flax-glass	7.16:11.72:2.30 (V_f ratio)	8.02 ± 0.68	137.95 ± 19.85	6.64 ± 0.49	153.16 ± 17.41	–	Petrucci et al. (2013)
Basalt/glass-hemp	11.38:2.59:8.56 (V_f ratio)	5.90 ± 0.42	126.22 ± 13.63	8.11 ± 0.60	128.84 ± 8.70	–	Petrucci et al. (2013)

(*Continued*)

Table 4.5 **(Continued)**

Hybrid biocomposites	Fiber ratio (by weight or volume)	Flexural modulus (GPa)	Flexural strength (MPa)	Tensile modulus (GPa)	Tensile strength (MPa)	Impact strengt (kJ m^{-2})	References
Carbon/ basalt-flax	12:14:27 (wt%)						Nisini et al. (2016)
	Laminate N1	16.42 ± 0.55	256.08 ± 9.79	16.20 ± 0.52	189.23 ± 3.75	–	
	Laminate N2	17.08 ± 1.00	286.67 ± 15.26	16.89 ± 0.31	185.24 ± 5.66	–	
Carbon/flax	51.1 ± 3.3 (total fiber content)	23.84 ± 0.74	160.42 ± 10.46	6.48 ± 0.32	288.03 ± 30.23	–	Fiore et al. (2012)
Carbon/sisal	18% NaOH treatment						Khanam et al. (2010)
	0:100	5.32	138.78	1.96	78.22	–	
	25:75	6.52	140.89	1.99	84.74	–	
	50:50	8.69	158.31	2.17	93.97	–	
	75:25	11.33	169.14	2.78	107.51	–	
	100:0	13.47	176.53	2.98	122.11	–	
Glass/abaca	60% fiber + 40% resin	0.621	68.23	0.750	93.29	1.458	Venkatasubramanian and Raghuraman (2015)
Glass/abaca-banana	60% fiber + 40% resin	0.222	82.85	0.567	97.28	1.090	Venkatasubramanian and Raghuraman (2015)
Glass/banana	60% fiber + 40% resin	0.235	139.66	0.750	96.00	1.315	Venkatasubramanian and Raghuraman (2015)

Glass/bamboo	1:7	–	–	4.8	24.4	–	Thwe and Liao (2003)
Glass/coir	Glass/glass/coir Glass/coir/glass Coir/glass/glass	2.358 2.881 2.361	77 65 71	1.349 1.453 1.373	51 47 52	144 101 140	Jayabal et al. (2011)
Glass/curaua	$V_f = 40\%$						Almeida Júnior et al. (2012)
	0:100 70:30 100:0	– – –	– – –	– – –	– – –	32.6 ± 1.7 149 ± 17 153.9 ± 19.7	
Glass/jute	60:40	12.38	159.85	12.46	124.44	–	Ahmed Sabeel and Vijayarangan (2008)
Glass/kapok	Untreated hybrid composites						Venkata Reddy et al. (2008)
	0:100 25:75 50:50 75:25 100:0	– – – – –	– – – – –	0.975 1.133 1.182 1.229 2.469	67.34 78.05 82.11 102.55 112.87	– – – – –	
	Alkali-treated hybrid composites						
	0:100 25:75 50:50 75:25 100:0	– – – – –	– – – – –	1.426 1.605 1.645 2.363 2.469	79.1 94.1 98.6 107.6 112.8	– – – – –	

(*Continued*)

Table 4.5 **(Continued)**

Hybrid biocomposites	Fiber ratio (by weight or volume)	Flexural modulus (GPa)	Flexural strength (MPa)	Tensile modulus (GPa)	Tensile strength (MPa)	Impact strengt (kJ m^{-2})	References
Glass/kenaf	–	12.0	223.6	7.5	151.8		Davoodi et al. (2010)
Glass/PALF	8.6:16.4	–	99	–	71	–	Mishra et al. (2003)
Glass/palmyra	Randomly mixed glass/ palmyra hybrid composites, $V_f = 55\%$ (by weight), Palmyra fiber length = 50 mm	3.54	59.19	1.515	42.65	60.5	Velmurugan and Manikandan (2007)
Glass/silk	0:100 10:90 20:80 30:70 40:60 50:50	1.503 1.847 3.015 4.221 5.251 5.440	60.81 94.31 97.31 106.5 108.2 114.5	0.844 0.891 0.922 0.944 0.992 1.008	58.35 60.99 64.87 70.12 77.81 84.04	– – – – – –	Priya and Rai (2006)
Glass/sisal	5.7:24.3 (wt%)	–	138	–	98	–	Mishra et al. (2003)

Note: OPEFB, oil palm empty-fruit bunches; PALF, pineapple leaf fiber; MFC, microfibrillated cellulose; PLA, poly-lactic acid; SLS, sodium lauryl sulfate; SR, Schopper–Riegler; V_f, fiber volume fraction.

of bamboo fiber-reinforced composites. MFC was dispersed in a PLA polymer matrix using a calendering process (usually employed to smooth or compress a material) with a three-roll mill. The purpose of using PLA, a bio-based and biodegradable polymer matrix, is to enhance interfacial bonding with the MFC. Bamboo fiber bundles have diameters of about 200 μm whereas MFC has much smaller diameters of a few microns. The MFC/PLA mixture was processed in the three-roll mill at progressively decreasing gap settings of 70, 50, 35, 25, 15, 10, and 5 μm. Significant increase in fracture energy (nearly 200%) was achieved when 1 wt% of MFC was added to the PLA matrix and the MFC/PLA composite was milled at the minimum gap setting of 5 μm. The hybrid bamboo/MFC/PLA composite, including the bamboo fiber and the PLA matrix reinforced with 1 wt% of MFC, was found to effectively prevent sudden crack path through the reinforcing bamboo fiber and result in substantial fracture strength improvements.

4.3.2.3 Banana/kenaf and banana/sisal hybrid composites

Banana fiber (extracted from the bark of banana trees) is a potential reinforcing material for various polymer composites. It has superior mechanical properties such as good tensile strength and modulus, resulting from its high cellulose content and low microfibrillar angle (Liu et al., 2009). According to FAOStat (FAOStat, September 12, 2016), the five largest countries of banana production in 2013–2014 are India, China (mainland), Philippines, Brazil, and Ecuador.

Kenaf fiber is extracted from bast fiber of kenaf plants. It is a promising reinforcement element for polymer composites because of its excellent mechanical properties, renewability, and ecofriendly. On the other hand, sisal is known as a durable fiber and one of the toughest reinforcing materials. Its composites have high impact strength and moderate tensile and flexural properties compared to other natural fiber-reinforced composites. It has been used for various applications such as marine and agriculture to make ropes, twines, cords, bagging and rugs, etc. (Jacob et al., 2004). The main disadvantage associated with natural fibers, including sisal and kenaf fibers, is their poor interfacial bonding with a polymer matrix (Akil et al., 2011).

Thiruchitrambalam et al. (2009) investigated woven and nonwoven hybrid banana/kenaf fiber reinforced with unsaturated polyester matrix. The fiber contents were kept constant at 40% with 50:50 ratio of banana and kenaf fiber-reinforced composites. The fibers were 30-minute treated with either 10% of NaOH solution or 10% of sodium lauryl sulfate (SLS). The specimens with SLS treatment showed better improvement in the mechanical properties than the ones with alkali treatment. The SLS treatment resulted in enhanced tensile, flexural, and impact strength of both woven and nonwoven hybrid banana/kenaf composites (Table 4.5).

Mechanical properties of hybrid banana/sisal fiber reinforced with epoxy matrix were evaluated by Venkateshwaran et al. (2011). The hybridization of banana and sisal fibers in the epoxy composite resulted in 16% increase in tensile strength, 4% increase in flexural strength, and 35% increase in impact strength. The fiber ratio of 50:50 by weight was found to enhance the mechanical properties of the banana/sisal hybrid composite while decreasing its moisture uptake.

4.3.2.4 Hybrid coconut/cork fiber-reinforced composites

Coconut fiber (a.k.a. “coir”) is a natural fiber extracted from coconut trees, which mainly grows in tropical regions in Asia countries such as India, Vietnam, and Thailand. Cork fiber is harvested from the bark of a specific species of cork oak trees (*Quercus suber*). The cork oak tree naturally regrows its new cork bark, making it a renewable resource.

Fernandes et al. (2013) prepared hybrid composites from high-density polyethylene (HDPE) reinforced with cork powder and randomly distributed short coconut fibers. Coupling agent (CA) based on maleic anhydride was used to improve the compatibility and interfacial bonding between the fiber and matrix. The coconut/HDPE/cork hybrid composites resulted in 27% increase in elastic modulus and 47% increase in the tensile strength as compared with the cork/HDPE composite. In addition, the use of CA enhanced the elongation at break and tensile properties of the hybrid composites. The addition of 10 wt% of short coconut fibers and 2 wt% of CA was recommended for the better mechanical performance of the cork-based composites.

4.3.2.5 Hybrid coir/silk fiber-reinforced composites

Silk is a light, soft, thin, and continuous protein fiber, which is produced by various insects. Silk fiber is synthesized by the silkworm and spun in the form of a silk cocoon. The silkworm produces massive amount of silk proteins (fibroin and sericin, which are major components of silk cocoons) during the final stage of larval development (Mondal, 2007). Silk fiber is known as the strongest natural material with high specific strength and stiffness. It has excellent drape and wonderful luster but possesses a poor resistance to sunlight exposure.

Khanam et al. (2009) investigated the hybrid composites of coir/silk fiber reinforced with unsaturated polyester matrix. Different fiber lengths (10 mm, 20 mm, and 30 mm) were studied. Coir fibers were treated with NaOH solution. The purpose of the NaOH treatment was to remove hemicellulose and lignin from the coir fiber, which may result in a better fiber-matrix bonding. The 20 mm fiber length composites were found to have higher flexural and tensile strength compared to the 10 mm and 20 mm fiber length counterparts. The NaOH-treated coir/silk hybrid composites were proved to have significant improvement in compressive, flexural, and tensile strength properties, resulting from the enhanced interfacial bonding between the coir fiber interface and the polyester matrix.

4.3.2.6 Hybrid corn husk/kenaf fiber-reinforced composites

Agricultural wastes (e.g., rice husk, rice straw, and corn husk) produce large amount of raw natural fibers, which can be used as reinforcing materials in polymer composites. Corn husks are thin, leafy sheaths that cover the corn cobs and contains cellulose-rich fibers (Mahalaxmi et al., 2010). Kenaf is an important source of fiber for paper industry and other sectors.

Kwon et al. (2014) prepared hybrid biocomposites composed of kenaf fiber and corn husk flour reinforced with poly-lactic acid (PLA) matrix. The ratio of fiber/matrix by weight was fixed at 30:70 while various ratios of kenaf fiber and corn husk flour were evaluated. The influence of the aspect ratios of kenaf fibers (measured before and after passing through extrusion process) to the mechanical properties was investigated. The results indicated that the aspect ratio determined after extrusion did not influence the predicted values obtained by the Halpin−Tsai equation. It should be noted that the Halpin−Tsai model for the prediction of elastic behavior of composite materials is based on the geometry/orientation and elastic properties of the fibers and matrix. It assumes no interaction between the fiber and matrix in the composite. The difference of Young's modulus of fibers was found to affect the stress transfer from matrix to fiber. It was reported that a scale ratio between reinforcements of different aspect ratios may be a controlling factor in optimizing the mechanical properties of a hybrid biocomposite.

4.3.2.7 Hybrid cotton fiber-reinforced composites

Cotton fibers are unbranched, unicellular (single-cell) seed hairs (or seed trichomes) and being among the longest plant cells ever characterized (they can elongate up to approximately 3 cm). Unlike many plant secondary cell walls, the cotton fiber wall contains no lignin (Kim and Triplett, 2001). Cotton fibers are considered the world's most important fibers and widely used in textile industry. They have rich cellulose content and possess many advantages such as good strength, excellent drape, and high absorbency. According to FAOStat (FAOStat, September 12, 2016), the top 4 countries with largest production of cottonseed in 2013−2014 include China, India, United States, and Pakistan.

De Medeiros et al. (2005) investigated mechanical properties of hybrid cotton/jute woven fabrics reinforced with novolac type phenolic matrix. The results indicated that the mechanical properties of the hybrid cotton/jute fabric composites were strongly dependent on fiber orientation, fiber content, fiber-matrix adhesion, and fabric characteristics. The anisotropy of the composites depended upon the characteristics of fiber roving/fabric and increased with the increase of the test angle. The mechanical properties were found to be inversely proportional to the test angle as the specimens tested at zero degree with respect to the jute roving direction showed best overall performance. The composites tested at 45 and 90 degrees with respect to the jute fiber direction exhibited a controlled brittle failure while those tested at zero degree to the longitudinal direction displayed a catastrophic failure without control. Jute fiber was found to be a strong reinforcing material and the combination of jute and cotton in the fabric composites can avoid catastrophic failure mode.

Mwaikambo and Bisanda (1999) prepared hybrid cotton-kapok fiber fabric incorporated with unsaturated polyester matrix with varying fiber volume fraction (V_f). The fabric composites were either untreated or treated with 5% NaOH to improve fiber-matrix bonding. Mechanical properties of the cotton-kapok composites subjected or not subjected to accelerated weathering condition were evaluated. It was found that the composites with untreated fibers exhibited higher V_f values than those with alkali treatments. The untreated fibers improved the tensile strength of the composites while the alkali-treated fibers enhanced the composites' tensile modulus. The increase of V_f resulted in decreasing the impact strength for both treated and untreated composites. The composites subjected to accelerated weather conditions showed reductions in flexural strength and modulus.

Ramie fibers are obtained from the bast/stem of the ramie plant (*Boehmeria nivea*) of the nettle family, Utricaceae (Lodha and Netravali, 2002). Ninety-nine percent of ramie plants are cultivated in Asian countries such as China, Laos, Philippines, and Republic of Korea and one percent is grown in Americas such as Brazil. Hybrid composites of ramie/cotton plain weave fabric reinforced with unsaturated polyester resin were investigated by Paiva Júnior et al. (2004). The results indicated that ramie fibers have a great potential as reinforcing fibers in polymer composites. The contribution of the cotton fibers was negligible because of their poor alignments in the composites and the weak fiber-matrix interfacial bonding.

4.3.2.8 Hybrid jute/oil palm EFB fiber-reinforced composites

Oil palm (*Elaeis guineensis*) is one of the most economical perennial oil crops for its valuable oil-producing fruits in tropical regions such as West/Southwest Africa and Southeast Asia. In the oil extraction process, the fruits or nuts are first stripped from fruit bunches, leaving behind the empty-fruit bunches as waste (Law et al., 2007). The oil palm industries generate abundant amount of biomass which can be a waste disposal challenge if not properly used. Oil palm fibers are derived from two sources of oil palm tree including oil palm empty-fruit bunches (OPEFB) and mesocarp. OPEFB fibers are the most commonly used for composite materials because they contain highest composition of hemicellulose compared to coir, pineapple, banana, and even soft and hardwood fibers (Hassan et al., 2010).

Jawaid et al. (2011) prepared three-ply hybrid composites of jute/OPEFB fibers reinforced with epoxy resin. The ratio by weight of the jute/OPEFB composites was fixed at 1:4. The chemical resistance, void content, and tensile properties of the hybrid composites were investigated. The results indicated that the jute/OPEFB/jute and OPEFB/jute/OPEFB composites were strongly resistant to the following chemicals: benzene (C_6H_6), toluene (C_7H_8), carbon tetrachloride (CCl_4), water (H_2O), hydrochloric acid (HCl), 40% nitric acid (HNO_3), 5% acetic acid (CH_3COOH), 10% sodium hydroxide (NaOH), 20% sodium carbonate (Na_2CO_3), and 10% ammonium hydroxide (NH_4OH). The jute/OPEFB/jute composites showed less void content compared to the pure OPEFB and OPEFB/jute/OPEFB composites. This was attributed to the fact that the jute fiber mats were tightly packed and more compatible towards the epoxy resin. The high-strength jute fibers at the outer ply were able to withstand the tensile stress while the OPEFB fiber core absorbed the stresses and evenly distributed them in the composites. As a result, the hybrid jute/OPEFB had higher tensile strength and modulus compared to the pure OPEFB composite (Table 4.5). The hybrid composites also exhibited better adhesion to the matrix than the pure OPEFB composite.

4.3.2.9 Hybrid kenaf/PALF fiber-reinforced composites

Pineapple (*Ananas comosus*) is a tropical plant, a member of the bromeliad family (Bromeliaceae) native to South America, and the third most important tropical fruit crop after banana and mango (in terms of total global production of fruit weight) (Davis et al., 2015). Pineapple leaf fibers (PALFs) are extracted from pineapple leaves, which are a waste product of pineapple cultivation. PALFs show excellent mechanical properties due to its high cellulose content (70−82%) and high degree of crystallinity (44−60%) (Reddy and Yang, 2005). Kenaf fiber has superior mechanical properties such as excellent flexural and tensile strength and the combination of kenaf and PALF in a polymer composite may yield robust materials for various applications.

Aji et al. (2011) investigated the effect of fiber size and fiber loading on the mechanical properties of hybridized kenaf/PALF fibers reinforced with high-density polyethylene (HDPE). All tested specimens were prepared at kenaf/PALF fiber ratio of 1:1. Four types of fiber lengths (0.25, 0.5, 0.75, and 2 mm) were evaluated at varying percentages of fiber loadings (ranged from 10−70%). The 0.25 mm fiber size showed the best tensile and flexural properties while the 0.75 and 2 mm fiber sizes exhibited enhanced impact strength. The increase of fiber length resulted in reduction in some mechanical properties, which was attributed to fiber entanglement rather than fiber attrition. Tensile and impact strengths were found to be inversely proportional while flexural strength generally satisfied the rule of mixture. Hybridization effect (resulting from the synergistic strengthening of kenaf and PALF fibers) was clearly observed. Scanning electron microscopy (SEM) was used to evaluate the composites' surface and the results showed good adhesion between the matrix and fibers.

4.3.2.10 Hybrid sisal fiber-reinforced composites

Sisal (*Agave sisalana*) is a member of the Agavaceae family, which are hard-fiber plants originally from Central America and Mexico but widely cultivated and naturalized in many tropical countries in Americas, Africa, and Asia. Sisal fibers are extracted from the leaves of sisal plants. According to FAOStat (FAOStat, September 12, 2016), world production of sisal fibers in 2011 is about 411,102 tons. Top three producers of sisal fibers include Brazil, Mexico, and Tanzania. Sisal fibers are tough and strong and being widely used in composite materials as well as in paper/plastic industries.

Roselle (*Hibiscus sabdariffa*) is a species of Hibiscus native to West Africa. The Roselle plant is found in abundance in nature and primarily used for its bast fibers and its fruit. Roselle fibers have been widely used in composite materials and textile industry as their mechanical properties are comparable to other natural fibers such as kenaf and jute. Athijayamani et al. (2009) investigated the effect of moisture absorption (under wet conditions) on mechanical properties of short sisal and roselle fibers (with sisal/roselle fiber ratio of 1:1) reinforced with unsaturated polyester resin. Different fiber lengths and contents were considered. The results revealed that the tensile and flexural strength of the hybrid sisal/roselle composites increased with the increase of the fiber length and the fiber content at the dry condition. On the other hand, at the wet condition, significant strength reductions were observed for both tensile and flexural properties. The impact strength was found to be inversely proportional to the fiber content and fiber length at both wet and dry conditions.

Khanam et al. (2007) prepared polyester based hybrid composites of sisal and silk fibers. Sisal/silk fiber ratio was at 1:1 and different fiber lengths were evaluated. It was found that the composites with 20 mm fiber length had higher tensile, compressive, and flexural strength than those with 10 mm and 30 mm fiber lengths. Significant improvements in mechanical properties (tensile, compressive, and flexural strength) were observed for the hybrid composites with alkali-treated fibers.

4.3.3 Hybrid natural/synthetic fiber-reinforced composites

The natural and synthetic fibers can be combined in the same matrix to produce hybrid composites that offer a range of properties that cannot be obtained with a single kind of reinforcement (Khanam et al. 2009). The following sections discuss mechanical properties of hybrid composites of some common synthetic fibers (aramid, basalt, carbon, and glass) and natural fibers.

4.3.3.1 Hybrid aramid fiber-based composites

Rashid et al. (2011) investigated mechanical properties of hybrid coir/Kevlar reinforced epoxy composites. Kevlar is the registered trademark of the E.I. du Pont de Nemours and Company (a.k.a. DuPont) for their para-aramid fibers. Kevlar has a unique combination of high strength, high modulus, toughness and thermal stability. Coconut or coir fibers have been increasingly used as a reinforcing material due to their low cost and good mechanical properties. It was found that the coir/woven Kevlar composites exhibited highest impact strength while their flexural strength was lowest. The results showed that the hybrid composites of woven coir yarn (warp) and Kevlar yarn (weft) had the flexural and impact strength of 16.7 MPa and 66.82 kJ m^{-2}, respectively (Table 4.5). The results suggested that coir fibers are promising reinforcements for high-impact resistant application such as body armors.

Yahaya et al. (2016) presented an evaluation on the effect of kenaf fiber orientation on the mechanical properties of hybrid aramid/kenaf reinforced epoxy composites for military application. The effect of kenaf structure including woven, nonwoven unidirectional (UD), and mat fabrics was investigated. Aramid fabric (Kevlar 129) was the plain weaved structure. It was found that the nonwoven mat kenaf/Kevlar hybrid composite had relatively low density because of its high void contents. The tensile and Charpy impact strength properties of the woven kenaf/

Kevlar composite were higher compared with those of other hybrid composites. On the other hand, the flexural strength of the hybrid composites with the UD kenaf was slightly higher than that of the woven kenaf hybrid composite. The scanning electron micrograph revealed that the mat kenaf hybrid composites exhibited higher void content than the woven and UD kenaf composites.

Zhong et al. (2011) investigated the effect of surface microfibrillation of sisal fiber on the mechanical properties of hybrid aramid/sisal fiber-reinforced phenolic composites. The results showed that surface microfibrillation of sisal fibers significantly influenced the mechanical properties of the hybrid aramid/sisal composites. Microfibrils and aggregates formed on the sisal-fiber surface resulted in a larger contact area between sisal fibers and the phenolic matrix, thus producing stronger mechanical interlocking strength. In addition, the microfibrils and aggregates inhibited the formation of spontaneous cracks in the composites. As a result, the compression, tensile and fiber/matrix interfacial bonding strengths and wear resistance of the hybrid composites were significantly enhanced.

4.3.3.2 Hybrid basalt fiber-based composites

Petrucci et al. (2013) evaluated mechanical properties of hybrid basalt fiber-based composite laminates manufactured by vacuum infusion process. Basalt fibers are made from basalt, a type of igneous rock formed by volcanic lava. The basalt fibers were combined with either flax, hemp, or glass fibers in the composites. The test results suggested that the hybrid basalt/flax-glass exhibited best general performance among all investigated composites. The hybrid composites with hemp fibers showed relatively low layer-interface quality. SEM observations of the tested hybrid composite laminates exhibited the diffuse presence of fiber pull-out in hemp and flax fibers and all laminates showed a brittle failure.

4.3.3.3 Hybrid carbon fiber-based composites

Nisini et al. (2016) investigated mechanical and impact properties of ternary hybrid composite laminates with carbon, basalt, and flax fibers. All laminates were fabricated by hand lay-up technique and then consolidated by vacuum bagging process. Basalt and flax fiber-layers were sandwiched between carbon-fiber layers on the outer faces. It was found that the intercalation of basalt with flax fiber layers resulted in enhanced flexural and interlaminar strength. Two laminates with different stacking sequences of basalt and flax fiber layers exhibited insignificant improvement in impact performance.

Fiore et al. (2012) studied mechanical behavior of hybrid carbon/flax/epoxy composite for structural applications. Two different bidirectional flax fabrics were used to produce flax fabric reinforced plastic (FFRP) laminates using vacuum bagging process. The test results showed that the addition of one external carbon-fiber layer in the FFRP composites remarkably increased their mechanical properties. The hybrid carbon/flax composites were recommended for several applications such as nautical and automobile.

Khanam et al. (2010) prepared hybrid composites of carbon/sisal fibers reinforced with unsaturated polyester matrix. Tensile, flexural, and chemical resistance properties were evaluated. The tensile and flexural strength of the hybrid carbon/sisal composites increased with the increase of the carbon fiber loading. Significant improvement in tensile and flexural properties were observed for the hybrid composites with alkali treatment of sisal fibers. The chemical resistance test results indicated that all hybrid composites were strongly resistant to all chemicals except carbon tetrachloride (CCl_4).

4.3.3.4 Hybrid glass fiber-based composites

Venkatasubramanian and Raghuraman (2015) evaluated the mechanical behavior of hybrid composites consisting of abaca/banana and glass fibers reinforced with orthophthalic resins. The hybrid banana–abaca/glass composites showed higher tensile strength than the abaca/glass and banana/glass composites. Flexural strength of the banana/glass composites was found to be highest, attributable to the good adhesion properties of the banana fiber. The abaca/glass composites exhibited highest impact strength, resulting from the high strength and stiffness of the abaca fiber.

Thwe and Liao (2003) investigated durability of bamboo fiber-reinforced polypropylene (BFRP) composites and hybrid bamboo/glass fiber-reinforced polypropylene (BGRP) composites. The results indicated that both tensile strength and tensile modulus of BFRP and BGRP decreased after exposing to water (25°C and 75°C) for prolonged period. The level of reductions in strength and stiffness depended upon the exposed time and water temperature. BGRP specimens exhibited a better resistance to the exposed environment in terms of retention of tensile strength and stiffness. The tensile strength and stiffness were enhanced by the incorporation of maleic anhydride polypropylene (MAPP) as a coupling agent in the polypropylene matrix, resulting in an improved interfacial bonding. The hybridization of high-durable glass fiber and bamboo fiber was found to be an effective way to enhance the durability of natural-fiber composites subject to environmental aging. The hybrid glass/bamboo composites showed better fatigue behavior than all bamboo fiber-reinforced composites.

Jayabal et al. (2011) developed hybrid composites incorporating woven coir/glass fabric fiber preimpregnated with the resin matrix consisting of unsaturated orthophthalic polyester, cobalt octoate accelerator, and methyl ethyl ketone peroxide (MEKP) catalyst in the ratio of 1:0.015:0.015. Polyvinyl acetate release agent was applied to the laminates' surface before placing in the mold. Different laminates' stacking sequences were considered to evaluate mechanical properties of the hybrid coir/glass composites. It was found that the glass/glass/coir and coir/glass/glass composites showed highest tensile, flexural, and impact strength. The hybrid composites with two plies of glass fibers (glass/glass/coir and coir/glass/glass) exhibited higher breaking resistance than the coir/glass/coir composites with a single glass ply. The coir fibers failed faster than the glass fibers and the incorporation of the glass woven fabric in the coir-fiber composites enhanced their mechanical properties. The glass fibers were found to have better interfacial bond with the polyester matrix than the coir fibers.

Curaua (*Ananas erectifolius*) plants are native to Brazilian Amazon region and belong to Bromeliaceae family. Curaua fibers exhibit excellent properties such as good breaking elongation, high specific strength, and low density (Almeida et al., 2013). Almeida Júnior et al. (2012) investigated thermal, mechanical, and dynamic mechanical properties of hybrid curaua/glass composites. The results showed that the density of the hybrid curaua/glass composites increased with the increase of the glass fiber content and overall fiber volume fraction. The incorporation of glass fibers in the curaua composites resulted in significant improvement in impact strength and hardness. This was attributed to the intrinsic characteristics of the glass fiber such as stronger interfacial bond to the resin matrix and higher energy dissipation compared to the curaua fiber. Dynamic mechanical properties exhibited an increase in storage modulus whereas the glass transition temperature showed no significant change with the intermingled glass fibers. It was found that the hybrid composites with 30% of curaua fibers showed similar properties compared to the pure glass fiber-reinforced composites.

The mechanical properties of other glass fiber-based hybrid composites including glass/jute (Ahmed Sabeel and Vijayarangan, 2008), glass/kapok (Venkata Reddy et al., 2008), glass/kenaf (Davoodi et al., 2010), glass/PALF (Mishra et al., 2003), glass/palmyra (Velmurugan and Manikandan, 2007), glass/silk (Priya and Rai, 2006), and glass/sisal (Mishra et al., 2003) are listed in Table 4.5.

4.4 Conclusions

Mechanical characterizations of various hybrid composites were reviewed in this chapter. Hybrid composites of all natural fibers generally exhibit satisfactory strength and can be potentially used for various applications. Hybridizations of natural and synthetic fibers in polymer composite effectively enhance mechanical properties (e.g., flexural, tensile, and impact strength) of all natural-fiber composites. The natural/synthetic fiber hybrid composites are thus promising for high-performance structural applications. Hybrid composites with chemical treatments or modifications of fibers generally show better mechanical properties compared with untreated composites, resulting from the improved fiber-matrix bonding in treated composites.

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