Hybrid bast fiber reinforced thermoset composites

by Enih Rosamah

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9 Hybrid bast fibre reinforced thermoset composites

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s0010 9.1 Introduction

p0125 Plant fibers extracted from the stem are called bast fibers (Table 9.1). Bast fibers are produced in the layer between the xylem and the epidermis where they are surrounded by phloem. These fibers occur in bundles/aggregates in many dicotyledonous plants, running parallel to the stem between nodes (Rials and Wolcott, 1996) up to over 2 m long depending on the length of the plant (Meshram and Palit, 2013) to provide structural rigidity to the stems. The bundles consist of 10−25 elementary fibers (Fig. 9.1) (2−5 mm length and 10−50 μm diameter) where both the bundles and the elementary fibers are glued together by lignin and pectin to form a three dimensional network (Munder et al., 2005).

p0130 During bast fibers extraction process, the lignin and pectin are removed through a separation process such as retting, degumming or decortication to yield bast fibers (Zimniewska et al., 2011) with required strength, fineness, length, and purity (Batog et al., 2006). The bast fibers obtained are used as raw materials not only in the production of textiles but also for composites used for various applications such as for the car interior (Holbery and Houston, 2006; Fimmm and Rosemaund, 2009; Shinoj et al., 2011) and exterior (Mussig et al., 2006) in the automative industry, building and construction (Drzal et al., 2002), aerospace (Subash and Pillai, 2015), sports, and more (Chand and Fahim, 2008).

s0015 9.2 Natural bast fibers

s0020 *9.2.1 Flax*

p0135 Flax (*Linum usitatissimum*) under genus *Linum* in the Linaceae family is an annual plant that grows to 1.2 m tall with a stem diameter of 3 mm or more (Zimniewska et al., 2011) in temperate regions (Elzebroek and Wind, 2008) and is endemic to the area from the eastern Mediterranean to India (Sen and Reddy, 2011). It is now grown in a lot of countries including Canada, USA, China, India, and throughout Europe for its fibers and seeds (Joshi, 2015; Hall, 2016). The seeds are converted to linseed oil for health supplements, paints, and other industrial products (Jhala and Hall, 2010).

p0140 The fibers are used to produce textiles (Pallesen, 1996), pulp and paper (Aracri et al., 2010) and as reinforcements for polymeric composites (Bos et al., 2002). Its fibers are lustrous (Sen and Reddy, 2011) with a good length at 0.6−1.4 m and a diameter of 40−80 μm (Cutter, 2011) while its elementary fibers have lengths between 0.2 and 0.5 m and diameters ranging from 10 to 25 μm (Bos et al., 2002). It is also soft and flexible (Sen and Reddy, 2011; Nair and Joseph, 2014) but this contradicted the statements made by Cutter (2011) and Yan et al. (2014) who found it to be the stiffest and strongest plant fibers due to the substantial degree of crystallinity in its structure.

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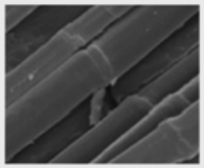
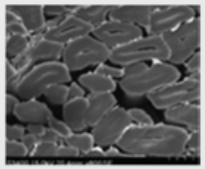
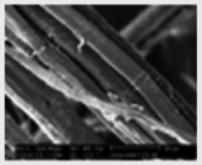
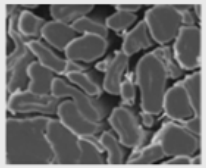
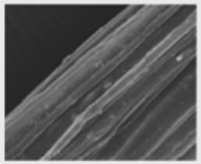
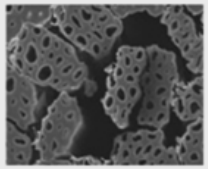
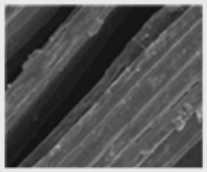
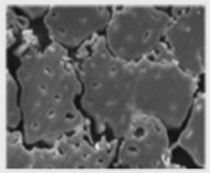
t0010 **Table 9.1 Tabular presentation of bast fibers**

Fiber	Botanical name	Plant photo	Longitudinal view of fibers	Image of fiber cross section
Flax	*Linum usitatissimum*			
Hemp	*Cannabis sativa*			
Kenaf	*Hibiscus cannabinus*			
Jute	*Corchorus capsularis*			

Source: Zimniewska, M., Wladyka-Przybylak, M., Mankowski, J. 2011. Cellulosic bast fibers, their structure and properties suitable for composite applications. In: Kalia, S., Kaith, B.S. and Kaur, I. (Eds.), Cellulose Fibers: Bio- and Nano-polymer Composites: Green Chemistry and Technology, Springer, Berlin, Germany, pp. 97–120.

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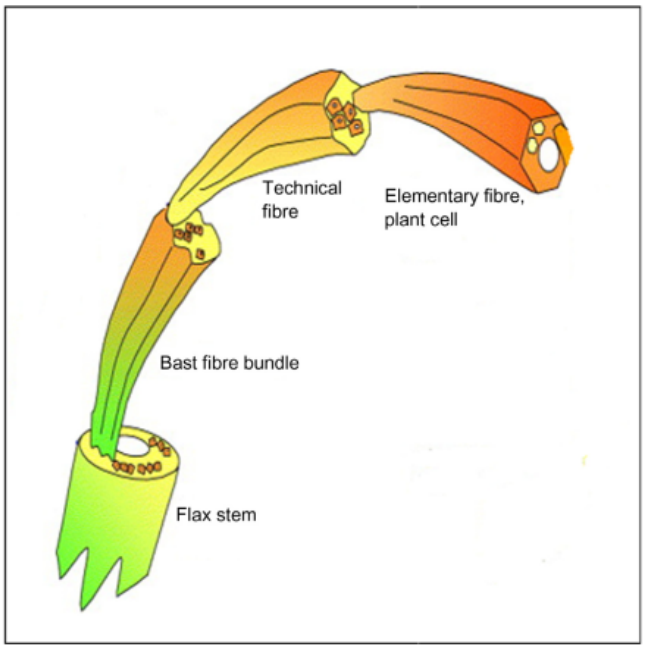

f0010 **Figure 9.1** Schematic representation of a flax fiber from stem to elementary fiber. *Source*: Bos, H.L., Mussig, J., van den Oever, M.J.A., 2006. Mechanical properties of short-flax-fibre reinforced compounds. Compos. A: Appl. Sci. Manuf. 37(10), 1591–1604.

p0145 Kers et al. (2010) also discovered that the flax bast fibers are strong where they are two times stronger than cotton and five times as strong as wool. Moreover, flax fibers have the added advantage in its ability to absorb up to 12% of its own weight when in contact with water which increases its strength by 20% (Murthy, 2015) unlike other bast fibers. Other than that, it also dries up quickly and is antistatic (Tahir et al., 2011) but exhibits relatively low longitudinal extension to failure when subjected to tensile loads (Cutter, 2011).

s0025 9.2.2 Jute

p0150 Jute [*Corchorus capsularis* (white jute) and *Corchorus olitorius* (dark jute)] (Summerscales et al., 2010) classified in the genus *Corchorus*, family Malvaceae (Ashby, 2012) are annual plants capable of growing up to 2–4.5 m in height (Lewington, 2003) with a stem diameter of 2–3 cm (Cutter, 2011). It originates from the Mediterranean (Cook, 1984) and thrives in hot humid environments like the tropical lowland areas which has a humidity of 60–90% (Yumnam et al., 2015) without needing fertilizers or pesticides. Today, it is widely grown in India, Bangladesh, Thailand, China, Brazil, and Indonesia (Summerscales et al., 2010; Cutter, 2011).

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p0155 Jute is grown exclusively for its long, soft and shiny off-whitish to brownish in color fibers (1−4 m length and 17−20 μm diameter) unlike flax and hemp (Cutter, 2011). Its fibers are strong and resilient to microorganism's attack (Murthy, 2015) but are fairly brittle (Ganguly et al., 1999), sensitive to chemical and photochemical attack (Ghosh, 2003), exhibit low elongation at break due to its high lignin content (Cutter, 2011) and has a lower tensile strength than other bast fibers like hemp and flax (Biagiotti et al., 2004).

p0160 Despite its shortcomings, their advantages far outweigh its shortcomings (John and Thomas, 2008) for it to be used in sackings, carpets, wrapping fabrics, and construction fabric manufacturing industries dating back to ancient times (Savastano Jr et al., 2009). Besides that, the fibers are used by itself or combined with other types of fibers to make twine and rope (Sreenath et al., 1996). Presently, it is also used as raw materials to produce pulp and paper (Sahin, 2003), textiles (Liu et al., 2010), polymer composites in the automotive (Punyamurthy et al., 2014) as well as in the building and construction industry (Roul, 2009).

s0030 9.2.3 Hemp

p0165 Hemp (*Cannabis sativa* L.) is an annual plant belonging to the Moraceae family which can only grow in temperate regions (Faruk et al., 2012) and are indigenous to central Asia including China where it was grown over 12,000 years ago and later reached central Europe (Shahzad, 2012). At present, it can be found in the EU, central Asia, Philippines, China, Chile, France, Korea, and Spain with China cultivating and producing almost half of the world's industrial hemp supply (Sanjay et al., 2016).

p0170 Hemp can grow up to 5 m in height (Kymalainen and Sjoberg, 2008) and a stem diameter of 4−20 mm in approximately 140−145 days (Batra, 2006; Zimniewska et al., 2011) with a bast fiber content in the range of 28−46% (Cutter, 2011). However, its growth rate can be sped up to reach a height of 4 m in just 84 days when grown in a suitably warm condition (Summerscales et al., 2010). Additionally, hemp has the added advantage of being very resilient compared to other fiber crops, requiring little to no herbicides, fungicides, pesticides, and fertilizers (Summerscales et al., 2010; Cutter, 2011).

p0175 The hemp bast fibers obtained from its stem have a length of 1.0−2.5 m (Summerscales et al., 2010) while its elementary fibers length averages at 12−25 mm (Cutter, 2011). Both fibers are fine, strong, lustrous, and light in color where their color and cleanliness greatly differs depending on the fiber extraction method used (Tahir et al., 2011). Their fibers are also highly resistant to moisture degradation as it rots very slowly in water although they are hygroscopic in nature similar to natural fibers of other sources (van Rijswijk et al., 2001).

p0180 Apart from that, hemp fibers also possess low elongation to break due to its low cellular microfibril angle (Bowen et al., 1994; Cutter, 2011) but excellent mechanical properties like specific strength and stiffness comparable to glass fibers (Shahzad, 2013). The above mentioned latter characteristics make hemp fibers an enticing material as reinforcements to replace synthetic fibers in the

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production of thermoset polymeric composites (Wotzel et al., 1999; Mwaikambo and Ansell, 2006).

9.2.4 Kenaf

p0185 Kenaf (*Hibiscus cannabinus* L.) of Malvaceae family is an annual plant originating from central Africa and is also commonly found as a wild plant in tropical and subtropical Asia (Cheng et al., 2004). It grows 1.5–3.5 m tall and 1–5 cm stem diameter (Nishino, 2013; Zimniewska et al., 2011) but other sources claimed that it can reach heights of 2.4–6.0 m in 4–5 months (Summerscales et al., 2010; Cutter, 2011). The stems have two distinct types of fibers, long bast fibers and woody like short core fibers in a 30:70 (w/w) ratio (Sanadi et al., 1996; Saba et al., 2015a) where these fibers differ in their appearance and anatomical structure (Voulgaridis et al., 2000).

p0190 However, both type of fibers are characteristically similar to wood fibers unlike jute, hemp, and flax fibers (Tahir et al., 2011). According to Tahir et al. (2011) and Tahir et al. (2014), kenaf dry fibers yield was reported to be 5–6% of fresh stems equivalent to 18–22% of dry plant which is higher than jute, hemp, and flax. Moreover, kenaf fibers yield was even found to be greater by 3–5 fold than southern pine with a production of 5–10 tons of dry fiber/acre (Sen and Reddy, 2011). This makes kenaf a cost effective and an attractive raw material for its natural fibers.

p0195 Kenaf bast fiber bundles consist of short elementary fibers with an average of 2.5 mm length (Saba et al., 2015a) while Cutter (2011) stated that the elementary fibers length is in the range from 1.5 to 6 mm. These fibers are thus too short for textile production (Calamari et al., 1997). Besides being too short, its fibers are brittle, coarse due to its striated surface, nonuniform as a result of its irregular shape making them difficult to process using existing textile equipment (Cutter, 2011; Tahir et al., 2011). Nevertheless, it possesses good mechanical properties similar to those of jute but with a relatively lower specific gravity as it has a lower cellulose content (Cutter, 2011; Sen and Reddy, 2011). Its favorable mechanical properties enables it to be used for pulp and paper (Ashori, 2006) as well as reinforcements for polymeric composites (Yousif et al., 2012). AU:2

9.2.5 Cell wall architecture of bast fibers

p0200 Bast fibers are defined as tightly joint fiber cells in bundles present in plant stems such as hemp, jute, flax, and kenaf (Haugan and Holst, 2013). Each of these bast fiber cells have an empty space called lumen surrounded by a cell wall (Bos et al., 2006) comprising of cellulose, hemicellulose, and lignin (Fig. 9.2) (Naik and Fronk, 2013). Its cell wall gradually thickens up till the point the lumen will appear as if it has almost disappeared as the bast fiber cells reaches maturity during plant development (Raven et al., 2005). The cell wall has two main layers, the primary (outermost layer) and secondary (innermost layer) wall with the secondary wall thicker than the primary wall and is only formed deposited inside the primary AU:3

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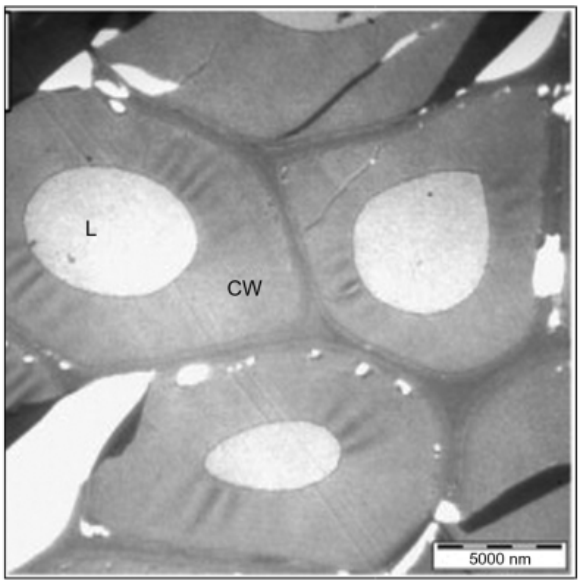

f0015 **Figure 9.2** Transverse section of kenaf bast fibers where L and CW indicates lumen and cell wall, respectively.
Source: Abdul Khalil, H.P.S., Ireana Yusra, A.F., Bhat, A.H., Jawaid, M., 2010. Cell wall ultrastructure, anatomy, lignin distribution and chemical composition of Malaysian cultivated kenaf fiber. Ind. Crops Prod. 31(1), 113–121.

wall after the primary wall is completely developed (Thamae et al., 2009). The secondary wall is made up of another three distinct layers known as S1, S2, and S3 with S2 being the thickest layer, thus playing a significant role in the bast fiber cells' mechanical properties (Meshram and Palit, 2013). On the contrary, Romhany et al. (2003) and Blake et al. (2008) discovered that secondary cell walls consist of multiple layers after examining the micrographs of bast fiber cross-sections and a speculative model of the bast fiber cell wall structure were drawn and shown in Fig. 9.3.

p0205 Every cell wall layers are reinforced with cellulosic macrofibrils (made up of cellulosic microfibrils) and microfibrils embedded in a hemicellulose, lignin and pectin matrix (Thamae et al., 2009 and Naik and Fronk, 2013). The cellulosic microfibrils are arranged differently in the primary and secondary wall (Hughes, 2004). In the primary wall, cellulosic microfibrils are generally randomly arranged in the longitudinal direction while the cellulosic microfibrils are arranged in a helical manner, winding around the fibers longitudinal axis in the secondary wall (Beck, 2005). In each of the three distinct secondary wall layers, the cellulosic microfibrils winds and twists in different directions. However, the twist orientation of the thickest layer, S2 is used to designate the overall cellulosic microfibrillar orientation of a bast fiber cell wall as either Z

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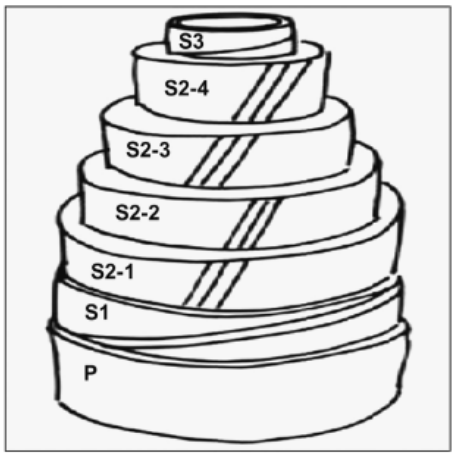
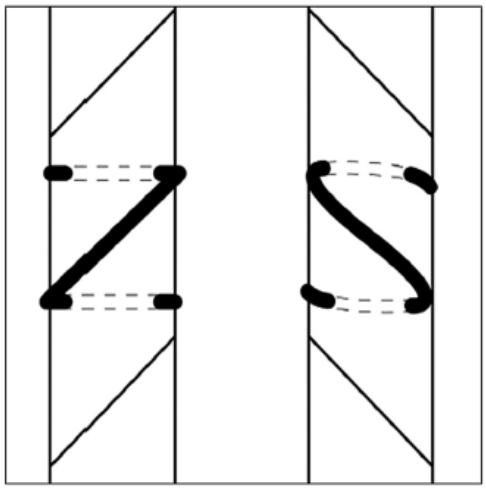


f0020 **Figure 9.3** Schematic of possible bast fiber cell wall structure.
Source: Eder, M., Burgert, I., 2010. Natural fibres – function in nature. In: Mussig, J. (Ed.), Industrial Applications of Natural Fibres: Structure, Properties and Technical Applications, Wiley, Hoboken, New Jersey, pp. 23–40.



f0025 **Figure 9.4** Cellulosic microfibrillar orientation—Z-twist and S-twist.
Source: Skoglund, G., Nockert, M., Holst, B., 2013. Viking and early middle ages northern Scandinavian textiles proven to be made with hemp. Sci. Rep. 3, <http://dx.doi.org/10.1038/srep02686> (accessed 15.04.16).

(right-handed) or S (left-handed) twist (Fig. 9.4). The S2 twist angle is also otherwise known as the fibrillar angle (φ). For example, the S1 is Z-twist and S2 is S-twist in flax and ramie but the S3 is Z-twist for flax while ramie has cellulosic microfibrillar orientation almost parallel to the bast fiber axis in S3.

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Accordingly, the overall cellulosic microfibrillar orientation of flax and ramie is S-twist with fibrillary angles (φ) of 6.5 and 7.0 degrees, respectively based on their S2 (Haugan and Holst, 2013).

s0045 9.3 Characterization of the bast fibers

s0050 9.3.1 Chemical composition

p0210 Bast fiber cells are chemically simple materials consisting of three main chemical constituents, cellulose, hemicellulose, and lignin with smaller amounts of pectin (Summerscales et al., 2010). All of these chemical constituents are distributed throughout the cell wall including the primary and secondary cell wall layers (Faruk et al., 2012). In the bast fiber cell wall layers, in which approximately half of it consists of cellulose bundles held together by roughly a quarter of hemicellulose and lignin matrix (Biagiotti et al., 2004). The remaining quarter of chemical constituents including pectin, protein, mineral substances, resin, tannin, dye, wax, and fat also helps in cementing the cellulose bundles (Bogoeva-Gaceva et al., 2007). Table 9.2 shows some of the main chemical constituents for a few bast fibers.

s0055 9.3.2 Physical properties

p0215 Natural fibers (fibers bundles or unit fibers) physical properties include their fineness, density, length, width, lumen diameter, cell wall thickness, microfibrillar angle, crystallinity, moisture content, and absorption (Table 9.3) (Franck, 2005; Goda and Cao, 2007; Celino et al., 2013). These physical properties of natural fibers including bast fibers vary considerably even for a specific given fiber like hemp, jute, kenaf, or flax fibers (Celino et al., 2013). For example, the hemp fibers' physical property, density was reported to be 1.48 g cm^{-3} by Faruk et al. (2012) but this data obtained differ a bit with the findings of Biagiotti et al. (2004) who found that it is supposed to be in the range of 1.40–1.50 g cm^{-3}. Another example will be the flax fibers physical property, moisture content which was revealed to be 8–12% (Thiruchitrambalam

t0015 **Table 9.2 Chemical constituents of bast fibers**

Bast fibers	Chemical composition (wt%)			
	Cellulose	Hemicelloluse	Lignin	Pectin
Jute	51.0–72.0	12.0–20.4	5.0–13.0	0.2
Hemp	70.0–78.0	17.9–22.0	3.7–5.0	0.9
Flax	60.0–81.0	14.0–18.6	2.0–3.0	1.8–2.3
Kenaf	36.0	21.0	18.0	2.0
Ramie	68.6–76.0	13.1–15.0	0.6–1.0	1.9–2.0

Source: Biagiotti, J., Puglia, D. and Kenny, J.M. 2004. A review on natural fibre-based composites–part 1: structure, processing and properties of vegetable fibres. J. Nat. Fibers 1(2), 37–68.

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t0020 **Table 9.3 Physical properties of bast fibers**

Bast fibers	Density (g cm^{-3})	Specific gravity (g cm^{-3})	Diameter (μm)	Microfibrillar angle (degree)	Moisture content (%)
Jute	1.30–1.50	1.30	10–200	8.0	10.0–13.7
Hemp	1.40–1.50	1.30	16–2000	2.0–6.2	6.2–12.0
Flax	1.40–1.50	1.20	20–620	5.0–10.0	8.0–12.0
Kenaf	1.19–1.40	1.04	17.7–100	—	12.0
Ramie	1.50–1.55	1.16	10–34	7.5	7.5–17.0

Sources: Bledzki, A.K., Gassan, J. 1999. Composites reinforced with cellulose based fibres. Prog. Polym. Sci. 24(2), 221–274; Mohanty, A.K., Misra, M., Hinrichsen, G., 2000. Biofibres, biodegradable polymers and biocomposites: an overview. Macromol. Mater. Eng. 276–277(1), 1–24; Biagiotti, J., Puglia, D., Kenny, J.M., 2004. A review on natural fibre-based composites – part 1: structure, processing and properties of vegetable fibres. J. Nat. Fibers 1(2), 37–68; Bogoeva-Gaceva, G., Avella, M., Malinconico, M., Buzarovska, A., Grozdanov, A., Gentile, G., et al., 2007. Natural fiber eco-composites. Polym. Compos. 28(1), 98–107; Goda, K., Cao, Y., 2007. Review paper: research and development of fully green composites reinforced with natural fibers. J. Solid Mech. Mater. Eng. 1(9), 1073–1084; Li, X., Tabil, L.G., Panigrahi, S., 2007. Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review. J. Polym. Environ. 15(1), 25–33; Cutter, A.G., 2011. Development and Characterization of Renewable Resource-Based Structural Composite Materials. ProQuest, Ann Arbor, Michigan; Faruk, O., Bledzki, A.K., Fink, H.P., Sain, M., 2012. Biocomposites reinforced with natural fibers: 2000–2010. Prog. Polym. Sci. 37(11), 1552–1596; Thiruchitrambalam, M., Alavudeen, A., Venkateshwaran, N., 2012. Review on kenaf fiber composites. Rev. Adv. Mater. Sci. 32(2), 106–111.

et al., 2012) but Mohanty et al. (2000) obtained a value of 10% for it. These differences occur due to the fibers chemical composition, plant size and maturity, environmental conditions during the plants growth (Bourmaud et al., 2013), different testing environmental conditions, and testing methods used (Placet et al., 2012) as well as different fiber extraction methods employed (Mohanty et al., 2000).

s0060 ### 9.3.3 Mechanical properties

p0220 Bast fibers (fibers bundles or unit fibers) like other natural fibers exhibit good specific mechanical properties especially when it comes to their strength and stiffness which is comparable to synthetic fibers like glass fibers but with the added advantage of a lower density (Li et al., 2007; Cutter, 2011). Table 9.4 lists some of the bast fibers main mechanical properties including tensile strength, Young's modulus, elongation at break, fracture stress, specific modulus, and specific strength (Bogoeva-Gaceva et al., 2007; Goda & Cao, 2007; Faruk et al., 2012). These mechanical properties are of great importance as they are usually evaluated when considering bast fibers suitability for a certain application (Bledzki and Gassan, 1999). However, one major drawback of bast fibers are their varying mechanical properties even among similar plant type fibers like hemp bast fibers mechanical properties may differ from one fiber to another (Celino et al., 2013). One such example is the considerable range of hemp bast fibers tensile strength at 580–1110 MPa or the flax bast fibers tensile strength from 343 to 1035 MPa (Biagiotti et al., 2004). These differences occur due to the very same factors that

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t0025 **Table 9.4 Mechanical properties of bast fibers**

Bast fibers	Tensile strength (MPa)	Specific Strength (GPa $cm^3 g^{-1}$)	Young's Modulus (GPa)	Specific Modulus (GPa $cm^3 g^{-1}$)	Fracture Stress (MPa)	Elongation at Break (%)
Jute	187–800	303.10	3–55	2.0–42.3	393–800	1.16–3.10
Hemp	550–1110	609.20	3–90	2.0–60.0	270–900	1.30–4.70
Flax	343–2000	1.60	27–85	19.0–71.0	345–1500	1.20–3.20
Kenaf	295–930	430.80	22–53	18.0–38.0	–	1.50–6.90
Ramie	220–938	482.80	44–128	21.1	–	1.20–3.80

Sources: Bledzki, A.K., Gassan, J. 1999. Composites reinforced with cellulose based fibres. Prog. Polym. Sci. 24(2), 221–274; Biagiotti, J., Puglia, D., Kenny, J.M., 2004. A review on natural fibre-based composites – part 1: structure, processing and properties of vegetable fibres. J. Nat. Fibers 1(2), 37–68; Bogoeva-Gaceva, G., Avella, M., Malinconico, M., Buzarovska, A., Grozdanov, A., Gentile, G., et al., 2007. Natural fiber eco-composites. Polym. Compos. 28(1), 98–107; Goda, K., Cao, Y., 2007. Review paper: research and development of fully green composites reinforced with natural fibers. J. Solid Mech. Mater. Eng. 1(9), 1073–1084; Li, X., Tabil, L.G., Panigrahi, S., 2007. Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review. J. Polym. Environ. 15(1), 25–33; Mohanty, A.K., Misra, M., Hinrichsen, G., 2000. Biofibres, biodegradable polymers and biocomposites: an overview. Macromol. Mater. Eng. 276–277(1), Cutter, A.G., 2011. Development and Characterization of Renewable Resource-Based Structural Composite Materials. ProQuest, Ann Arbor, Michigan; Faruk, O., Bledzki, A.K., Fink, H.P., Sain, M., 2012. Biocomposites reinforced with natural fibers: 2000–2010. Prog. Polym. Sci. 37(11), 1552–1596.

affect the bast fibers physical properties which also affects its mechanical properties (Celino et al., 2013). Besides that, the bast fibers physical properties also influence its mechanical properties (Bogoeva-Gaceva et al., 2007). For example, the fibers mechanical properties, strength, and stiffness are mainly influenced by its chemical composition, cellulose content and also its physical property, microfibrillar angle where a higher cellulose content and a lower microfibrillar angle increases its mechanical properties (Mohanty et al., 2000).

s0065 9.4 Hybrid bast fibers reinforced thermoset composites

p0225 The term hybrid originates from Greek-Latin and is often used in the polymer composites field to refer to two or more reinforcing and filling materials being incorporated into a single matrix leading to the formation of hybrid composites (Jawaid and Abdul Khalil, 2011). The reinforcing materials can either consist of a mixture of bast fibers and other cellulosic fibers or bast fibers and synthetic fibers while the matrix used is a thermoset matrix (Sathishkumar et al., 2014). The incorporation of hybrid fibers was shown to enhance the physical and mechanical properties of the hybrid composites produced where the advantages of one type of fiber offsets what are lacking in the other fiber type and vice versa (Shahzad, 2011). Furthermore, the hybridization of fibers as reinforcements for thermosets aids in achieving a balance between performance and cost of composites, hence propelling the utilization of hybrid composites prospects in a variety of applications including higher load

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bearing structural applications (Al-Harbi, 2001). For example, the hybridization of synthetic fibers and bast fibers into thermosets not only offsets the bast fibers inferior mechanical properties (Sanjay and Yogesha, 2016) but also reduces the composites moisture absorption due to the lower content of bast fibers (Salman et al., 2015). Similarly, the addition of bast fibers with synthetic fibers into thermosets lessen the composites production cost as well as the composites weight while maintaining the composites desired mechanical properties (Salman et al., 2015) and its biodegradability although at a lower level (Shahzad, 2011).

s0070 9.4.1 Potential and challenges in development of hybrid composites

s0075 9.4.1.1 Fiber–polymer matrix interface

p0230 The fiber–polymer matrix interface may be a distinct phase or in some cases a planar region consisting of only a few atoms in thickness as a result of a reaction between the fiber and the polymer matrix where its properties differ from both the fiber and the polymer matrix. Despite its thinness, the bonding occurring in the fiber–polymer matrix interface significantly influences the composites mechanical properties as it assists in transferring stress from the polymer matrix to the fiber (Jawaid and Abdul Khalil, 2011). Thus, there must be a strong bonding between the fiber and the polymer matrix to produce composites with desirable mechanical properties, strength, and stiffness. However, an interface bonding that is too strong results in the composites being too brittle (low resistance to fracture) whereas a weak interface bonding produces composites exhibiting low stiffness and strength (Park and Seo, 2011). Hence, there is a need to achieve optimum interfacial bonding. In order to achieve optimum interfacial bonding, there must be an intimate contact between the fiber and the polymer matrix. This is affected by wettability defined as the extent to which a polymer matrix spreads over the fiber. A good wettability means that the polymer matrix liquid spreads and covers every bumps and dips of the fiber rough surface displacing air in the process. This promotes intimate contact between both the fiber and the polymer matrix. A poor wettability produces composites with interfacial defects acting as stress concentrators in it (Pickering et al., 2016).

p0235 There are a few types of interfacial bonding mechanism such as mechanical interlocking, chemical bonding, and interdiffusion bonding where one or more types of bonding mechanism may occur at the same time in the composites interface (Pickering et al., 2016). Mechanical interlocking is more effective with rougher fiber surface, increasing the composites shear strength considerably but has very little strengthening effect on the transverse tensile strength. Unlike mechanical bonding, chemical bonding strength does not depend on the fiber surface roughness but on the reactivity of the chemical groups on the fiber surface with the polymer matrix chemical groups to form chemical bonds per unit area and on the type of chemical bonds formed. Interdiffusion bonding occurs from the two components (fiber and polymer matrix) molecules interdiffusion and intertwining in which its bonding strength are affected by the distance and degree of molecules intertwined and also the number of molecules per unit area at the

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interface (Park and Seo, 2011). Unfortunately, weak interfacial bonding occurs between the fiber and the polymer matrix due to the incompatibility of fiber (hydrophilic) and polymer matrix (hydrophobic) (John and Anandjiwala, 2008). To improve this, extensive research had been carried out and reported that mechanically or chemically treating the fibers helps to enhance the weak interfacial bonding. Mechanical treatments include corona, plasma, ultraviolet (UV), heat treatments electron radiation and fiber beating while some of the chemical treatments available are alkali, acetyl, silane, acrylonitrile, and maleated anhydride grafted coupling agent (Adekunle, 2015).

s0080 #### 9.4.1.2 Moisture content of bast fibers

p0240 Bast fibers constitute primarily of cellulose in its cell walls similar to other types of natural fibers and usually have moisture contents (5−15%) (Jawaid and Abdul Khalil, 2011) in its voids as well as in its noncrystalline/amorphous regions (Bledzki and Gassan, 1999). The bast fibers chemical constituent, cellulose contains many hydroxyl groups forming hydrogen bonds between its macromolecules within the bast fiber cell walls. These hydrogen bonds will break as soon as moisture (water molecules) from the surrounding environment comes into contact with cellulose, thereby freeing the cellulose macromolecules hydroxyl groups. The cellulose macromolecules free hydroxyl groups will next form new hydrogen bonds with water molecules instead (Kabir et al., 2012). Thus, resulting in bast fibers being hydrophilic in nature (Saheb and Jog, 1999). This causes polymer composites reinforced with bast fibers to exhibit a high moisture absorption when exposed to water even with the presence of hydrophobic polymer matrix. The moisture absorbed into the composites induces the bast fibers within it to swell leading to diminishing bonding strength at its interface and ultimately results in the composites microcracking, dimensional instability, and poorer mechanical properties (Biagiotti et al., 2004).

p0245 One such example was reported by Raghavendra et al. (2015) who found that jute fiber reinforced epoxy composites exhibited depreciating mechanical properties, tensile and flexural strength after being immersed in water. In contrast, Phani and Bose (1987) had discovered the added benefits of jute fibers incorporation into glass fiber reinforced thermoset composites where jute fibers assisted in lowering its composites degradation rate after being exposed to moisture for more than 70 hours. This was either probably due to the swollen jute fiber layers accommodation of the resin swelling strain or the swollen jute fibers protection to a central glass fiber layer. Despite the findings of Phani and Bose (1987), it is evidently essential to remove moisture from the bast fibers before its used as a reinforcement in polymers. A few other researchers had also suggested subjecting bast fibers to chemical treatments which removes its hydrophilic hydroxyl groups to reduce its moisture absorption (Wang et al., 2007). Besides that, bast fiber chemical treatments also enhance the bast fibers reinforced polymer composites interfacial adhesion as a good interfacial adhesion lowers the rate and amount of water absorbed by the composites. Other alternatives include coating the bast fibers reinforced polymer composites with surface barriers but this might be too costly (Biagiotti et al., 2004).

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s0085 ### 9.4.1.3 Dispersion of bast fibers in the matrix

p0250 Bast fibers for the most part are made up of cellulose which imparts polarity and hydrophilicity to the fibers due to the high density of hydroxyl groups on its surface at the cell walls (Saheb and Jog, 1999). These hydroxyl groups on its surface has a tendency to form hydrogen bonding with hydroxyl groups occurring on the surface of other bast fibers adjacent to it while having less interaction with the polymer matrix (Wang, 2008). Thus resulting in agglomeration/entanglement of the bast fibers or otherwise known as weak dispersion of bast fibers when used as reinforcements in nonpolar and hydrophobic polymer matrix unlike polar polymer matrix. Bhatnagar (2004) discovered that the dispersion of natural fibers in thermoplastic polymer matrix, polyvinyl alcohol (PVA) was not an issue due to the polarity and hydrophilicity of the polymer matrix used. However, the majority of polymers are nonpolar and hydrophobic in nature. The findings of Bhatnagar (2004) was supported by Barkoula and Peijs (2011) who explained that the occurrence of a strong interaction between natural fibers and polymer matrix is a result of their similar polarity.

p0255 This in turn promotes natural fibers wetting by molten polymer matrix, thus leads to a good dispersion of natural fibers in the polymer matrix. Various methods and treatments can be employed to change the natural fibers polarity to make it less polar, hence less hydrophilic as this will increase its compatibility with the hydrophobic polymer matrix. Some of the treatments include physical and chemical treatments (Rahman et al., 2015). Other than that, Nando and Gupta (1996) had suggested the wetting of natural fibers to prevent hydrogen bonding between fibers before mixing them with the polymer matrix but this will induce the formation of pores in the composites formed. Apart from that, increased mixing time assists in fibers dispersion in polymer matrix rapidly but only up to a certain extent as it was found that fibers dispersion gradually slows down with mixing time. Shorter natural fibers were also recommended for use as longer fibers are more inclined to agglomerate (Pickering et al., 2016).

s0090 ### 9.4.1.4 Thermal stability

p0260 Bast fibers thermal stability is defined as the bast fibers resistance to decomposition/degradation at higher temperatures up to a certain extent. The fibers thermal stability is influenced by their chemical constituents, cellulose, hemicellulose, lignin and pectin. Each of these chemical constituents are sensitive to a different range of temperatures, hence the different stages of fibers decomposition resulting in the fibers weight loss (Saheb and Jog, 1999). Hemp fibers for example, starts to decompose and suffer from weight loss at 50°C due to the evaporation of its moisture content. Once the temperature reaches above 160°C, hemp fibers binding material, lignin begins to soften causing physical and chemical changes within the fibers. At about 270°C, the hemp fibers weight loss is attributed to the decomposition of hemicellulose or pectin while the weight loss at 360°C are associated with cellulose decomposition (Shahzad, 2011). Troedec et al. (2008) reported that the hemp fibers hemicellulose and pectin degradation corresponds to 320−370°C while its cellulose

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degradation occurs at 390−420°C. Generally, natural fibers starts degrading at 200°C (Jawaid and Abdul Khalil, 2011).

p0265 These researchers revealed that the fibers goes through changes in its physical and chemical properties after exposure to high temperatures. Studies showed that the changes in the fibers physical and chemical properties also affects its mechanical properties negatively. This was supported by Sridhar et al. (1982) who observed a 60% decrease in jute fibers tensile strength after heating under vacuum at 300°C for 2 hours. Mohanty et al. (2000) also had the same findings in their review paper where ramie fibers were reported to suffer from nearly 10% reduction in its tensile strength after being exposed to a high temperature at about 200°C for a duration of only 10 minutes. The reduction in the natural fibers mechanical properties will in turn affect the natural fiber reinforced polymer composites strength. Therefore, there is a need to consider the temperature and duration in the processing of the polymer composites to avoid thermal degradation of the natural fibers within it (Summerscales et al., 2010). Besides that, there are also ways to improve the natural fibers thermal stability by grafting monomers onto the fibers evidently shown by Saheb and Jog (1999).

s0095 *9.4.1.5 Biodegradability*

p0270 Bast fibers are easily biodegraded by microorganisms, bacteria, and fungi as these organisms are capable of recognizing the lignocellulosic materials such as cellulose, hemicellulose, and lignin present in its cell walls (Saheb and Jog, 1999). Next, the bacteria and fungi produces the necessary specific enzymes to break down the lignocellulosic materials in the fibers cell wall into smaller units to be assimilated into the microorganisms for its nutritional needs and growth (Mohanty et al., 2000). Out of the two microorganisms, bacteria were found to degrade lignocellulosic materials at a slower rate than fungi (Kuhad et al., 1997). As a result of the natural fibers biodegradation, the fibers losses its mechanical strength and this will in turn drastically lower the natural fibers reinforced polymer composites mechanical strength and its service life (Walentowska and Kozlowski, 2012). Additionally, the incorporation of biodegradable natural fibers into either biodegradable or nonbiodegradable polymers enhances the polymers biodegradability. Thus, limiting these polymer composites from outdoor applications (Jawaid and Abdul Khalil, 2011). However, certain measures can be taken to reduce the fibers biodegradability by altering its cell wall chemistry through chemical treatments (Joseph et al., 1999).

s0100 9.5 Hybrid bast fiber reinforced thermoset composites processing

p0275 There are a few methods frequently used by researchers to produce hybrid bast fiber reinforced thermoset composites such as hand lay-up, compression moulding and pultrusion where some methods are favoured over the other (Table 9.5). Out of all

t0030 **Table 9.5 Reported works on hybrid bast fibers reinforced thermoset composites processing**

AU:6

Fibers	Matrix	Fiber fraction (wt%/vol%)	Processing	Tensile strength	Tensile modulus	Flexural Strength	Flexural modulus	Impact strength	References
Flax/basalt/glass	Epoxy	21.18 vol% (flax: basalt:glass, 11.72:7.16:2.30)	Vacuum infusion	153.16 ± 17.41 MPa	8.11 ± 0.60 GPa	137.95 ± 19.85 MPa	8.02 ± 0.68 GPa		Petrucci et al. (2013)
Hemp/basalt/glass		22.53 vol% (hemp: basalt:glass, 8.56:11.38:2.59)		128.84 ± 8.70 MPa	6.64 ± 0.49 GPa	126.22 ± 13.63 MPa	5.90 ± 0.42 GPa	–	
Flax/hemp/basalt		21.18 vol% (flax: hemp:basalt, 9.11:7.85:5.57)		115.97 ± 3.77 MPa	7.69 ± 0.63 GPa	128.46 ± 29.14 MPa	7.45 ± 0.67 GPa		
Jute/Glass *Note*: i. Jute (J) ii. Glass fibers (GF) iii. Glass chopped strand mat (GCSM) iv. Surface veil (SV)	Unsaturated polyester	*Dry composites*	Pultrusion	*Dry composites*				–	Akil et al. (2014)
		70 vol% (J:GF, 1:1)		261.22 ± 8.06 MPa	25.70 ± 0.82 GPa	366.38 ± 21.05 MPa	23.40 ± 0.46 GPa		
		70 vol% (J:GF:GCSM, 1:1:1)		266.22 ± 17.85 MPa	27.50 ± 0.69 GPa	343.32 ± 23.19 MPa	24.60 ± 0.31 GPa		
		[70 vol % (J:GF, 1:1)] + SV		122.71 ± 7.03 MPa	15.90 ± 1.02 GPa	136.80 ± 9.89 MPa	15.40 ± 0.78 GPa		
		Soaked composites (4076 h)		*Soaked composites (4076 h)*					
		70 vol % (J:GF, 1:1)		152.40 ± 9.86 MPa	18.30 ± 1.06 GPa	297.54 ± 15.61 MPa	19.50 ± 0.86 GPa		
		70 vol % (J:GF:GCSM, 1:1:1)		166.49 ± 10.95 MPa	20.10 ± 0.69 GPa	276.35 ± 7.04 MPa	21.50 ± 0.58 GPa		
		[70 vol % (J:GF, 1:1)] + SV		64.48 ± 8.31 MPa	11.70 ± 0.88 GPa	119.61 ± 9.60 MPa	11.90 ± 0.61 GPa		
Kenaf/Glass	Unsaturated polyester	–	Hand lay-up & Compression molding	–	*Dry composites* Day 1 till Week 4 8.36 GPa *Distilled water soaked* Day 1−6.53 GPa Week 1−6.66 GPa Week 2−6.46 GPa Week 3−6.83 GPa	–	–	–	Ghani et al. (2012)

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					Week 4−5.64 GPa *Rain water soaked* Day 1−8.27 GPa Week 1−6.65 GPa Week 2−6.92 GPa Week 3−6.74 GPa Week 4−6.06 GPa *Sea water soaked* Day 1−7.19 GPa Week 1−7.15 GPa Week 2−6.37 GPa Week 3−6.64 GPa Week 4−5.80 GPa				
Jute (J)/banana (B)	Epoxy	Weight ratio J:B, 100:0 Weight ratio J:B, 75:25 Weight ratio J:B, 50:50 Weight ratio J:B, 25:75 Weight ratio J:B, 0:100 *(Fiber fraction not stated)*	Hand lay-up & Compression molding	16.62 MPa 17.89 MPa 18.96 MPa 18.25 MPa 17.92 MPa	664 MPa 682 MPa 724 MPa 720 MPa 718 MPa	57.22 MPa 58.60 MPa 59.84 MPa 59.30 MPa 58.06 MPa	8956 MPa 9065 MPa 9170 MPa 9056 MPa 9048 MPa	13.44 kJ/m^2 15.81 kJ/m^2 18.23 kJ/m^2 17.89 kJ/m^2 16.92 kJ/m^2	Boopalan et al. (2013)
Flax/carbon	Epoxy	2 cross ply flax fiber + *unidirectional ply carbon fiber* 2 unidirectional ply flax fiber + *unidirectional ply carbon fiber* *(Fiber fraction not stated)*	Compression molding	284.80 ± 0.02 MPa –	11.90 ± 0.01 GPa –	145.00 ± 0.18 MPa 318.83 ± 0.22 MPa	9.71 ± 0.34 GPa 28.83 ± 0.29 GPa	–	Dhakal et al. (2013)
Jute/Palmyra palm leaf stalk (PPLS)	Unsaturated polyester	30 wt % (jute:PPLS, 0:100) 30 wt % (jute:PPLS, 25:75) 30 wt % (jute:PPLS, 50:50) 30 wt % (jute:PPLS, 75:25) 30 wt % (jute:PPLS, 100:0)	Compression molding	56.90 ± 1.60 MPa 60.30 ± 1.59 MPa 64.30 ± 1.95 MPa 83.30 ± 5.13 MPa 77.10 ± 3027 MPa	2.28 ± 0.34 GPa 2.84 ± 0.34 GPa 2.45 ± 0.40 GPa 3.78 ± 0.60 GPa 5.07 ± 0.20 GPa	105.49 ± 2.41 MPa 116.83 ± 15.20 MPa 145.66 ± 9.35 MPa 164.00 ± 12.14 MPa 176.00 ± 3.50 MPa	15.32 ± 1.53 GPa 16.83 ± 0.64 GPa 17.95 ± 0.53 GPa 18.23 ± 0.95 GPa 19.26 ± 1.29 GPa	36.38 ± 8.14 kJ/m^2 34.87 ± 6.12 kJ/m^2 27.01 ± 4.13 kJ/m^2 26.02 ± 3.34 kJ/m^2 24.71 ± 3.09 kJ/m^2	Shanmugam & Thiruchitrambalam (2013)

(*Continued*)

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Table 9.5 (Continued)

Fibers	Matrix	Fiber fraction (wt%/vol%)	Processing	Tensile strength	Tensile modulus	Flexural Strength	Flexural modulus	Impact strength	References
Flax (F)/ Glass (G)	Phenolic	67 vol % (F:G, 50:50) stacked GF 67 vol % (F:G, 50:50) stacked GGFF 67 vol % (F:G, 50:50) stacked GGGGFFFF	Compression molding	450.1 ± 16.5 MPa 412.5 ± 12.7 MPa 392.5 ± 20.0 MPa	40.1 ± 1.7 GPa 40.8 ± 1.4 GPa 39.7 ± 0.6 GPa	–	–	–	Zhang et al. (2013)
Hemp/Glass Hemp/Banana/ Glass	Epoxy	–	Hand lay-up	37.5 MPa 28.0 MPa	–	0.29 kN 0.51 kN	–	5.33 J 8.66 J	Bhoopathi et al. (2014)
Flax (F)/ Banana (B)/ Glass (G) Flax (F)/ Glass (G)	Epoxy	[40 vol % (F layer, B layer, F layer)] + G surface veil [40 vol % (3 F layers)] + G surface veil	Hand lay-up	30 MPa 32 MPa	–	13.54 MPa 11.59 MPa	–	16 J 11 J	Srinivasan et al. (2014)
Jute/Vetiver Jute/Vetiver/ Glass	Vinyl ester	*Treated vetiver* 34 wt % (jute:vetiver, 17:17) 34 wt % (jute:vetiver, 24:10) 34 wt % (jute:vetiver, 10:24) 34 wt % (jute:vetiver: glass, 13:13:8) 34 wt % (jute:vetiver: glass, 10:10:14)	Hand lay-up	71.73 MPa 63.30 MPa 64.53 MPa 74.14 MPa 70.96 MPa	–	133.11 MPa 114.79 MPa 121.31 MPa 131.90 MPa 137.60 MPa	–	11.00 J 10.33 J 11.67 J 15.33 J 18.33 J	Vinayagamoorthy & Rajeswari (2014)

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the fabrication methods, hand lay-up is often used as it is the simplest method (Gupta and Srivastava, 2016) but it still requires the necessary workmanship skills to ensure the polymer composites uniformity (in terms of thickness), fiber to polymer matrix ratio and void content throughout the polymer composites produced (Kabir et al., 2012). This method basically requires the manual placement and arrangement of fibers in woven fabric form or in chopped form in the mould. Next, a mixture of molten thermosetting polymer and hardener is poured onto the fibers in the mould to wet the fibers. A brush is later used to evenly spread the molten polymer while a roller is used in the removal of air as well as excess molten polymer before the mould is closed and left to cure or pressed at room temperature (Sreenivasan et al., 2013; Ghani et al., 2012).

p0280 Other than hand lay-up, compression moulding are also often used to form hybrid bast fiber reinforced thermoset composites by placing the fibers, fiber mats (Abdellaoui et al., 2015) or loosely chopped fibers either randomly oriented (Gopinath et al., 2014) or aligned (Coroller et al., 2013) together with molten polymer matrix into the mould cavity. The mould is later closed and placed in a compression molder for compression moulding at the required temperature, pressure, and time before the composites formed are removed from the mold. In order to produce good quality polymer composites, the temperature and time needs to be carefully controlled (Pickering et al., 2016) so as to prevent the bast fibers degradation from occurring when exposed to temperatures above 200°C for a long duration of time. Hence reducing its fibers strength significantly. This was supported by Herrmann et al. (1998) who observed a 10% reduction in natural fibers strength after being heated at 200°C for only 10 minutes. With careful control of temperature and time, researchers had found that this method has the added advantage of producing polymer composites with a low number of air voids in it and the possible incorporation of various fibers length from short to long (Sreenivasan et al., 2013).

p0285 The other less frequently used method are pultrusion in the production of hybrid bast fiber reinforced thermoset composites (Sathishkumar et al., 2014; Saba et al., 2015b). Pultrusion is a continuous process involving the pulling of continuous fibers (cords or strands) through a polymer resin bath to impregnate the fibers with polymer resin. This is followed by a separate preforming system where it is shaped and rid of excessive polymer resin before it is guided through a heated die to allow the polymer resin to cure (Anandjiwala and Blouw, 2007). The final product obtained a constant cross-sectional shaped composite which exhibits good mechanical properties and also dimensional stability (Sreenivasan et al., 2013). This was shown by Akil et al. (2011) who proved that the pultrusion fabricated composites achieved a good flexural strength at 250 MPa with 70% fiber composition which can only be attained through this method. However, there are also some drawbacks to this method where its composites good mechanical properties and dimensional stability are only limited to the cross-sections. Besides that, the composites fabricated shape is also limited to cylindrical form (Sreenivasan et al., 2013).

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s0105 9.6 Physical and mechanical properties of hybrid bast fibers reinforced thermoset composites

s0110 9.6.1 Epoxy based hybrid composites

p0290 The physical and mechanical properties of epoxy based bast fiber hybrid composites had been studied by several researchers as reported by Saba et al. (2015b) and Gupta and Srivastava (2016) in their review papers. Some of the researchers include Ramesh and Nijanthan (2016) who fabricated kenaf-glass fiber reinforced epoxy composites with two different fiber orientations at 0 and 90 degrees. These composites were tested for their mechanical properties, tensile strength, impact strength, and flexural strength. They concluded that the kenaf-glass fiber reinforced epoxy composites mechanical properties with 0 degree fiber orientation are better than the 90 degrees. Finite element analysis (FEA) carried out also validated the experimental results obtained as the experimental results are very close to the FEA model results. Similar study was also conducted by Gujjala et al. (2014) on the mechanical properties of woven jute–glass fibers reinforced epoxy composites where the woven jute and glass mat were stacked in a different sequence. Karahan and Karahan (2015) also investigated the tensile and impact properties as well as the water absorption of jute–carbon woven fabric epoxy composites. They found that the hybridized jute–carbon woven fabric epoxy composites showed significant improvement in its tensile and impact strength compared with the jute woven fabric epoxy composites. The hybrid epoxy composites also exhibited reduced moisture absorption when soaked in water for 2 and 24 hours, respectively.

s0115 9.6.2 Polyester based hybrid composites

p0295 Ramesh et al. (2013) investigated the mechanical property of sisal–jute–glass fiber reinforced polyester composites in comparison with jute–glass fiber reinforced polyester composites. In terms of tensile strength, they reported that jute–glass fiber reinforced composites exhibits higher tensile strength whereas sisal–jute–glass fiber reinforced composites showed superior flexural and impact strength. Unlike Ramesh et al. (2013), Scutaru and Baba (2014) only focused on hybridizing two type of fibers, carbon, and hemp fabric as polyester composite fillers to determine the composites impact strength with different impact speed and falling heights. They concluded that the hybridized composites produced had a good stiffness. This is in agreement with the findings made by Ahmed et al. (2007) who observed an increased in their fabricated hybrid composites stiffness. In their study, Ahmed et al. (2007) produced woven jute–glass fiber reinforced polyester composites where its stiffness was enhanced with increasing glass fiber content in the hybrid composites. The hybrid composites stiffness enhancement of Scutaru and Baba (2014) and Ahmed et al. (2007) is the result of the glass and carbon fibers high stiffness. Ahmed et al. (2007) also discovered that the addition of glass fibers into woven jute reinforced composites increased the composites tensile strength due to the greater extensibility of glass fibers.

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s0120 9.6.3 Phenolic based hybrid composites

p0300 Ozturk (2010a) is among one of the few researches to report on the influence of synthetic fibers hybridization into phenolic based bast fiber composites. In his research, he hybridized rockwool fibers into jute fiber reinforced phenol formaldehyde composites. He found that the addition of rockwool fibers to jute reinforced phenol formaldehyde composites increases the hybrid composites flexural strength but also decreases its tensile and impact strength. Another researcher by the same last name, Ozturk (2005) investigated the hybridization of basalt fibers into hemp phenol formaldehyde composites. His findings are almost similar in which the hybridization of basalt fibers decreases not only the tensile and impact strength but also the flexural strength. These findings are in agreement with his recent work where he also observed a decreasing trend for the hybrid composites mechanical properties with the addition of fibrefrax fiber into kenaf reinforced phenol formaldehyde composites (Ozturk, 2010b). All of these results are attributed to the weak adhesion between the synthetic fibers (rockwool fiber, fibrefrax fiber, and basalt fiber) with the phenol formaldehyde polymer matrix. Medeiros et al. (2005) on the other hand studied the addition of cellulosic fibers, cotton to jute reinforced phenolic composites by weaving both cotton with different jute roving textures together into a fabric as a reinforcement for phenolic polymer matrix. Next, the hybrid composites mechanical properties were tested in relation with the different test angles and jute roving textures. They concluded that the hybrid composites mechanical properties are strongly dependent on the test angles and jute roving textures. The best overall mechanical properties were the ones tested along the jute roving direction and these properties are reduced with increasing test angles.

s0125 9.6.4 Unsaturated polyester based hybrid composites

p0305 The physical and mechanical properties of unsaturated polyester resin based bast fiber hybrid composites had been studied by a few researchers already. One of them is Zamri et al. (2011) who had conducted an experiment to determine the effect of water absorption on the jute−glass fiber reinforced unsaturated polyester composites. The hybrid composites were immersed in three different types of water: distilled water, sea water, and an acidic solution for up till 3 weeks to determine the composites water absorption. From the results obtained, they concluded that the water absorption pattern follows the non-Fickian behavior. The composites also exhibited the highest values for diffusion coefficient and maximum moisture content when immersed in distilled water followed by acidic solution with sea water having the lowest value. Besides that, the incorporation of synthetic glass fibers into jute reinforced unsaturated polyester composites were observed to lower the composites moisture absorption and at the same time enhance its mechanical properties, flexural, and compression strength. Similarly, Salleh et al. (2012) had also conducted a research on the water absorption effect on long kenaf-woven glass fiber unsaturated polyester composites where their findings are in agreement

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with Zamri et al. (2011). Others like Kafi et al. (2006) and Lai et al. (2008) had conducted their research focusing on enhancing the mechanical properties of bast fiber hybrid reinforced unsaturated polyester composites either by chemical or physical fiber treatments. Unlike the others, Hashemi et al. (2015) instead focused on the relationship between the kenaf fiber volume fraction and void volume fraction of kenaf/glass fiber unsaturated polyester composites.

s0130 9.6.5 Vinyl ester based hybrid composites

p0310 Vinayagamoorthy and Rajeswari (2014) investigated the hybrid woven jute–vetiver–glass fiber reinforced vinyl ester composites mechanical performances in terms of tensile, compressive, flexural and impact strength. In this study, only the vetiver fibers were chemically treated with alkaline solution before undergoing heat treatment to enhance the hybrid composites properties with differing hybrid fiber weight ratios. They found that the vetiver fiber treatments, an increase in glass fiber weight ratio up till 15% and hybridization substantially enhanced the hybrid composites mechanical properties. They also discovered that it is possible to replace the fiber glass in the hybrid woven jute–vetiver–glass fiber reinforced composites with other natural fibers without affecting the hybrid composites mechanical properties negatively except for its impact strength. Li et al. (2015) who studied the hybridization of jute–ramie fiber reinforced polyester composites also came to a similar conclusion that hybridization enhances the mechanical properties only when the ramie fiber fractions are increased. They also discovered that by increasing the jute fiber fractions, this will in turn improved the hybrid composites permeability. Kannan et al. (2015) like Vinayagamoorthy and Rajeswari (2014) also studied the effect of alkaline treatment on natural fibers, jute and banana fibers where both jute and banana fibers were later used together as fillers for vinyl ester polymer matrix. These alkaline treated and untreated hybrid jute–banana fiber reinforced composites were tested for their mechanical properties. In contrast to the findings of Vinayagamoorthy and Rajeswari (2014), Kannan et al. (2015) inferred that the untreated hybrid jute–banana fiber reinforced composites exhibits stronger mechanical properties compared with the treated ones.

s0135 9.7 Applications of hybrid bast fibers reinforced thermoset composites

p0315 Atiqah et al. (2014) attempted the development of hybrid kenaf-glass reinforced unsaturated polyester composites for structural applications in their research. First, they fabricated the hybrid kenaf-glass reinforced composites where the different fractions of kenaf fibers used were either alkaline treated or untreated before subjecting the hybrid composites for mechanical testing. They discovered that the hybrid composites with 15% volume of treated kenaf fibers possess the highest flexural, tensile and impact strength due to good interfacial bonding between the kenaf fibers and the polymer matrix. Based on their findings, they came to a

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conclusion that the 15% volume treated kenaf-glass hybrid reinforced composites is suitable for structural applications. This finding is in agreement with Burgueno et al. (2005a), Ray and Rout (2005), Dittenber and GangaRao (2012) and Alam et al. (2015). These researchers concluded that the hybridization of natural fibers with glass and/or carbon fibers significantly reduces the thermoset composites water absorption properties and also enhances the composites mechanical and thermal properties. These improvements allow the hybridized natural fibers−glass fibers or natural fibers−carbon fibers reinforced thermoset composites to compete with conventional structural materials in their application. Similarly, Burgueno et al. (2005b) also investigated the applicability of hybrid biofibre based composites for structural applications, specifically on structural cellular plates. They hybridized chopped natural fibers (hemp and flax) with synthetic (glass and carbon) or natural (jute) based fabrics as fillers for unsaturated polyester polymer matrix. These hybridized composites were tested and also analyzed with micromechanics and sandwich analysis. Results indicated that they are a viable alternative to conventional structural materials for current and future applications.

p0320 Besides the utilization of hybrid bast fibers reinforced thermoset composites on structural and building materials, it can also be applied for car structural components. This was done by Davoodi et al. (2010) where they fabricated hybrid kenaf-glass fiber reinforced epoxy composites and evaluated its mechanical properties. The hybrid composites mechanical properties were compared with glass mat thermoplastic (GMT) which is the material used to produce passenger car bumper beam. The hybrid composites had comparable mechanical properties with GMT except for the hybrid composites lower impact strength but based on its overall properties, it has the potential to be used as a material for the production of car bumper beams. Devireddy and Biswas (2016) focused their research on the applicability of hybrid banana-jute fiber reinforced epoxy composites in relation with its physical and thermal properties for not only car components but also building materials. They also came to the same conclusion that hybrid bast fibers reinforced thermoset composites are suitable for building materials and car components. Other researchers with similar findings on hybrid bast fiber thermoset composites applicability as automotive components includes Yahaya et al. (2016), Mansor et al. (2013) and Suresh et al. (2015). Other than building and car materials, hybrid bast fiber reinforced thermoset composites were also found to possess the potential for use as curved pipes where three hybrid fibers, kenaf-glass fiber, flax-glass fiber and hemp-glass fiber were evaluated (Cicala et al., 2009). Another utilization is its development as a combat armor made from hybrid ramie-kevlar 29 polyester composites as it meets the ballistic threats equivalent to the third level of protective ballistic limits in the National Institute of Justice (NIJ) standards (Radif et al., 2011).

s0140 9.8 Conclusion

p0325 Bast fibers like jute, flax, hemp and kenaf had been thoroughly investigated by numerous researchers up till today where most of them had focused on the fibers

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chemical constituents, physical and mechanical properties as well as its cell wall architecture. These properties of bast fibers makes it a suitable reinforcement for thermoset polymers with the added benefits of being environmentally friendly and also possessing high specific strength comparable to synthetic fibers. Despite the advantages, bast fibers also lack behind in certain properties like moisture absorption. In order to offset what bast fibers are lacking, hybridization of bast fibers with other natural fibers or synthetic fibers were done and the results were promising as hybridization enhances the reinforced thermoset composites. To further improve the hybrid bast fiber thermoset composites, researchers had also conducted several studies on its fiber-matrix interface, bast fiber thermal stability, moisture content, biodegradability, and dispersion in the matrix. This had led to the development of hybrid bast fiber thermoset composites exhibiting properties comparable to synthetic thermoset composites with the exception of one or two lower properties for the hybrid composites. Due to these comparable properties, the hybrid composites has the potential for application in building and structural materials, automotive components, piping and body armor. However, there is still a need for future research to broaden its application to other utilizations by further improving the bast fibers moisture absorption, thermal stability and durability, allowing them to completely replace synthetic fibers one day.

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