7 Jute and Kenaf

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7.1 INTRODUCTION

Jute is the common name given to the fiber extracted from the stems of plants belonging to the genus *Corchorus*, family *Tiliaceae.* whereas kenaf is the name given to a similar fiber obtained from the stems of plants belonging to the genus *Hibiscus*, family *Malvaceae*, especially the species *H. cannabinus* L. Only two species of *Corchorus*, namely *C. capsular* L. and *C. olitorius* L., are grown commercially, although around 40 wild species are known, whereas other species of *Hibiscus*, particularly *H. sabdariffa* L. are sometimes also marketed as kenaf.

These plants are examples of a number of woody-stemmed berbaceous dicotyledons grown in the tropics and subtropics. Fibers can be extracted from the bast of stems of these plants. Most of the plants cultivated for fiber are grown from seeds annually, as are jute and kenaf, but a few are grown as perennials. Jute is the most important fiber of this type, and it is probable that, in the industrial and engineering uses of textiles. jute is used more than any other single fiber. Kenaf finds use in the domestic market in many countries, but its demand in the international market is much less than that of jute, and estimates of world kenaf production are liable to be erroneous. In many marketing statistics. the production or utilization of "jute and allied fibers" is given to include all the fibers in this group. "Allied fibers" are suitable for processing on jute spinning systems.

Favorable conditions for jute cultivation are found in the deltas of the great rivers of the tropics and subtropics such as the Ganges, the Irrawaddy, the Amazon, and the Yangtze, where alluvial soils and irrigation, often by extensive flooding. are combined with long day lengths to provide an opportunity for considerable vegetative growth before flowering (see Table 7.1). Jute has an optimum growing temperature between 18 and 33°C with a minimum annual moisture requirement of 250 mm in a soil pH between 6.6 and 7.0. Kenaf has an optimum growing temperature between 22 and 30°C with a minimum annual moisture requirement of 150 mm in a soil pH between 6.0 and 6.8. Jute has a growing cycle of approximately 120–150 days with an average yield of 2200 kg/ha, while kenaf has a growing cycle of 150 to 180 days with an average yield of 1700 kg/ha. Since kenaf requires less water to grow than jute, it is now grown in several countries in Europe and South America. and in Mexico. United States, Japan, and China.

Both jute and kenaf grow to 2.5–3.5m in height at maturity. but kenaf, although it still requires a long day length for vegetative growth, flourishes in drier conditions than jute and can adapt to a wider variety of soils and climates. As a result, it is preferred to jute as a fiber

TABLE 7.1
Climatic Requirements for Growing jute and Kenaf

Common name	Optimum temperature (°C)	Minimum moisture (mm)	Optimum soil pH	Growing cycle (days)	Fiber yield (kg ha)
Jute	18–33	250	6.6-7.0	120-150	2200
Kenaf	22-30	120	6.0-6.8	150-180	1700

[a] Water required during the growing season.

crop by many countries in Africa and Latin America. although usually only for internal use. Bangladesh remains the world's principal exporter of this type of fiber. with exports of jute fiber currently running at around 500,000 t/year. This compares with an FAO forecast for world consumption of manufactured jute goods of 4 million tons in 1985.

The commercial use of the base fibers dates back over 150 years, and, although during that time there has been little change in the nature of the technical fiber, considerable developments have taken place in the techniques of conversion to yarn and fabric, and in the end-uses of these products. Scientific studies began around 60 years ago, and although the base fibers did not receive publicity on the scale given to cotton and wool, the broad features of the internal structure and physical characteristics of fibers were elucidated sufficiently long ago for a great deal of common knowledge to he built up. The literature is now extensive. and is contained in a variety of journals. A number of hooks have become standard for reading, and critical reviews of the literature have appeared from time 10 time [1–8]. In the description that follows of the structure and properties of jute and kenaf. this common knowledge is presented without critical annotation of references; instead. a list of the principal books and papers considered relevant is appended

7.2 FORMATION OF FIBER

Jute and kenaf fibers develop in the phloem, or bast. region of the stem of the plants, and they appear as wedge-shaped bundles of cells intermingled with parenchyma cells and other soft tissues (Figure 7.1) in the transverse sections of the stem. In the growing part of the stem, a circumferential layer of primary fibers develops from the protophloem, but, as vertical growth ceases in the lower parts. secondary phloem fibers develop as a result of cambial activity. In mature plants, which reach a height of 2.5–3.5 m and a basal diameter of about 25 mm, the secondary fiber accounts for about 90% of the total fiber bundles.

The plants pass from the vegetative to the reproductive phase when the day length falls below 12.5 h. Vertical growth then ceases and cambial activity declines. The production of cell bundles is much reduced, but, at the same time. the secondary fiber cells begin to mature

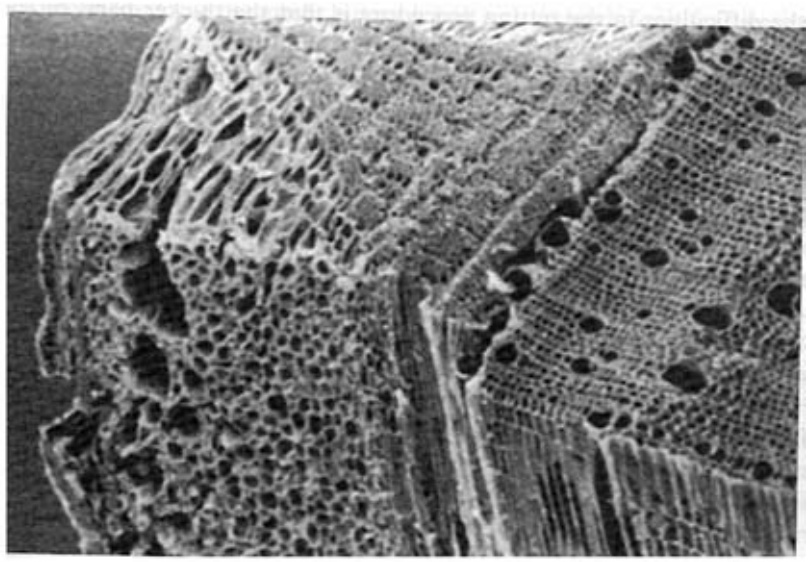


FIGURE 7.1 Jute stem (combined transverse section and longitudinal section). Magnification × 70. (Courtesy of Dr. C.G. Jarman, Tropical Development and Research Instititute, London, UK.)

rapidly. Their walls. which have remained thin during the vegetative period. become thicker. and they increase in weight and strength.

Harvesting the plants at the correct time is most important and requires vast experience. For kenaf. the optimum time for harvesting is when about ten flowers are in bloom. and the older flowers have already set their seed. For jute, the optimum time is judged to be when the plants are in the small-pod stage. Harvesting before flowering generally results in lower yields and weaker fiber, whereas, if the seeds are allowed to mature, the fiber becomes harsh and coarse and difficult to extract from the plant.

The plants are harvested by hand with a sickle and cut close to the ground. The cut stems are then tied into bundles, the leaves removed as much as possible, and the bundles submerged in water for retting. This is the process by which the bundles of cells in the outer layers of the stem are separated from the woody core. and from nonfibrous matter, by the removal of pectins and other gummy substances. The action involves water, microorganisms. and enzymes. and takes between 5 and 30 days for completion, depending on the temperature of the water. Constant supervision is required and the time of removal is critical: if the degree of retting is insufficient, the fiber cannot be easily stripped from the woody core and may be contaminated with cortical cells, whereas, if retting proceeds too far, the fiber cells themselves may be attacked and weakened by microorganisms. Stripping the fiber from the stem is done by hand, after which the fibers are washed and dried.

7.3 SEPARATION OF BAST FIBER FROM CORE

The historical removal of the bark and the separation of bast fiber from the core is done by biological retting. Jute has been retted in India and Bangladesh for several hundreds of years by placing the entire plant in a pond and letting the natural decay process remove the bark and separate the long bast fiber from the core or stick. The process takes from 2 to 3 weeks and requires large quantities of water. Since the water contains a mixture of organisms, many biological reactions take place other than retting. The quality of the bast fiber coming from this process is often reduced due to the mixture of organisms and the dirty water. The core is then used for fuel or for fence posts and the bast is sold for use in textiles.

One of the difficulties in the retting procedure is that the thicker parts of the stem take longer to ret than the thinner parts, and, consequently. if the butt ends of the stem are full) retted, the top ends are over-retted and damaged. This can be avoided by stacking the bundles of stems upright with the butt ends in water for a few days, before immersing the whole stem. However. with the fiber intended for export. it is usual to cut off the partly retted butt ends and sell these separately as “cuttings.”

Correct retting is an essential first step in the production of good-quality fiber. A comprehensive account of the techniques used, and their effect on fiber quality, has been given by Jarman [9]. Controlling the quality of water along with improving microorganisms used in the process are the keys to improve fiber quality. The use of clean water and specific microorganisms has been shown to greatly improve both the efficiency of the retting process and the quality of the bast fiber.

Extensive research has been done on the mechanical separation of the bast from the core on kenaf. The U.S. Department on Agriculture sponsored a research in mechanical “retting” at the Mississippi State University [10] and with a private firm in Bakersfield, California [11]. Chopped whole stock was used in a process involving a spiked cylinder and an airline cleaner [12]. Separation efficiencies of 42 to 48% were achieved. It was found that the moisture content was a critical factor in the separation efficiencies and, if controlled, the separation was cleaner and quicker. Fisher [11] used a modified cotton gin and found separation efficiencies of more than 90%.

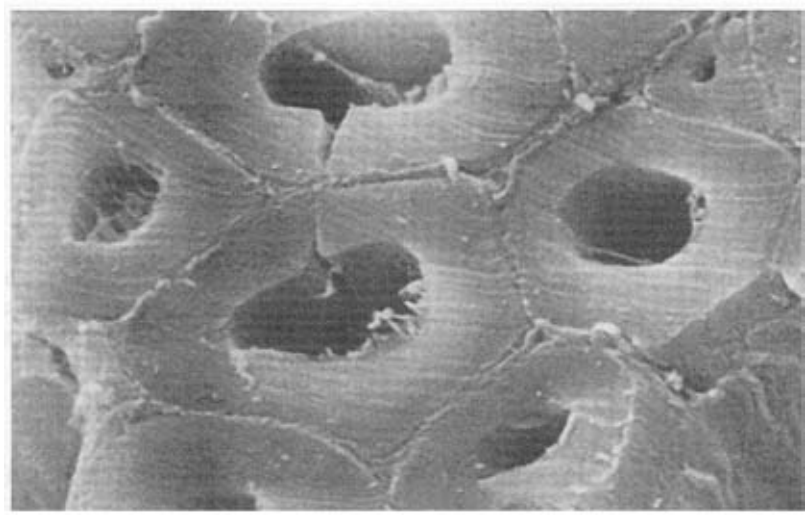


FIGURE 7.2 Part of a fiber bundle of jute as seen in transverse view under the scanning electron microscope. The cementing material between the ultimate fibers can be clearly seen. Magnification × 7600. (Scanning electron micrograph by Mr. A.J. Canning. Courtesy of Tropical Development and Research Institute, London, UK. Crown Copyright, 1982.)

Chemical retting has also been studied using 1, 4, and 7% sodium hydroxide to separate the bast fiber from the core [13].

7.4 FIBER STRUCTURE

In each plant, the rings of fiber cell bundles form a tubular mesh that encases the entire stem from top to bottom. Two layers can usually be distinguished and connected together by lateral fiber bundles, so that the whole sheath is really a lattice in three dimensions [14]. The cell bundles form the links of the mesh, but each link only extends for a few centimeters before it divides or joins up with another link. After extraction from the plant, the fiber sheath forms a flat ribbon in three dimensions.

The jute or kenaf fiber of commerce refers to the sheath extracted from the plant stems. whereas a single fiber is a cell bundle that forms one of the links of the mesh. Staple length. as applied to cotton and wool fibers. has no counterpart in the base fibers. and. ai a preliminary to spinning. it is necessary to break up the sheaths by a carding process. The fragments so produced are the equivalent of the staple fibers of the cotton and wool industries.

When a transverse section of a single jute fiber is examined under the microscope, the cell structure is seen clearly. Each cell is roughly polygonal in shape, with a central hole, or lumen, comprising about 10% of the cell area of cross section, as shown in Figure 7.2. In the longitudinal view the fiber appears as in Figure 7.3, which shows the overlapping of the cells along the length of the fiber. The cells are firmly attached to one another laterally, and the regions at the interface of two cells is termed “the middle lamella.” Separation of cells can be effected by chemical means. and they are then seen to be thread-like bodies ranging from 0.75 to 5 mm in length, with an average of about 2.3 mm. The cells are 200 times longer than they are broad, and, in common terminology, are referred to as “ultimate” cells. A single fiber thus comprises a bundle of ultimates.

Transverse selections of single fibers show that the number of ultimate cells in a bundle ranges from a minimum of 8 or 9 to a maximum of 20 to 25. Bundles containing up to

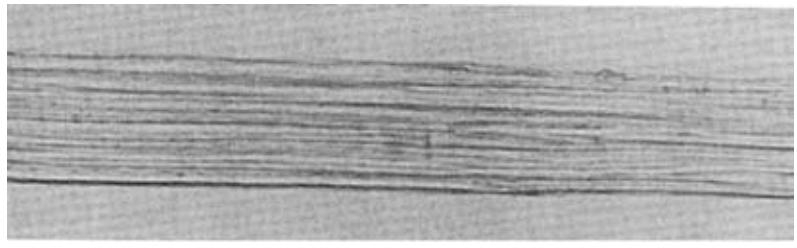


FIGURE 7.3 Longitudinal view of a single fiber strand of jute showing ultimate fibers. The tips of the ultimate can he seen slightly to the right of the center. Stained in safranin. Magnification × 500. (Photomicrograph by Mr. A.J. Canning, Courtesy of Tropical Development and Research Institute, London, UK, Crown Copyright, 1982.)

50 ultimate cells are sometimes reported, but it is then questionable whether the fiber is truly single in the botanical sense, or whether it is two fibers adhering together. A minimum number of cells in the cross section is evidently necessary to provide a coherent and continuous overlapping structure.

Kenaf and many other fiber-bearing dicotyledons have similar ultimate cell dimensions to jute. A distinction must be made between jutelike fibers and flax; however, the ultimate cells in flax are much longer, averaging 20–25mm, although all are described as base fibers. They are also greater in cross-sectional area. and, because of the longer length. a coherent fiber structure can be built up from only two or three overlapping ultimates. The single fibers of flax are thus much finer than those of jute.

The difference between the bast and core fibers in kenaf is shown in Figure 7.4. The bast fibers have thicker walls (see Figure 7.5) as compared to the core fibers. The longitudinal axis of a kenaf bast fiber is shown in Figure 7.6.

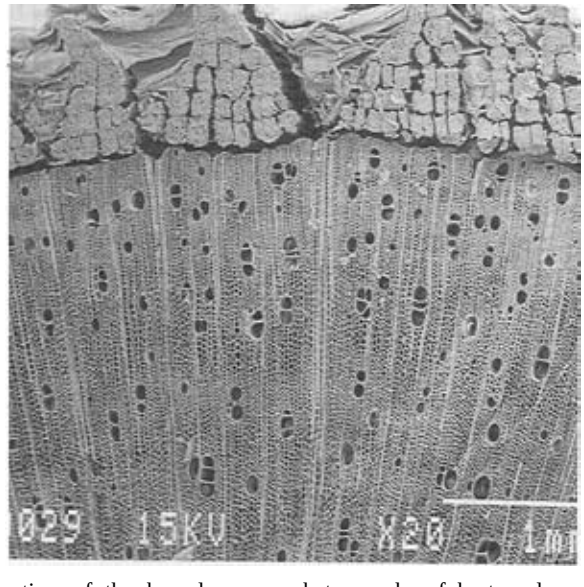


FIGURE 7.4 Cross section of the boundary area between kenaf bast and core. Magnification × 20 (USDA.)

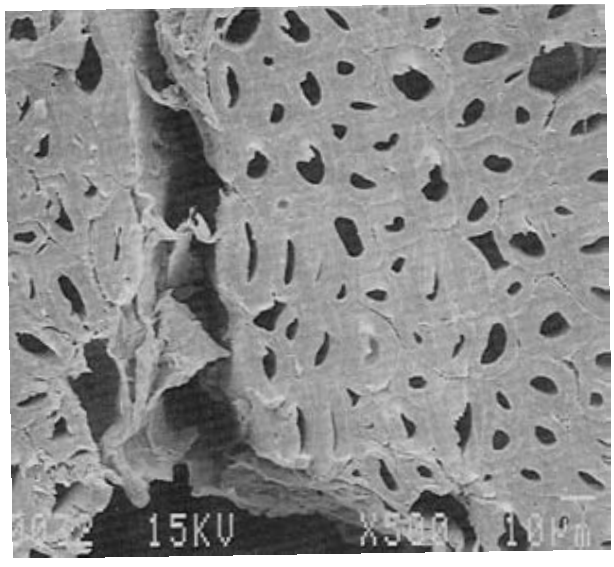


FIGURE 7.5 Cross section of kenaf bast fibers. Magnification × 500 (USDA).

7.5 CHEMICAL COMPOSITION

Retted fibers such as jute and kenaf have three principal chemical constituents, namely, a-cellulose, hemicelluloses, and lignin. The lignin can be almost completely removed by chlorination methods in which a soluble chloro-lignin complex is formed, and the hemicelluloses are then dissolved out of the remaining holocellulose by treatment with dilute alkali. The final insoluble residue is the a-cellulose constituent. which invariably contains traces of sugar residues other than glucose.

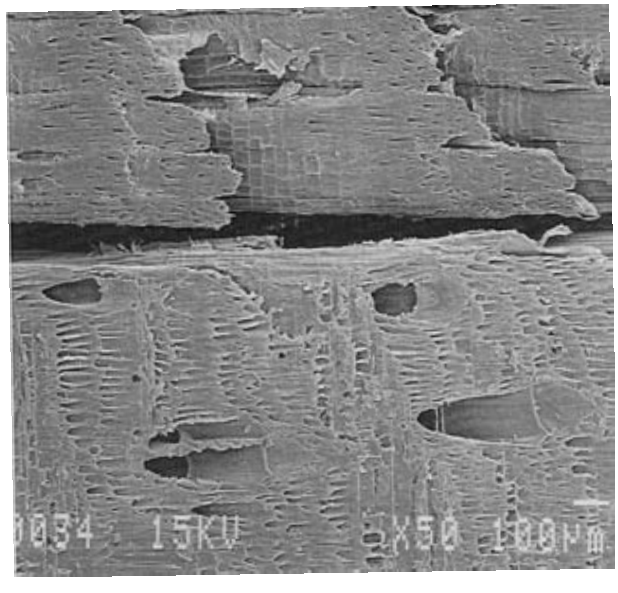


FIGURE 7.6 Longitudinal view of kenaf bast fibers Magnification × 50 (CSDA).

The cellulose has an average molecular weight between 130,000 and 190,000 with an average degree of polymerization of approximately 800 to 1200.

The hemicelluloses consist of polysaccharides of comparatively low molecular weight built up from hexoses, pentoses, and uronic acid residues. In jute, capsularis and olitorius have similar analyses, although small differences occur between different fiber samples. Fiber extracted from jute plants grown in Bangladesh is composed of 12–14% lignin. 58–63%, a-cellulose, and 21–24% hemicellulose [15a]. The average molecular weight of the hemicelluloses is in the range of 24,000 to 27,000.

In addition, analysis of the hemicellulose isolated from a-cellulose and lignin gives 8–12.5% xylan, 24%, galactan, 3-4% glucuronic acid, together with traces of araban and rhamnosan. The insoluble residue of a-cellulose is composed of 55–59% glucosan, 1.8–3.0% xylan. 0.8–1.2% glucuronic acid, together with traces of galactan. araban. mannan. and rhamnosan. All percentages refer to the weight of dry fiber.

Along with the three principal constituents. jute and kenaf contain minor constituents such as fats and waxes, 0.4-0.8% inorganic matter, 0.3–5%, nitrogenous matter, 0.8–1.5%, and traces of pigments. Totally, these amount to about 2%. Table 7.2 shows the chemical composition of both kenaf and jute reported by different laboratories in the United States, India. and Bangladesh [15b].

The detailed molecular structure of the hemicellulose component is not known with certainty, although, in the isolated material, the major part [3] consists of a straight chain of D-xylose residues, with two side branches of D-xylose residues, whose position and length are uncertain. In addition, there are other side branches formed from single residues of 4-*O*-methyl glucuronic acid, to the extent of one for every seven xylose units.

The third major constituent, lignin, is a long-chain substance of high molecular weight which, like the hemicelluloses. varies in composition from one type of vegetable material to another. The molecular chains are built up from comparatively simple organic units that may differ from different sources, and also in the way in which they are combined.

Most of the studies in lignin have been concerned with wood. and the base fibers have been rather neglected. It seems unlikely that any major difference exist between jute and wood lignin: however. many details of the molecular structure still remain unresolved.

7.6 ACETYL CONTENT

Jute and kenaf, like most vegetable fibers, contain a proportion of acetyl goups that are readily hydrolyzed by dilute alkali to acetic acid. Estimation of the quantity of acetic acid produced per unit weight of fiber then provides an index of the acetyl content.

The acetyl content of any particular type of fiber shows some variation according to where it is grown, and under what conditions, but often these intrafiber variations are small compared to the variations arising between fiber types. This is the case with hibiscus and corchorus fibers, for example, and Soutar and Brydon [16] have reported acetyl contents averaging 110 for hibiscus, 89 for *C. capsularis*, and 76 for *C. olitorius*, all expressed in milliequivalents of acetic acid per 100 g of dry fiber. The higher acetyl content of capsularis than oliturius has since been confirmed by Manzoor-i-Khuda [17].

Soutar and Brydon's results show no significant difference between *H. cannabinus* and *H. sabdariffa*, which is, perhaps, surprising in view of the difference between the two juts varieties, but the acetyl content does appear to offer a means of differentiating between jute and kenaf. For such a comparison to be valid, of course, there must have been no prior treatment of the fiber with alkali, which occasionally happens in chemical retting experiments.

TABLE 7.2
Chemical Composition of Kenaf and Jute Reported by Different laboratories

Botanical name	Common name	Location	Cross and Bevan cellulose	a-Cellulose	Lignin	Pentosans	Alcohol benzene	Hot water	1% NaOH	Ash
Hibiscus cannabinus	Kenaf, hurds	IL	53.8d	34.7	15-18	—	3.7	—	30.9	—
Hibiscus cannabinus	Kenaf	FL	52.2d	34.0	10.5	21-23	3.4	—	29.4	—
Hibiscus cannabinus	Kenaf	—	47-57	31-39	12.1	18.3	—	—	—	2-5
Hibiscus cannabinus	Kenaf, stem	MD	53.1cc	36.5	13.2	22.7	4.3	11.2	33.0	—
Hibiscus cannabinus	Kenaf, stem	GA	58.0cc	40.2	7.7	19.7	3.3	7.4	28.4	—
Hibiscuscannabinus	Kenaf, whole	—	54.4cc	37.4	8.0	16.1	—	—	—	4.1
Hibiscus cannabinus	Kenaf, bast	—	57.2cc	42.2	17.4	16.0	—	—	—	5.5
Hibiscus cannabinus	Kenaf, core	—	51.2cc	33.7	13.4	19.0	—	—	—	2.9
Hibiscus cannabinus	Kenaf, bottom	—	53.9d	35.3	—	20.1	3.4	9.7	32.4	—
Hibiscus cannabinus	Kenaf, top	—	46.4d	29.8	—	—	5.5	12.8	39.6	—
Hibiscus cisplantinus	Kenaf	NC	46.1d	30.5	—	—	2.5	—	33.2	—
Hibiscus eelveldeanus	Kenaf	FL	51.9d	36.3	—	—	7.5	—	31.0	—
Corhorus capsularis	Jute	FL	56.3d	39.1	—	—	3.5	—	28.6	—
Corhorus capsularis	Jute	—	57-58	—	21-26	18-21	—	—	—	0.5-1
Corhorus capsularis	Jute	—	58.0	—	26.8	—	0.6	1.4	25.9	1.9
Corhorus capsularis	Jute	—	71.5c	—	8.1	21.6	—	—	—	—
Corhorus capsularis	Jute	India	—	60.7	12.5	—	0.9	—	—	0.8
Corhorus olitorius	Jute	India	—	61.0	13.2	15.6	—	—	—	0.5
Corhorus capsularis	Jute	India	—	58.9	13.5	15.9	—	—	—	0.5
Corhorus capsularis	Jute	India	57.6c	—	21.3	17.0	—	1.1-1.8	—	0.3-5
Corhorus capsularis	Jute	Bangladesh	21-24m	58-63	12-14	18.8	—	—	—	—

Source: From Man, J.S., and Rowell, J.S., *Paper and Composites from Jute and Kenaf Resources*, CRC/Lewis Publishers, Boca Raton, FL 1997, MS 83.

An interesting feature of this study is the measurement of the acetyl content for other fibers covering a wide range of hemicellulose and lignin contents. The authors conclude that the acetyl content shows a steady increase with increase in hemicellulose content, as the latter ranges from about 4 to 26%, but the correlation with varying lignin content is not marked.

An alternative method of distinguishing between jute and kenaf is by means of the crystals in the ash of the fiber after incineration. These crystals are present in the parenchyma and retain their original form during asking. In kenaf. cluster crystals are commonly found in the ash. whereas they are relatively uncommon in the case of jute. Jarman and Kirby [18], however, have shown that jute can be distinguished by the fact that the ash contains solitary crystals occurring in chains. Solitary crystals may occur in kenaf, but not in chains.

7.7 CHANGES IN CHEMICAL AND FIBER PROPERTIES DURING THE GROWING SEASON

Different parts of a plant have different chemical and physical properties. That is, the chemical composition and fiber properties of the plant tissue taken from the roots, stern. trunk, and leaves are different. The chemical composition and fiber properties of the plant tissue are different at different stages of the growing season.

The University of Manchester. the Shirley Institute. and the British Textile Technology Group in the United Kingdom have spent years working on jute. While some of the research has been published, the results relating to the changes in the properties ofjute fiber as a function of the growing season were done for the International Jute Organization in Bangladesh, but were not published [19]. The research records are stored in Bangladesh, and attempts to gain access to them have failed. Personal communications concerning these results indicate that juvenile jute fiber looks and feels like silk, but this has never been documented in print.

Chatterjee, working at the Technological Jute Research Laboratories in Calcutta, India, first reported the changes in chemical composition at different stages of jute plant growth [20]. Table 7.3 shows a summary of his results. These results show that there is little difference in cellulose. holocellulose, and the lignin content, but the content of xylan, ash, and iron decreases as the plant matures. The aggregate fiber length increases as the growing season progresses. Without defining what is meant by “best.” Chatterjee reports that the best fiber is obtained at the bud stage.

Later, Mukherjee et al. while working at the Indian Jute industries’ Research Association in Calcutta, studied characteristics of the jute fiber at different stages of growth [21]. They

TABLE 7.3
Changes in Chemical Composition of Jute at Different Stages of Plant Growth

	Stage of plant growth reported on 100 g of dry material				
Component	Pre-bud	Bud pod	Flower pod	Small	Large
a-Cellulose	58.2	57.6	59.4	58.7	59.1
Holocellulose	86.8	87.8	87.3	87.1	86.8
Xylan	15.5	14.8	14.4	13.7	13.9
Lignin	12.7	12.1	12.4	12.0	12.0
Ash	0.57	0.53	0.47	0.67	0.47
Iron	0.020	0.018	0.009	0.011	0.008
Reed length (mm)	198	273	279	288	321

TABLE 7.4
Changes in Chemical Composition of Kenaf at Different Stages of Plant Growth

	Data from the top 0.66 m of the plant, % by weight					
Component	**90 days after planting**	**120 days after planting**	**138 days after planting**	**147 days after planting**	**158 days after planting**	**244 days after planting**
Hot water extractives	37.4	39.0	35.2	31.6	30.6	12.8
Lignin	4.5	3.9	6.4	7.2	7.4	11.4
a-cellulose	10.6	14.5	18.5	18.1	20.6	29.8
Pentosan	5.0	12.5	16.1	17.0	16.7	20.1
Protein	25.0	17.9	16.1	13.3	14.9	11.1

found that, at the early stages of growth, there was an incomplete formation of the middle lamella in the cell wall and the parallel bundles of fibrids were oriented at an angle with respect to the fiber axis that gradually decreased with growth. After about 35 days of growth, the fibrils run parallel to the fiber axis. In the mature plant, a few helically oriented fibrils were observed in the 2-direction just below the primary cell wall layer.

Clark and Wolff carried out the first studies on the changes in the chemical composition of kenaf as a function of the growing season [22]. They also studied the chemical differences along the stem and between leaves and stem. This data showed that the pentosans, lignin, and a-cellulose content increases with age. while the protein and hot water extractives content decreases with age. Data taken from the top part of the plant shows similar trends: however, the top part has less cellulose. pentosans. and lignin, but higher hot water extractives and protein than the bottom part of the plant (Table 7.4).

TABLE 7.5
Changes in Fiber Properties of Kenaf at Different Stages of Plant Growth

	Stage of plant growth			
Component	90 days after planting	120 days after planting	150 days after planting	180 days after planting
Bast fiber				
Length (mm)	3.34	2.28	2.16	2.42
Width (microns)	18.3	14.5	13.6	15.1
Lumen width (microns)	11.1	5.4	6.8	7.7
Cell wall				
Thickness (microns)	3.6	4.6	3.4	3.7
Core fiber				
Length (mm)	0.55	0.54	0.45	0.36
Width (microns)	36.9	31.2	32	31.6
Lumen width (microns)	22.7	14.8	18.6	18.7
Cell wall				
Thickness (microns)	7.1	8.2	6.7	6.4

TABLE 7.6
Crystallinity Values (dap = Days after Planting)

	C-108		1-1		E-41		45–9	
after planting	fiber	core	fiber	core	fiber	core	fiber	core
56	84.25	78.38	80.77	87.72	78.4	81.08	80.53	82.35
84	78.87	72.13	76.43	73.85	81.48	72.22	77.62	76.92
112	78.91	78.87	73.94	70.63	80.43	71.79	78.32	75.41
140	80.71	72.31	80.29	79.39	78.17	66.93	78.10	68.18
168	73.57	66.93	77.77	65.19	70.90	64.00	74.64	67.19
196	72.34	68.18	72.86	73.11	70.63	69.53	68.38	70.83

Clark et al. also studied the changes in fiber properties during the growing season [23]. Table 7.5 shows that the bast single fibers are longer than core fibers and both decrease in length with age. Core single fibers are twice as wide and have twice the cell wall thickness as bast single fibers and both dimensions decrease with age. Finally. the lumen width is wider in pith fibers as compared to bast single fibers and both decrease with age.

In a recent study, Han et al. reported changes in kenaf as a function of the growing season [24]. Their data do not necessarily agree with that of Clark and Wolff. The most critical difference between Han et al. and Clark and Wolff was the difference in fiber lengths. The average length of a bast and core (stick) fiber increased as the plant aged in contrast to that of Clark and Wolff.

Han et al. studied changes in the chemical composition during the growing season for four varieties of kenaf. C-108, Tainung-1, Everglade 45-49, and Everglade 41 [24]. Samples were collected weekly starting from about 50 days after the planting (dap) to the end of growing at about 170 days after planting.

X-ray diffraction of kenaf samples were used for crystallinity values (Table 7.6). Cystallinity values decreased as the plant matured.

Ash contents of fibers and cores were determined before and after extraction (Table 7.7). Ash content decreased as the plant reached maturity.

The protein content of fibers and cores was determined before and after the extraction (Table 7.8). The protein content decreased as the plant reached maturity.

Extractives, lignin, and sugar contents were also determined (Table 7.9). The values are. averages of four different cultivars. Klason lignin analysis was done after the extraction. The Klason lignin values increased from ca. 4% at the beginning to 10% at the end of the growing season (Bagby et al. reported about 10% using Florida kenaf) [25]. This value is significantly lower than that of softwood (26–32%)and hardwood (10–28%).The actual value of Klason

TABLE 7.7
Ash Content (T-1) (% Dry Basis)

Growth days after planting	Fiber-(Unext)	Fiber-(Ext)	Core-(Unext)	Core-(Ext)
49	13.08	9.54	14.52	7.77
98	7.52	6.83	5.10	4.21
147	6.24	6.00	4.55	4.44
175	3.76	3.84	2.84	2.39

TABLE 7.8
Protein Content (T-1) % (Dry Basis)

Growth days after planting	Fiber-(Unext)	Fiber-(Ext)	Core-(Unext)	Core-(Ext)
49	10.6	7.65	12.75	8.00
98	4.25	3.25	4.85	4.65
147	2.05	3.35	3.40	3.20
175	1.43	1.23	4.15	3.28

lignin could be lower than it appears to be due to the presence of protein in the kenaf. Kjeldahl determination of protein was performed. (Han et al. combined several batches of Klason lignin samples and measured the amount of protein in the Klason lignin.) [24]. The protein content of kenaf was between 4 to 14% of the Klason lignin. depending on the age of the plant. Only 38% of the protein was found in the Klason lignin and the rest was found in the hydrolysate :unpublished FPL Data). In general, the protein content decreased with plant age.

The solvent extractive content varied as a function of growth. In general. it was high in the beginning, decreased during the first part of the growing time. and then increased again. L-Arabinose, L-rhamnose, L-galactose, and D-mannose content decreased as a function of growth. while D-glucose and D-xylose content increased over this same period of time.

The fiber length increased as a function of growth (Table 7.10). The core fiber lengths were ca. 0.8 mm at the end of 84 growing days with an average diameter of ca. 0.5 mm.

The weights ratio between the fiber and the core (core/fiber) increased as the growing days advanced (Table 7.11). A maximum of 1.8 was reached at 175 days after planting in T-1.

The holocellulose content was measured after the extraction (Table 7.12). The juvenile samples had low holocellulose values and gradually increased as the plant aged.

The height of the plant increased with the age of the plant at an even rate. This is a function of the growing conditions and would change with different moisture and sun

TABLE 7.9
Chemical Composition of Kenaf Fiber (% Oven Dry Basis)

Growth days after planting	Extractives	Klason lignin	Polysaccharides content (% anhydro sugars on oven dry basis)					
			arabinan	rhamnan	galactan	glucan	xylan	mannan
35	14.87	4.32	3.95	2.72	0.78	28.86	6.54	1.76
42	8.80	6.00	3.18	1.82	0.62	33.20	7.31	1.63
57	5.13	8.32	2.21	1.46	0.55	35.45	8.08	1.59
63	4.34	7.74	2.43	1.18	0.62	37.08	8.61	1.53
70	4.63	8.70	2.03	1.25	0.46	40.53	9.37	1.47
77	4.99	9.23	2.05	1.36	0.39	40.52	9.16	1.34
84	5.07	8.33	2.27	1.63	0.49	39.88	9.39	1.53
91	5.68	9.38	1.91	1.35	0.42	42.82	9.98	1.31
98	2.42	8.81	2.13	1.43	0.48	41.60	9.69	1.35
133	8.03	8.94	1.67	1.15	0.48	41.98	9.72	1.31
155	7.83	9.99	1.27	0.87	0.38	46.39	11.20	1.19
161	11.51	10.22	2.54	1.52	0.56	39.22	9.75	1.33
168	12.31	9.74	2.18	1.37	0.47	41.41	10.36	1.39
175	8.23	9.69	1.40	0.87	0.36	49.33	12.29	1.02

TABLE 7.10
Fiber Length (Unit = mm)

Growth days after planting	C-108		Tainung - 1		45-49	
	Bast	Core	Bart	Core	Bast	Core
50	2.3	0.7	2.2	0.7	2.2	0.7
60	2.7	0.7	2.8	0.7	2.7	0.7
17	2.9	—	3.0	—	3.0	—
84	3.4	0.8	3.1	0.8	3.7	0.8

conditions. The diameter of the stalk was also increased gradually with age until 160 days after planting. At the end of 160 days after planting, the rate of the growth became more significant. However, this dramatic increase in volume is indicative of an increase in the core and not the bast fiber. A maximum weekly growth of 30 cm was achieved during high temperature and a good rainfall.

Scanning electron microscopy (SEM) studies indicate that the bast fiber bundles are thin walled at 63 days after planting and are in the process of thickening. The middle lamella is not well formed, as suggested by the weak bonding. The fibers' tendency to gelatinize may be due to the wind effect that often results during the bending of plants. At this stage. the parenchyma bands separating the bast fiber bundles are well formed and occupy a considerable area of tissue system.

At 71 days after planting, the plants become comparatively stronger as bast fiber bundles occupy more area, the fiber wall thickens. and lignification of middle lamella becomes

TABLE 7.11
Weight Ratio of Fiber versus Core

Growth days after planting	C-108	T-1	45-49	E-41	C/F Ave
53	0.88	0.90	0.87	0.74	0.85
57	0.93	1.17	1.02	1.03	1.03
63	1.02	1.10	1.11	1.05	1.07
70	1.29	1.10	1.31	1.14	1.21
77	1.19	1.03	1.15	1.31	1.17
84	1.10	1.33	1.12	1.25	1.20
91	1.42	1.23	1.22	1.41	1.32
98	1.14	1.33	1.03	1.22	1.18
105	1.23	1.94	1.09	1.22	1.37
112	1.16	1.36	1.03	1.80	1.34
120	1.23	1.30	1.01	1.29	1.21
126	1.21	1.62	1.19	1.41	1.36
133	1.28	1.70	1.25	1.30	1.38
110	1.24	1.82	1.41	1.78	1.57
147	1.31	1.31	1.45	1.24	1.32
155	1.40	1.71	1.39	1.98	1.62
161	1.57	2.12	1.69	1.64	1.76
175	1.31	1.81	1.33	1.83	1.57

TABLE 7.12
Holocellulose Content

Growth days after planting	Holocellulose (%)	Growth days after planting	Holocellulose (%)
35	55.97	42	64.47
49	68.24	57	69.02
63	73.91	70	75.69
77	76.52	84	74.15
91	76.13	98	74.87
105	73.65	126	75.40
133	75.27	140	78.50
147	76.18	161	73.88
168	76.27	175	78.60

apparent. Parenchyma cells tend to crash due to the development of fiber bundles, thus allowing more area to he occupied by fiber bundles. At 84 to 108 days after planting, the bast fiber bundles comprising of primary and secondary phloem fibers tend to show more thickening, and the separation of primary and secondary phloem fibers becomes obvious. The secondary phloem fibers start thickening, but with a somewhat weak middle lamella. At this stage of development, in addition to wall thickening, a deposition of silica on the wall surface is seen. The fibers are long and broad and are mainly comprised of an S_2 layer that is encrusted with amorphous silica. At 112 days after planting, bast fiber bundles comprising of primary phloem fibers and secondary phloem fibers are thickened with prominent middle lamella formation. The cells are compact with thickened cell walls and decreased lumen width. The middle lamella is not well lignified at this stage of maturity. The fibers are long and broad with a well-formed S_2 layer [24].

Similar sequential development is seen in secondary phloem fibers. At 63 days after planting, there is little thickening of the fiber wall and the fibers thicken gradually with maturity from 73 days to 112 days after planting.

7.8 FINE STRUCTURE

The location of the three main chemical components of the fibers are reasonably well established. Alpha cellulose forms the hulk of the ultimate cell walls, with the molecular chains lying broadly parallel to the direction of the fiber axis. The hemicellulose and lignin, however. are located mainly in the area between neighboring cells, where they form the cementing material of the middle lamella, providing strong lateral adhesion between the ultimates. The precise nature of the linkages that exist between the three components. and the role played by the middle lamella in determining the fiber properties. are not completely understood. Lewin [26], some years ago. in an interesting literature survey on the middle lamella of base fiber, brought together a great deal of relevant information that highlighted man? of the problems, but a thorough understanding of the intercell structure is still awaited.

X-ray diffraction patterns show the basic cellulose crystal structure. but. in jute and kenaf. although the crystallite orientation is high, the degree of lateral order is relatively loa in comparison with. for example, flax. There is also considerable background x-ray scattering arising from the noncellulosic content of the fiber.

The cellulose molecular chains in the secondary walls of ultimate cells lie in a spiral around the fiber axis. The effect of this is to produce double spots in the x-ray diffraction

patterns. the centers of the spots separated by an angular distance of twice the Bragg angle. For large angles. such as those that occur in coir fiber, and some leaf fibers such as mauritius hemp, the two spots are visibly separated, but. for the small angles found in jute and kenaf. the spots overlap. In this case, the distribution of intensity across the width of the spots. instead of reaching a peak at the center of each, is spread out into a single, flatter, peak. The [002] equatorial reflection shows these effects particularly well, and the analysis of the intensity distribution allows calculation of the Hermans RMS spiral angle. A wide range of base and leaf fibers have been examined in this way [27], with results showing the Hermans angle to range from about 8° for jute and kenaf to up to 23° for sisal. Coir fiber, *Cocos nuciferos,* is an exception, having a Hermans angle of about 45°.

The leaf fibers cover a wide range of ultimate cell dimensions along with covering a good range of spiral angles. The results indicate that. among this group of fibers, the spiral structure averages a constant number of turns per unit length of cell. about 10 per mm. and, with this arrangement, the spiral angle then depends solely on the breadth of the cell. Whether this constancy of turns applies to individual cells. or whether as in wood. the longer cells tend to have steeper spirals, was not, however, investigated.

For the secondary base fibers, the cell dimensions show little variation between plant species, but the number of spiral turns per unit length of cell averages only about four per millimeter, appreciably less than for the leaf fibers.

The importance of the spiral angle measurements lies in the control that the spiral structure exercises on the extension that the fiber can withstand before breaking. Regarding the structure as a helical spring, the extension necessary to straighten a spring of initial angle q, to the axis is (sec q - 1) × 100%. A 10° spring will thus extend by 1.54%, a 20° spring by 6.4%, and a 30° spring by 15.5%.

The coconut fiber coir has a spiral of about 35° and its helical spring extension is 41.4%. Such a large extension is easily measured and has been shown to be reasonably correct. Moreover, it is possible to carry out the extension in stages and to measure the angle whereas the fiber is stretched and under tension. X-ray measurements showed the angle to decrease with the extension as predicted by the spring structure. and it was concluded that the extensibility of coir fiber is almost entirely due to the spiral structure of the ultimate cells [28]. This has been confirmed by other studies in which the spirality of the cell wall was investigated microscopically using replica and ultrathin sectioning techniques [29].

It is interesting to note that when coir fiber relaxes after stretching, it shortens in length and the spiral angle increases according to the spring theory. There is usually a semipermanent set left in the fiber after relaxation. but this can be removed by steaming and the fiber can be restored virtually to its original unstretched length.

It is difficult to carry out similar measurements of the extension–spiral angle relationship for low-angle fibers such as jute and kenaf because, as the changes in angle are small, the overlapping of the spots in the x-ray diffraction pattern could introduce significant errors. With coir, the angles over most of the extension range are measurable to a higher degree of accuracy.

Assuming. therefore. that the coir results are of general applicability to fiber cells, it appears that the helical spring theory could be used to calculate the order of magnitude of the extensibility of the fiber, and to rank fibers accordingly.

7.9 PHYSICAL PROPERTIES

Jute and kenaf are strong fibers, exhibiting brittle fracture, but having only a small extension at break. They have a high initial modulus, but show very little recoverable elasticity. Tenacity measurements recorded in the literature vary widely, and, although some of this

variation is due to differences in the methods of measurement, a major part arises from variations in the linear density of the fibers themselves. All linear densities are given in tex units of grams per kilometer.

Taking account of all the available evidence. a tenacity of 70 g/tex is a reasonable middle value for a wide range of jute fibers, based on single fiber test lengths of 10 mm or less, and a time to break of 10 s. This value of tenacity is appropriate to fibers of linear density 1.8 tex. and it is important to state the linear density, because, statistically, an increase of 0.1 tex reduces the tenacity by about 1.5 g/tex. This inverse dependence of tenacity on linear density is common to most fibers and also to tine metal wires.

The elongation at which a fiber breaks is a more invariant and fundamental property than the load at which it breaks. It is neither affected significantly by changes in linear density nor by changes in the method of loading. The length of the test specimens does have an effect, however, as irregularities in diameter prevent all sections of a long fiber from being elongated equally. For test lengths of 10 mm, the elongation is generally between 1 and 2% of the initial length. but is difficult to measure accurately with such short lengths. In one particular case, 500 fibers from a bulk of medium-quality jute had a mean elongation of 1.60% (of the 10-mm test length) with a coefficient of variation (CV) of 25%. The breaking load of the fibers, however, had a much higher CV of 40% [30]. It may be noted that 1.6% elongation corresponds to a spiral angle of 10° 12′, which, although slightly greater than the Hermans angle reported. is still within the uncertainty of the comparison.

The initial Young's modulus of the fibers, calculated from the slope of the load–elongation curve, has a mean value of about 4 × 103 g/tex/ 100% extension. The value for any particular group of fibers will, of course, be dependent on the linear density, to some extent, owing to the dependence of tenacity values on this factor.

The bending of jute fibers has been studied by Kabir and Saha, who calculated the Young's modulus from measurements of the force required to deflect the free ends of a fringe of fibers arranged in a cantilever fashion [31]. For this calculation, it is necessary to know the fiber diameter instead of the linear density. and this causes difficulty because the cross section of the fibers is irregular in outline and often far from circular. The authors assumed an elliptical configuration, and measured minimum and maximum diameters of a number of cross sections microscopically for insertion in the appropriate formula. Their calculations showed that. over a wide range of commercial fiber qualities. Young's modulus decreased over 60% between an average diameter of 46 mm to a diameter of 68 mm. These values correspond to 3050 and 815 g/tex/100'% extension, respectively, and again demonstrate the marked effect of variations in fiber dimensions. Extrapolations of Kabir and Saha’s data to smaller diameters show that the tensile value for the modulus of 4000 g/tex/100% extension would he reached at a mean diameter of about 40 mm.

Kabir and Saha also examined the effect of delignification on the bending modulus of jute. using the fringe technique. and showed that successive extractions of lignin on the same fibers resulted in increasing flexibility and decreasing Young's modulus [32]. The deligification method was treatment with sodium chlorite solution followed by extraction with sodium bisulfate, and removal of 10% of lignin reduced the modulus by more than 30%. At the same time, however. the diameter of the fibers was reduced significantly. and this may have affected the flexibility.

7.10 GRADING AND CLASSIFICATION

The grading and classification of base fibers such as jute and kenaf for commercial purposes has a long history, but is still done subjectively by hand and eye. Official standards hare been formulated. but these are purely descriptive and no quantitative values are assigned to the

stated criteria. Nevertheless, a surprising degree of consistency is achieved. particularly for export purposes, and experienced buyers and sellers do not find it too difficult to find out whether or not the grade assigned to a particular consignment of fiber is correct.

For jute fiber exported from Bangladesh, for example. the current grading system first separates *C. capsularis* and *C. olitorius* into white and tossa categories, respectively, and then further classifies each into five grades denoted by the letters A to E. The highest prices are paid for Grade A, although sometimes a special grade is introduced for which a higher price can be demanded.

The principal criteria used are color, luster, strength, cleanliness, and freedom from retting defects. From a spinning point of view. color is irrelevant. but certain end-users traditionally prefer particular colors of fiber for the sake of appearance. Luster is commonly an indication of strength. for if. for example, the fiber has been over-retted so that the cellulose. or middle lamella, has been attacked and weakened, the surface appears dull. A lack of luster thus downgrades the fiber. although occasionally this same effect may result from inadequate washing, without any loss of strength. The strength of the fiber is also assessed by snapping a few strands by hand—a qualitative procedure that gives a useful indication to an experienced operator.

Cleanliness and freedom from nonfibrous matter is an important feature, and, in this respect, the physical imperfections that may result from improper retting can have a profound effect on the allotted grade. Adhering hark in any form results in downgrading. irrespective of the intrinsic value of the fiber, and, in the case of plants grown on flooded land. which stand in water, the hark becomes so difficult to remove that. for export, the root ends are cut off and sold separately as "cuttings" to he used in heavy yarns of low quality.

The linear density of the individual fibers making up the network is given little consideration. despite the importance of this characteristic in staple fibers. where it is a major factor controlling the levelness of the spun yarn. Adhering bark increases the linear density of the fiber and makes subjective assessment difficult.

Manzoor-i-Khuda et al. [17] have studied the variation in chemical constituents of jute fiber taken from different grades of both white and tossa and concluded that certain correlations exist between the analytical results and the commercial grade. Thus. it is claimed that the lignin content increases as the grades go from higher to lower, and that the ash content and copper number show similar negative correlations.

Although it might he expected that variations in the chemical composition would result in variations in physical characteristics, a correlation with grade is surprising. The chemical composition is that of the fiber itself, and can scarcely take account of the physical imperfections resulting from inadequate retting. which are so important in commercial grading.

The essential feature of any system of grading is that it be self-consistent in the sense that buyers and sellers can mutually agree on the attributes of fiber placed in a particular grade. However. it does not follow that a subjective system based on appearance and feel will classify fiber in a similar manner to an objective system based on measurement. Both systems may be valid. but in different ways, and there is no need to seek a close correlation between them except. perhaps. for the top and bottom grades.

Commercial buying and selling takes place by a subjective system. A buyer selects a range of fiber grades from which blends are made appropriate to the different yarn qualities required. If these fiber grades can now be measured for quality on an objective system, more precision in blending will be possible.

Any system of objective grading based on measurable characteristics must, in fact, be concerned with the fiber as it is, including nonfibrous matter, and not merely with the single fibers themselves. With this precondition in view. Mather [33], in work extending over a decade at the British Jute Trade Research Association laboratories in Scotland, studied the classification of a bulk of jute for its "spinning quality."

7.11 FIBER AND YARN QUALITY

The principal outlets for jute yarns are for industrial purposes in which. to give a satisfactory performance, adequate strength is essential. Appearance and color are of little significance. and so for jute yarns "quality" relates specifically to tensile properties. An objective classification of fiber in bulk thus requires the identification of those attributes of the raw fiber that affect yarn strength. Each grade of fiber bought commercially must then have these attributes measured and the grades assessed for corresponding yarn quality. By blending together fibers having different values of these attributes, the average value serves to predict the tensile strength properties of the yarn spun from the blend.

From an extensive series of correlations between fiber properties and yarn properties. Mather concluded that the tensile properties of a yarn could be predicted from two measurements only on the raw fiber, namely. the linear density and the ballistic work of rupture of uncarded strands of fiber.

The linear density was measured by an air-flow method using a modification of apparatus designed for cotton and wool. A sample of fiber weighing 27 g was used. and care was taken to include in the sample a similar amount of nonfibrous matter as was contained in the bulk. The nonfibrous component effectively increased the linear density, and a less regular yarn resulted when spun to a fixed count.

The ballistic work of rupture was measured by stretching strands of fiber. of known linear density, transversely across the path of a falling pendulum and recording the energy lost by the pendulum in breaking the strands. The energy lost per tex is then a measure of the specific work of rupture and is related to the product of tensile strength and extensibility. The particular feature of the work of rupture is that it appears to control the average length of fiber after carding. Staple length has no meaning in the bulk fiber, and it is only after the mesh has been fragmented by carding that average length becomes meaningful.

The yarns were spun on a standard system of carding, drawing, and spinning frames, programmed to produce yarn of linear density 275 tex. Different spinning systems and different linear densities also affect yarn strength. and this must be taken into account. It is inappropriate todiscuss the technology of jute spinning in this article, but a detailed account oftheexperimental work on which Matheis conclusions are based has been compiled by Stout [34].

Quantitatively. Mather concludes that for jutes exported from Bangladesh (or the erstwhile East Pakistan), the range of linear density is about 1.3–2.4tex, whereas work of rupture ranges from 4.0 to 8.3 g/cm/tex. For kenaf, although work of rupture is little different, the linear density is often higher than for jute. and a survey of *H. sabdariffa* grown in Thailand showed a range of 1.9–3.0rex.

Moreover, in the overlapping region of linear density 1.9–2.4g/cm/tex, it was noticeable that the kenaf fibers were intrinsically coarse but free from nonfibrous matter, whereas the jute fibers were intrinsically much finer but carried a significant amount of adhering bark.

It was also concluded from the statistical correlations that the change in the tenacity of a jute yarn, resulting from a certain percentage change in fiber linear density, is about three times greater than that resulting from a similar percentage change in ballistic work of rupture. Moreover, no correlation was found between linear density and work of rupture, so that these two parameters must exercise their effects quite separately.

The fiber linear density is a measure of the average number of fibers in the cross section of a given yarn. and this controls the yarn irregularity. The more fibers in the cross section, the more uniform is the yarn thickness from point to point. As yarns break at their thinnest points. the breaking load is greater. irrespective of the intrinsic fiber strengh.

The high modulus of jute has, in turn, made jute materials a partial substitute for glass fiber as a reinforcement for polyester or epoxy resins in resin transfer technologies. It has not,

however. found general acceptance in this reinforcement field, partly because it provides lower impact strength than glass and partly because the economic advantages are not sufficiently attractive. Jute and kenaf have found success as reinforcement fillers in thermoplastic composites. This is discussed in another section in this chapter.

7.12 CHEMICAL MODIFICATION FOR PROPERTY IMPROVEMENT

The performance of any lignocellulosic fiber composite is restricted by the properties of the fiber itself. Jute and kenaf composites change dimensions with changes in moisture content, are degraded by organisms, are degraded by ultraviolet radiation, and burn. If these negative properties of the natural fiber can be improved. all types of jute and kenaf composites can have a greatly improved performance. To understand how jute and kenaf fiber can be used in property-enhanced applications, it is important to understand the properties of the components of the cell wall and their contributions to fiber properties.

Jute and kenaf, like all agro (lignocellulosic) fibers, are three-dimensional polymeric composites, primarily made up of cellulose, hemicelluloses, lignin, and small amounts of extractives and ash. The cell wall polymers and their matrix make up the cell wall and are. in general, responsible for the physical and chemical properties of the jute and kenaf fiber. Properties such as dimensional instability, flammability, biodegradability, and degradation caused by acids, bases, and ultraviolet radiation are a result of the environment trying to convert the natural composites back into their basic building blocks (carbon dioxide and water).

Jute and kenaf fibers change dimensions with changing moisture content because the cell wall polymers contain hydroxyl and other oxygen-containing groups that attract moisture through hydrogen bonding. The hemicelluloses are mainly responsible for moisture sorption. but the accessible cellulose. noncrystalline cellulose, lignin, and surface of crystalline cellulose also play major roles. Moisture swells the cell wall and the fiber expands until the cell wall is saturated with water. Beyond this saturation point. moisture exists as free water in the void structure and does not contribute to further expansion. This process is reversible and the fiber shrinks as it loses moisture.

Jute and kenaf fibers are degraded biologically because organisms recognize the carbohydrate polymers (mainly the hemicelluloses) in the cell wall and have very specific enzyme systems capable of hydrolyzing these polymers into digestible units. Biodegradation of the high-molecular-weight cellulose weakens the fiber cell wall because crystalline cellulose is primarily responsible for the strength of the cell wall. Strength is lost as the cellulose polymer undergoes degradation through oxidation, hydrolysis, and dehydration reactions. The same types of reactions take place in the presence of acids and bases.

Jute and kenaf fibers exposed outdoors undergo photochemical degradation caused by ultraviolet light. This degradation takes place primarily in the lignin component, which is responsible for the characteristic color changes. The lignin acts as an adhesive in the cell walls. holding the cellulose fibers together. The surface becomes richer in cellulose content as the lignin degrades. In comparison to lignin, cellulose is much less susceptible to ultraviolet light degradation. After the lignin has been degraded, the poorly bonded carbohydrate-rich fibers erode easily from the surface, which exposes new lignin to further degradative reactions. In time. this “weathering” process causes the surface of the composite to become rough and can account for a significant loss in surface fibers.

Jute and kenaf fibers burn because cell wall polymers undergo pyrolysis reactions with increasing temperature to give off volatile, flammable gases. The hemicellulose and cellulose polymers are degraded by heat much before the lignin is degraded. The lignin component

contributes to char formation, and the charred layer helps insulate the composite from further thermal degradation.

Because the properties of the jute and kenaf fiber result from the chemistry of the cell wall components. the basic properties of a fiber can he changed by modifying the basic chemistry of the cell wall polymers.

Dimensional stability can he greatly improved by bulking the fiber cell wall either with simple bonded chemicals or by impregnation with water-soluble polymers. For example. acetylation of the cell wall polymers using acetic anhydride produces a fiber composite with greatly improved dimensional stability and biological resistance. The same level of stabilization can also he achieved by using water-soluble phenol–formaldehydepolymers followed by curing.

Biological resistance of fiber-based materials can he improved by several methods. Bonding chemicals to the cell wall polymers increases resistance due to the lowering of the equilibrium moisture content point below that needed for microorganism attack and by changing the conformation and configuration requirements of the enzyme–substrate reactions. Toxic chemicals can also he added to the composite to stop biological attack. This is the basis for the wood preservation industry.

Resistance to ultraviolet radiation can he improved by bonding chemicals to the cell wall polymers, which reduces lignin degradation. or by adding polymers to the cell matrix to help hold the degraded fiber structure together so that water leaching of the undegraded carbohydrate polymers cannot occur. Fire retardants can be bonded to the fiber cell wall to greatly improve the fire performance. Soluble inorganic salts or polymers containing nitrogen and phosphorus can also be used. These chemicals are the basis of the fire-retardant wood-treating industry.

The strength properties of fiber-based composites can be greatly improved in several ways. The finished composites can be impregnated with a monomer and polymerized *in situ* or impregnated with a preformed polymer. In most cases. the polymer does not enter the cell wall and is located in the cell lumen. By using this technology. mechanical properties can he greatly enhanced. For example, composites impregnated with acrylates, methacrylate. epoxy. or melamine monomers, and polymerized to weight gain levels of 60 to 100% show increases (compared to untreated controls) in density from 60 to 150%, compression strength from 60 to 250%, and tangential hardness from 120 to 400%. Static bending tests show 25% increase in modulus of elasticity, 80% in modulus of rupture, 80% in fiber stress at proportional limit, 150% in work to proportional limit. and 80% in work to maximum load, and at the same time a decrease in permeability of 200 to 1200%

Many chemical reaction systems have been published for the modification of agrofibers. These chemicals include ketene, phthalic, succinic, maleic, propionic and butyric anhydrides. acid chlorides. carboxylic acids, many types of isocyanates, formaldehyde, acetaldehyde. difunctional aldehydes, chloral, phthaldehydic acid, dimethyl sulfate, alkyl chlorides, beta-propiolactone, acrylonitrile, ethylene, propylene, and butylene oxide, and difunctional epoxides [35,36].

7.12.1 ACETYLATION

By far, maximum research has been done on the reaction of acetic anhydride with cell wall polymer hydroxyl groups to give an acetylated fiber. Jute [37–39] and kenaf [40, 41] have been reacted with acetic anhydride. Without a strong catalyst, acetylation using acetic anhydride alone levels off at approximately 20 weight percent gain (WPG). The equilibrium moisture content (EMC) and thickness swelling at three relative humidities for fiberboards made from these fibers is shown in Table 7.13.

The rate and extent of thickness swelling in liquid water of fiberboards made from control and acetylated fiber are shown in Table 7.14. Both the rate and extent of swelling are greatly

TABLE 7.13
Equilibrium Moisture Content (EMC) and Thickness Swelling (TS) of Fiberboards Made from Control and Acetylated Fiber

Fiber	Weight percent gain	EMC and TS at 27 C					
		30% RH		65% RH		90% RH	
		TS	EMC	TS	EMC	TS	EMC
Kenaf	0	3.0	4.8	96	10.5	33.0	26.7
	18.4	0.8	2.6	2.4	5.8	10.0	11.3
Jute	0	3.7	5.8	5.6	9.3	17.4	18.3
	16.2	0.6	2.0	1.7	4.1	7.3	7.8

reduced as a result of acetylation. At the end of 5 days of water soaking, control boards swelled 45%, whereas boards made from acetylated fiber swelled 10%. Drying all boards after the water-soaking test shows the amount of irreversible swelling that has resulted from water swelling. Control boards show a greater degree of irreversible swelling as compared to boards made from acetylated fiber.

Table 7.15 shows the results of jute cloth acetylated to different levels of acetylation in a fungal cellar test. The fungal cellar is made using unsterilized soil that contains a mixture of white-, brown-, and soft-rot fungi. Control cloth shows a fungal attack at 2 months and is completely destroyed at 6 months. The acetylated cloth at 7.4 PWG shows a slight attack at 3 months and is destroyed at 12 months. At a level above 16% weight gain, the acetylated cloth is not attacked at 36 months [42].

The modulus of rupture (MOR). modulus of elasticity (MOE) in bending, and tensile strength (TS) parallel to the board surface are shown in Table 7.16 for fiberboards made from control and acetylated kenaf fiber. Acetylation results in a small decrease in MOR, but about

TABLE 7.14
Rate and Extent of Thickness Swelling in liquid Water of Kenaf Fiberboards Made from Control and Acetylated Fiber and a Phenolic Resin [Resin content of boards: 8%]

Fiber	Thickness swelling at–							
	<— minutes —><—><— hours —>							
	%							
	15	30	45	1	2	3	4	5
Control	15.5	17.1	21.1	22.6	24.7	26.8	31.1	32.6
18.4 WPG	6.7	6.8	6.5	7.0	7.0	7.0	8.0	8.1

	Days					Oven drying	Weight loss after test
	1	2	3	4	5		
Control	37.7	41.5	42.6	43.5	44.5	19.0	2.0
18.4 WPG	8.5	8.5	8.7	8.8	9.0	0.7	2.8

TABLE 7.15
Fungal Cellar Tests of Jute Cloth Made from Control and Acetylated Fiber[a]

	Rating at intervals (months)[b]							
Weight percent gain	2	3	4	5	6	12	24	36
0	2	3	3	3	4	—	—	—
7.4	0	1	1	2	3	1	—	—
11.5	0	0	0	1	2	3	4	—
13.3	0	0	0	0	0	1	2	3
16.8	0	0	0	0	0	0	0	0
18.3	0	0	0	0	0	0	0	0

[a] Nonsterile soil containing brown-, white-, and soft-rot fungi and tunneling bacteria.
[b] Rating system: 0 = no attack; 1 = slight attack; 2 = moderate attack; 3 = heavy attack; 4 = destroyed.

equal values in MOE and TS. All strength values given in Table 7.16 are above the minimum standard as given by the American Hardboard Association [43]. The small decrease in some strength properties resulting from acetylation may be attributed to the hydrophobic nature of the acetylated furnish. which may not allow the water-soluble phenolic or isocyanate resins to penetrate into the flake. The adhesives used in these tests hare also been developed for unmodified lignocellullsics. Different types of adhesives may be needed in chemically modi-lied boards [44].

7.12.2 CYANOETHYLATION

Jute can be made to react with acrylonitrile in the presence of alkali under conditions that do not reduce the tensile strength of the fibers to any important extent. The properties of cyanoethylated cotton have been know for some time [45], and this particular chemical modification is claimed to provide increased stability against degradation by acids and by heat. Cotton containing more than 3% nitrogen is also said to show high resistance to microbiological deterioration [46].

Experiments with jute yarn at the British Jute Trade Research Association have shown that although untreated yarn subjected to hydrolysis with 0.2 *N* sulfuric acid at 100°C for 60

TABLE 7.16
Modulus of Rupture (MOR), Modulus of Elasticity (MOE), and Tensile Strength (TS) Parallel to the Board Surface of Fiberboards Made from Control or Acetylated Kenaf Fiber and 8% Phenolic Resin

Board	MOR	MOE	TS
	MPa	GPa	MPa
Kenaf			
Control	47.1	4.6	31.0
18.4 WPG	38.6	5.1	27.1
ANSI Standard	31.0	—	10.3

min retained only 20% of its initial strength, a yarn cyanoethylated to 4.6% nitrogen content retained 80% of its strength under similar conditions.

Jute yarns cyanoethylated to different extents showed increasing resistance to degradation by heating, and whereas untreated yarn heated at 150°C for 24 h retained only 55% of its initial strength, and similar yarn with a nitrogen content of 4.9% retained 90%.

Resistance to rotting was also examined by incubation of yarns under degrading conditions, which caused complete breakdown of strength after 3 weeks. Cyanoethylation up to 1.5% nitrogen showed little improvement. but for 2.8% nitrogen and more, even 16 weeks incubation reduced strength by only 10%. A copper naphthenate treatment with 1.2% copper, for comparison. retained only 30% of strength under similar conditions of exposure. Thus, cyanoethylation gives effective protection against rotting, provided the nitrogen content approaches about 3%At [46].

7.13 PHOTOCHEMICAL AND THERMAL DEGRADATION

All cellulose-containing fibers lose strength on prolonged exposure to sunlight. This effect is mainly attributable to the ultraviolet component of the radiation. and its scale is such that, in cotton. about 900-h exposure reduces the strength to 50% of the initial value. In jute, however, a similar strength reduction occurs after about 350-h exposure, and so, although the exposure times are not precise, it is clear that jute loses strength at more than twice the rate for cotton.

In both fibers, there is a loss in strength due to primary bond breakages in the cellulose constituent. but. when seeking an explanation for the difference in behavior, the important question is whether it arises entirely from a greater rate of bond breakage in jute than in cotton. or whether the cohesion between the ultimate cells in jute is also reduced as a result of changes in the middle lamella.

The rate of breakage of cellulose bonds in cotton is readily found from the changes in the degree of polymerization (DP) as exposure continues. using the cuprammonium fluidity as a measure of the DP. In jute, however, this method is not always satisfactory because it is difficult to achieve a complete dissolution of the cellulose component in cuprammonium hydroxide because of interference from the lignin in the fiber. Moreover, preliminary removal of lignin is not advisable. as whatever the process used. it is always liable to cause some degradation of the cellulose.

Nitration techniques that do not degrade the cellulose component have been used successfully to determine the DP of wood cellulose [47], and similar methods are equally satisfactory for jute or other lignified materials [48, 49]. In one study carried out in the laboratories of the British Jute Trade Research .Association [50], the nitrated lignin and hemicellulose components were first removed by solvent extraction and fractional precipitation. and the DP of the residual cellulose nitrare then determined from viscosity measurements in acetone solution. The viscosities have to be referred to a standard rate of shear and the whole procedure is rather lengthy, but the results showed that after the same exposure conditions jute and cotton had similar DPs within experimental limits of error. Moreover, a plot of 1/DP against time of exposure in standard sun hours was linear, suggesting that the kinetic equation for random breakdown of a polymer chain, namely $1/(DP)_t = 1/DP)_o * kt$ applies in this case. $(DP)_o$ and $(DP)_t$ are the DPs measured before exposure and after exposure for time t, whereas k is a constant representing the rate of bond breakage.

Exposure to sunlight for periods up to 600h gave values of k equal to 15.4×10^{-7} and 13.3×10^{-7} for jute and cotton. respectively. in units of reciprocal DP per hour exposure. Exposure to artificial sources of UV light such as a mercury arc lamp or a xenon arc lamp gave lower values of k than for sunlight, but again jute and cotton were similar. With the

mercury lamp, the *k* values were 8.0×10^{-7} and 8.9×10^{-7} units for jute and cotton, whereas the xenon lamp gave 5.9 and 6.1×10^{-7} units, respectively, for jute and cotton.

The rate of photochemical breakdown of cellulose thus appears largely independent of whether lignin is present or not, and. contrary to views that have been expressed in the past. lignin does not act as a photosensitizer for the breakdown. The greater loss in strength ofjute compared to cotton must therefore he related to photochemical changes taking place in the middle lamella, which reduce the cohesion between ultimate cells.

Cellulose-containing fibers also lose strength on prolonged exposure to elevated temperatures. but. in this case, cotton and jute show only minor differences in strength losses under similar heating conditions. At 140°C, both fibers lose 50% of strength after 80–85h exposure. whereas at 160°C only about 10-h exposure is required for the same fall in strength. Thus. although the temperature is a major factor determining the rate of loss in strength. cotton and jute behave similarly and there is no suggestion that the cohesion of the middle lamella is changed by exposure to heat.

Measurement of the change in DP in heating presents difficulties. as the cellulose nitrate now becomes insoluble in acetone or other solvents. This may be due to cross-linking between reactive groups produced in the cellulose molecules by the thermal exposure. In any case, it appears that the chemical changes taking place in thermal degradation are different from those occurring in light-induced degradation.

The nitration techniques used in the measurement of the DP of a-cellulose merit further discussion, particularly in relation to the effect of time of nitration on the cellulosic constituents ofthe fiber. Nitration of lignin results in products soluble either in the nitrating acids or in methanol. and. by a suitable extraction procedure, the lignin component of the fiber can be completely removed.

After removal of lignin. the nitrated cellulosic products can be separated into three fractions. which are designated A, B, and C, of which Fraction A is insoluble in acetone; Fraction B is soluble in acetone, but insoluble in water; and Fraction C is soluble in both acetone and water. Analysis shows the acetone-soluble fractions B and C to consist of nitrated a-cellulose of DP about 4450, and nitrated hemicellulose, respectively, Both these products are also found in the acetone-insoluble fraction, A.

The amount of a-cellulose that is released as the acetone-soluble Fraction B increases as the time of nitration is increased. and. although small at first, finally reaches the analytical value of about 60% of the whole fiber. The time required for reaching the analytical value is temperature dependent, and, although Lewin and Epstein [49] report that at 3°C more than 24-h nitration is required, they point out that Timell [48] obtained a similar result in only 1 h at 17°C.

As the acetone-soluble Fraction B increases, the acetone-insoluble Fraction A decreases. Interpolation in Lewin and Epstein's results suggests that the two fractions become equal after 11- or 12-h nitration, and that, at this point of equality, their value is about 50% of the maximum value achieved by Fraction B, namely the analytical value.

This pattern of behavior is considered by Lewin and Epstein to indicate the presence of chemical linkages between a-cellulose and the hemicelluloses in jute that hold these components together in Fraction A and render the complex insoluble in acetone. The release of increasing amounts of acetone-soluble nitrated a-cellulose in Fraction B then arises from breakage of the links by the nitrating acids, with more breakages occurring as the time of nitration is increased.

7.14 MOISTURE EFFECTS

The equilibrium moisture held by jute when exposed to an atmosphere of different relative humidity (RH) shows appreciable hysteresis according to whether there is absorption from low humidities or desorption from high humidities. Thus, at 65% RH and 20°C, the

equilibrium moisture regain is about 12.5% for absorption by dry fiber and 14.6% for desorption of wet fiber, whereas exposure to 100% RH gives an equilibrium regain of 34-35%. These are average values. and different samples of fiber may show minor differences. It is noted that at 65%, RH the equilibrium regain ofjute is about 6% higher than that of cotton.

Jute swells in water to an extent of about 22%, a value similar to that of cotton, despite a greater proportion of noncrystalline material in jute. Delignification has a pronounced effect, and it is reported that when the lignin content has been reduced to 0.78%, the swelling may reach almost 40% [51].

Apart from swelling, delignification also affects the equilibrium regain of jute fiber, and Kabir et al. have shown that when delignified by 10%, using a chlorite treatment followed by sodium bisulfite solution extraction, the absorption and desorption regains at 65% RH are each increased by about 1% [52].

7.15 FASTNESS TO LIGHT

7.15.1 UNDYED JUTE

A major practical difficulty affecting the performance of dyed or bleached jute materials is the change in color that occurs when jute fiber is exposed to sunlight. In the UV region of the spectrum, exposure to light of wavelengths between 3000 and 3600 Å results in yellowing of the fiber, whereas exposure to wavelengths between 3800 and 4000 Å, on the fringe of the visible spectrum, has a bleaching effect. The final color is the resultant of the two processes. and, in general, the initial color change is an obvious yellowing, or darkening, of the fiber, but on longer exposure this color slowly gets lighter and less intense.

Bleaching before exposure generally accentuates the discoloration of the fiber compared to unbleached jute, although part of this is due to the heightened contrast between the nearly white bleached fiber and the exposed fiber. The onset of yellowing varies considerably with different bleaches. Alkaline or neutral hypochlorite, a cheap bleaching medium, gives a product with a rather rapid yellowing tendency. whereas alkaline hydrogen peroxide gives a good white color and a less marked yellowing than hypochlorite. Sodium chlorite, applied under acid conditions, shows the least yellowing tendency, but care must be taken that in obtaining the best conditions to prevent yellowing no drastic loss of strength takes place.

A bleaching process developed in the United States and patented for jute by Fabric Research Laboratories involves treatment with hydrogen peroxide and acid permanganate and gives a better resistance to yellowing than chlorite bleaching. Treatment with acid permanganate alone leaves the natural color of the jute almost unchanged and also provides a higher resistance to yellowing. This improvement probably represents a true reduction in yellowing, although part of it may be due to the smaller contrast between the original bleached color and the exposed color than found with the whiter bleaches.

Improvements in the stability of jute to light exposure result from acetylation or methylation. Treatment with acetic anhydride in xylene solution. for example, combined with a reduction process using sodium borohydride may confer virtually complete stability, whereas methylation with diazomethane confers a marked improvement without preventing yellowing entirely.

Color changes in jute are associated with the lignin content of the fiber, the isolated a-cellulose and hemicellulose fractions being unaffected by exposure to UV light of the correct wavelength band. The importance of lignin has also been demonstrated by irradiating cellulosic fibers of different lignin contents, and, for a series of fibers covering the range of 0% (cotton) to 13% (*Phormium tanax*), it was evident that the intensity of yellowing became more pronounced as the lignin content increased [53].

The formation of colored products from irradiated lignin involves complex reaction chains that are difficult to elucidate fully. It is probable that orthoquinone groups are responsible for the yellow color, formed from orthophenol groups as intermediates. Acetylation blocks both phenolic and aliphatic hydroxyl groups and prevents the objectionable reactions from taking place. The less effective methylation. however, blocks only the phenolic hydroxyl groups.

7.15.2 Dyed Jute

Jute can he dyed with a wide range of dye stuffs. All those generally used for cellulosic fibers, such as direct, vat. and reactive dyes, can be used successfully on jute, but, in addition, jute has a strong affinity for both acid dyes and basic dyes, which normally have little or no dyeing capacity for cotton or rayon but are used extensively for wool.

Many acid and basic dyes give strong, bright colors on jute, but performance is disappointing in regard to color fastness on exposure to sunlight. Some of the dyes used have intrinsically poor light fastness. but it has long been apparent that many acid dyes that give excellent light fastness on wool became fugitive when applied to jute. Yellowing of the jute background causes an apparent change in the color of dyed jute, and although poor fastness to light usually means fading of color, any change in color is in fact regarded as a lack of fastness.

Although systematic studies of dye stuffs on jute have not been frequent, the comprehensive studies carried out at the British Jute Trade Research Association merit discussion [53]. In these studies, a number of dyes were taken from each of several different classes and used to dye a standard jute fabric. both natural and after bleaching. The fastness to light of these dyed samples was then assessed by exposure to xenon light, alongside a series of light fastness standards. and the results compared with the known fastness value of the dye stuff on cotton. There are eight standards in all; No. 1 is the most fugitive and No. 8 the most resistant, and the experimental conditions for assessment are well standardized [54].

The results indicated that with vat dyes, accelerated fading of the dye stuff on jute compared with cotton was largely absent and that the yellowing was the main factor on which the apparent light fastness depended. With acid and basic dyes, however. accelerated fading appeared to he the predominant effect. although the balance with yellowing varied with both color and chemical structure of the dye. A number of acid dye stuffs known to give fastness ratings of 6 or more on wool were rated only 3-4 on jute, with loss of dye color the main cause, whereas a group of basic dyes with ratings of 6 or more on acrylic fibers were reduced to ratings of 2–3 on jute. Again. although yellowing was evident. accelerated fading was the principal cause.

A selection of 200 direct dyes, representative of the range of chemical types in this class and all having fastness ratings of 4 or more on cotton. were used for test dyeing on jute, both natural, chlorite bleached, and peroxide bleached. On cotton, 66% of dyes had fastness grade 6 or more, but on natural jute only 17% retained this grade; the number fell further to 12% on chlorite bleached jute and 5% on peroxide bleached. The average grading was 5.7 on cotton and 4.5 on natural jute, 4.7 on chlorite bleached, and 4.6 on peroxide bleached. Thus, on average. the grade on jute was about 1.0 lower than that on cotton.

The drop in grade was. however. far from regular for different dyes. and the balance between yellowing and accelerated Fading did not follow a predictable pattern. Dye color played an important role, for yellow dyes dropped only about 0.5 grade on jute against cotton, whereas for blue colors the average drop was 1.4 grades.

In the case of reactive dyes, test dyeing was done on natural and chlorite-bleached jute. Of the dyes used, 55% were graded 5–6and more than 6, but on jute only 2% were retained in this

category. The mean grade for cotton was 5.3, compared to 4.2 on natural jute and 4.1 on chlorite bleached.

In general, therefore, few dye stuffs retain the same light fastness on jute, natural or bleached, as on cotton. Reduction of the underlying yellowing is helpful in many cases, but there are examples of accelerated fading on jute. Acetylation and methylation can improve the fastness considerably, by preventing the background yellowing, and possibly this prevention may also affect the accelerated fading. However, these treatments are expensive and not simple to use, and alternative methods of obtaining light stability are needed if the standard of jute dyeing is to be raised.

7.16 WOOLENIZATION

When jute fiber is treated with strong alkali. profound changes occur in its physical structure. Lateral swelling occurs, together with considerable shrinkage in lengths, as a result of which the fiber is softened to the touch and develops a high degree of crimp or waviness. The crimp gives a wool-like appearance to the fiber, and much attention has been given to assessing the commercial possibilities for this chemical modification.

On stretching the fibers to break, the crimp is straightened and thereby the extensibility of the fiber is increased. The effect is small at alkali concentrations up to about 10%, but the extensibility increases rapidly at concentrations of 15% and upward and may reach 8 or 9%. At the same time. however. the tensile strength of the fiber decreases with increasing alkali concentration, but the product of extensibility and tensile strength. the breaking energy, appears to pass through a maximum at 15–20% concentration [55]. This has a beneficial effect on spinning because the carded fiber has a longer average length than normal and this results in a more uniform yarn.

The rapid change in extensibility in the vicinity of 15% concentration is similar to the effect of slack mercerization on cotton. The nature of the chemical changes occurring in jute on mercerization have been discussed by Lewin [26], especially in regard to the role played by lignin in the fiber structure. The sheathing of the ultimate cells by a lignified membrane affects the free swelling of the cells and produces tension, whereas the irregular shape of fibers in cross section leads to folding under tension once the middle lamella material is weakened by the treatment.

The crimp statistics have been studied in detail at the Institute for Fibers and Forest Products Research in Jerusalem, and much information has been brought together by, for example. Lewin et al. [56]. Two parameters are measured to define the crimp, namely the RMS value of the width (D) and the number of crimps per unit length of the stretched fiber (n). As the crimp is three dimensional. the fiber is rotated during the measurements. Typical values for jute fibers immersed in 12.5% NaOH, for 1 h at a temperature of 2°C are reported to be about 1.6 mm for D. with a standard deviation of 0.55 mm, and about 0.098 mm^{-1} for n, with a standard deviation of 0.035 mm^{-1}. The extension of the fibers at break was 15% relative to the initial length of the crimped fiber under a load of 10 mg, and the crimp disappeared for loads of about 2000 mg. The energy required to uncrimp the fiber was equivalent to about 3.9 g per 1% of extension.

The above figures refer specifically to an alkali concentration of 12.5%. At concentrations below 6%, no crimp is formed, whereas at 9% alkali, D reaches a maximum value of about 1. 9 mm. At concentrations of 15% and above, D takes up a reasonably constant value of about 1.35 mm. The value of n, however, is scarcely affected by changes in alkali concentration.

It is said that the optimum temperature for crimp formation is about 2°C and that at higher temperatures the crimp parameters are reduced, becoming zero at 40°C. An immersion time of at least 0.5 h is necessary for the crimp to be formed.

Banbaji [57] has examined the tensile properties of jute fibers before and after alkali treatment and has shown that the tenacity decreases with increasing concentration: an initial value of 3.6 g/den falling to 2.5 g/den at 9% alkali and to 1.5 g/den at 24% alkali, at 2°C and 1-h immersion. The extension at break, referred to the fiber length before immersion. increased from 1.2% without alkali treatment to 3.6% at 9% alkali and then fell slightly to 2.4% at 24% alkali.

The tenacity changes are no doubt linked with the losses in weight that occur with alkali treatment, but there may be more profound changes taking place internally within the ultimate cells. Such changes are at present imperfectly understood. but. if useful commercial developments are to be made. further investigation of structural changes appears essential. Moreover, the crimp is a "once only" effect, and to be really useful a small degree of elasticity must be introduced into the fiber.

The stability of the crimp is poor, and, once the fiber has been straightened under tension, there is no tendency to revert to the crimped state when the tension is removed; that is. the woolenizing treatment does not confer elasticity on the fiber.

Under mercerizing conditions, the fibers lose considerable weight (15% or more) and give the appearance of being opened up. It is commonly said that there is a considerable reduction in diameter. which implies a lower linear density and hence the production of more regular yarns. However. just as in natural jute, there appears to be a limit below which the diameter does not fall as with mercerized fiber.

The physical effects of the mercerizing process are different when the jute material is kept under tension, instead of being slack. Experiments reported from the Bangladesh Jute Research Institute with treated jute yarns [58] show that the shrinkage is greatly reduced by tension. falling from 11–12% when slack to 1.5–2.5% under 3-kg tension. The loss in weight of 12–13% when slack was reduced by a few percent under 3-kg tension. The effect of temperature change from 30 to 60°C was small in all cases.

The appearance and feel ofjute fabrics is much improved by the woolenizing process, and bleached and dyed fabrics appear to have commercial possibilities. The problem is the cost of the treatment. and to achieve similar effects more cheaply may require a deeper knowledge of the internal changes that take place within the fiber.

7.17 APPLICATIONS AND MARKETS

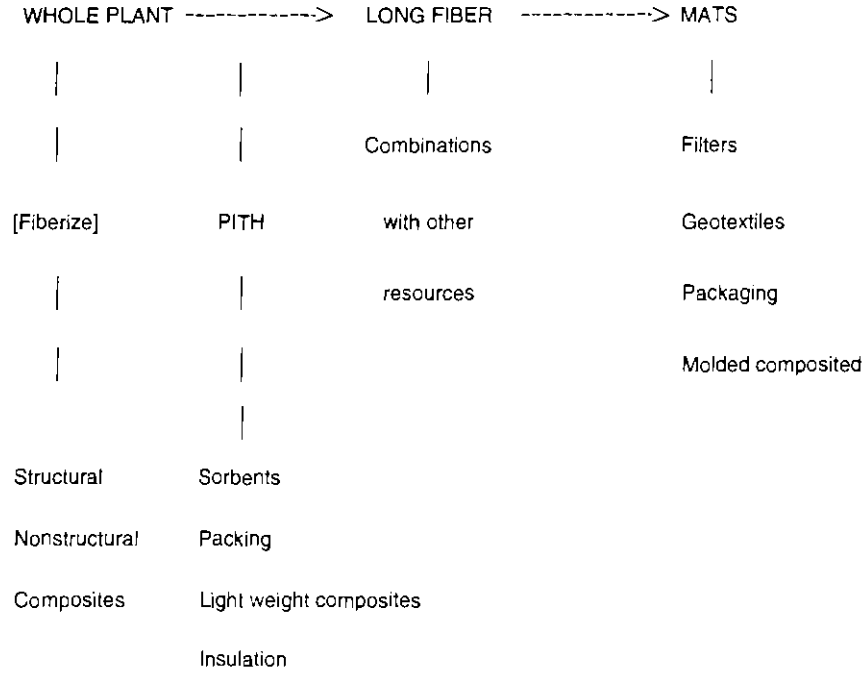
The large historic markets for jute in sacking, carpet backing, cordage, and textiles have decreased over the years and have been replaced by synthetics. Fiber from jute and kenaf can be used in handicraft industries, to make textiles. to make paper products, or to produce a wide variety of composites. A great deal of research is presently underway in each of these fields: however, the largest potential markets are in composite products. These composites range from value-added specialty products to very large volume commercial materials. These markets are potentially larger than the past markets for jute and kenaf and could lead to new dynamic uses for these and other natural fibers.

7.17.1 COMPOSITES

A composite is any combination of two or more resources held together by some type of mastic or matrix. The mastic or matrix can be as simple as physical entanglement of fibers to more complicated systems based on thermosetting or thermoplastic polymers. The scheme shown below, gives possible processing pathways that lead to the composite products identified in this report that can come from each fraction of the plant. The entire plant (leaves. stock. pith. roots) can be used directly to produce structural and nonstructural composites

such as particleboards or fiberboards. By using the entire plant, processes such as retting, fiber separation, fraction purification, etc. can be eliminated, which increases the total yield of plant material and reduces the costs associated with fraction isolation. This also gives the farmers a different option in their crop utilization: that is, bringing in the entire plant to a central processing center and not having to get involved in plant processing [59].

Another option is to separate the higher value long fiber from other types of shorter fibers and use it in combination with other materials to make value-added structural composites. When the long fiber is separated, the by-product is a large amount of short fiber and pith material that can be used for such products as sorbents, packing, light-wight composites. and insulation. By utilizing the by-product from the long fiber isolation process. the overall cost of long fiber utilization is reduced.



The isolated long fiber can then be used to make mats that have value-added applications in filters, geotextiles, packaging, molded composites. and structural and nonstructural composites. Composites can be classified in many ways as follows: by their densities, by their uses, by their manufacturing methods, or other systems. For this report, they will be classified by their uses. Eight different classes are covered: geotextiles, filters, sorbents, structural composites, non-structural composites. molded products, packaging, and combinations with other materials. There is some overlap between these areas. For example, once a fiber web has been made it can be directly applied as a geotextile, filter, or sorbent, or can further be processed into a structural or nonstructural composite, molded product, used in packaging, or combined with other resources. Within each composite made there are opportunities to improve the performance of that composite by improving the performance of the fiber used in the composite.

7.17.2 GEOTEXTILES

The long bast or leaf fibers can be formed into flexible fiber mats, which can be made by physical entanglement, nonwoven needling, or thermoplastic fiber melt matrix technologies.

The two most common types are carded and needle-punched mats. In carding, the fibers are combed, mixed, and physically entangled into a felted mat. These are usually of high density. but can be made at almost any density. In the mid-1960s. a mechanical system was developed to process long synthetic fibers for use in medium density fiberboard (Figure 7.7). Section A in Figure 7.1 is where the kenaf or jute bast fiber is fed into the system. Section B is a fiber opener where fiber bundles are separated and can be mixed with other fibers. Between 4 and B, the fibers are formed into a continuous mat, which is fully formed at C, At D, the web can go on through a needle board where the web is "needled" together in a nonwoven process. Another option at D is to run the mat through a heated chamber or heated metal rollers to melt a plastic fiber that was blended into the web at stage C. Other similar systems have been made using the same principles. Figure 7.8 shows a web that has been made using the needed system.

Work has been done that demonstrates how additives. such as super absorbent powders and binders, can be added to the web during the forming process. In the case of super absorbents. one advantage of this approach is that the super absorbent powder when near the area of maximum void space in the web can absorb liquids faster and in greater quantity than if added to a finished web as part of a laminate in an off-line process. Also, because of their uniform dispersion. powdered binders can perform in much the same manner to insure maximum strength with a minimum add-on. Medium- to high-density fiber mats can be used in several ways. One is for the use as a geotextile. Geotextiles derive their name from the two words geo and textile and, therefore, mean the use of fabrics in association with the earth.

Geotextiles have a large variety of uses. These can be used for mulch around newly planted seedlings (Figure 7.9). The mats provide the benefits of natural mulch; in addition. controlled-release fertilizers. repellents, insecticides, and herbicides can be added to the mats as needed. Research results on the combination of mulch and pesticides in agronomic crops have been promising.

The addition of such chemicals could be based on silvicultural prescriptions to ensure seedling survival and early development on planting sites where severe nutritional deficiencies, animal damage. insect attack. and weed problems are anticipated. Medium-density fiber mats can also be used to replace dirt or sod for grass seeding around new homesites or along highway embankments (Figure 7.10). Grass or other type of seed can be incorporated in the

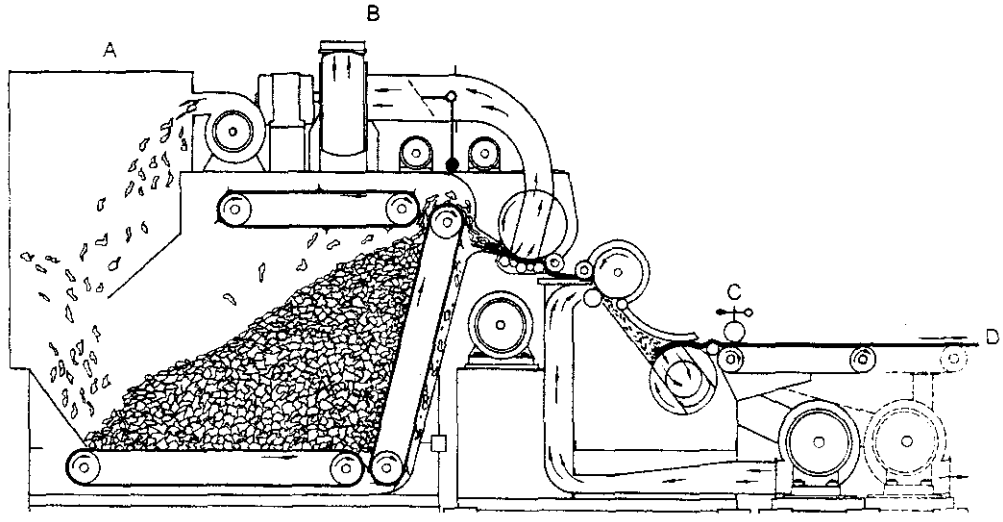


FIGURE 7.7 Schematic diagram of a web making machine (USDA).

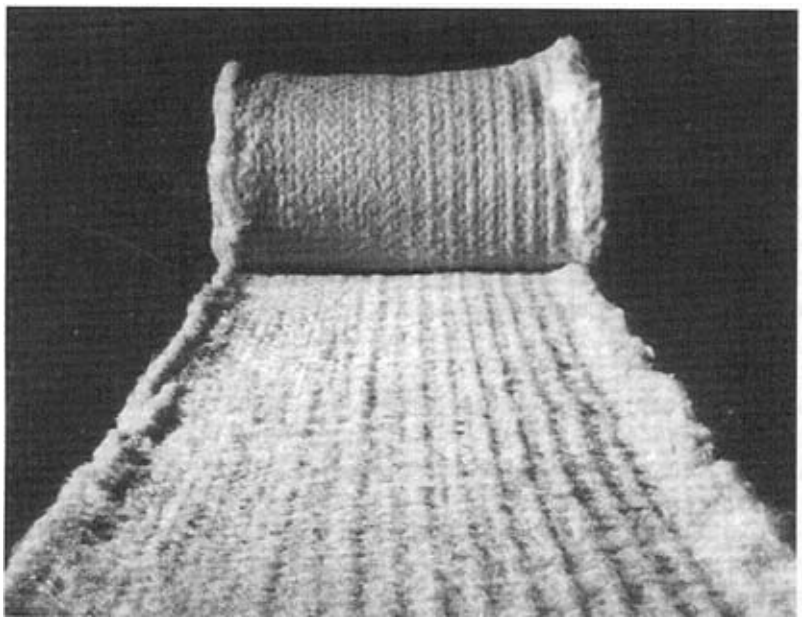


FIGURE 7.8 Fiber web (USDA).

fiber mat. Fiber mats promote seed germination and good moisture retention. Low- and medium-density fiber mats can be used for soil stabilization around new or existing construction sites. Steep slopes, without root stabilization, lead to erosion and loss of top soil.

Medium- and high-density fiber mats can also be used below the ground in road and other types of construction as a natural separator between different materials in the layering of the back fill. It is important to restrain slippage and mixing of the different layers by placing

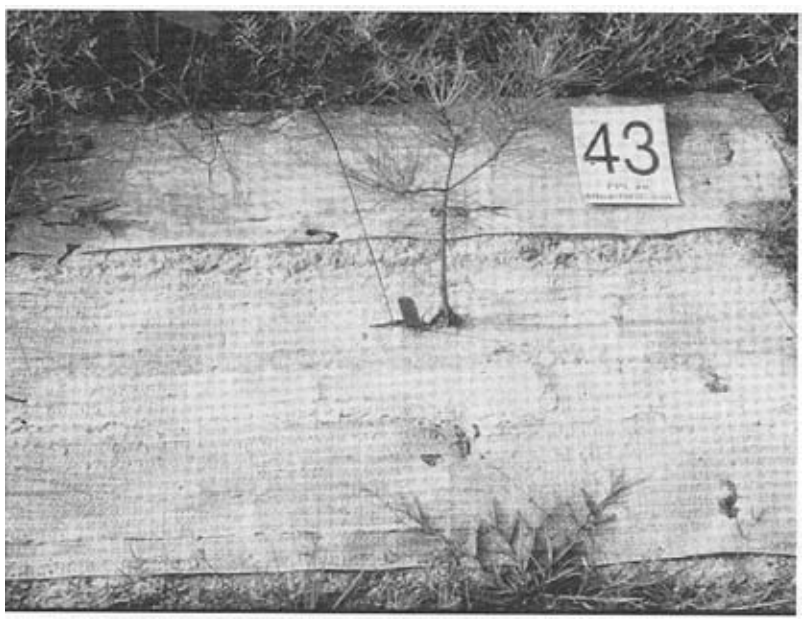


FIGURE 7.9 Mulch mat used to plant tree seedlings (USDA).

FIGURE 7.10 Geotextile used to stabilize a steep slope (USDA).

separators between the various layers. Jute and kenaf geotextiles have been shown to work very well in these applications, but the potential exists for any of the long jute and kenaf fibers.

7.17.3 FILTERS

Medium- and high-density fiber mats can be used as air filters. The density of the mats can he varied, depending on the size and quantity of the material being filtered and the volume of air required to pass through the filter per unit of time. Air filters can he made to remove particulates and can he impregnated or reacted with various chemicals as an air freshener or cleanser.

Medium- to high-density mats can also be used as filtering aids to take particulates out of waste and drinking water or solvents. Figure 7.11 shows a filter unit that is in place to remove metal ions from water that has come from an abandoned coal mine. Jute and kenaf fibers can also he modified to become more efficient in removing a wide variety of contaminates from water.

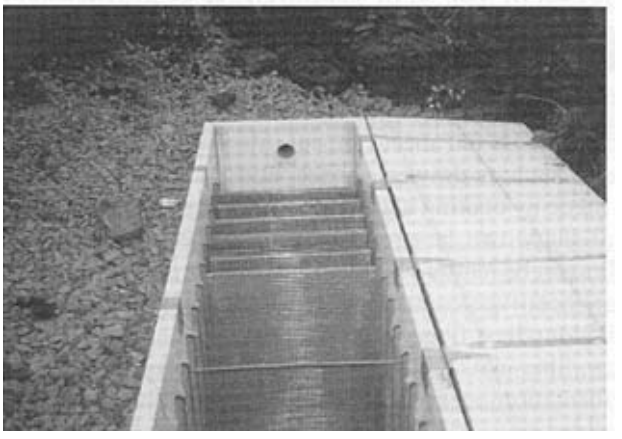


FIGURE 7.11 Filter unit containing filters made of kenaf fiber (USDA)

7.17.4 Sorbents

Tests are presently underway to use jute and kenaf sorbents to remove heavy metals. pesticides. and oil from rain water run off in several cities in the United States. Medium- and high-density mats can also be used for oil spill clean up pillows. It has been shown that the core material from kenaf preferentially sorbs oil out of seawater when saturated with water. There are many other potential sorbent applications of agrofiber and core resources such as removal of dyes, trace chemicals in solvents, and in the purification of solvents.

It is also possible to use core materials as sorbents in cleaning aids such as floor sweep. While this is not a composite, it does represent another way in which jute and kenaf resources can he used as sorbents.

7.17.5 Structural Composites

A structural composite is defined as one that is required to carry a load in use. In the housing industry, for example, these represent load-bearing walls, roof systems, subflooring, stairs, framing components, furniture, etc. In most. if not all. cases, performance requirements of these composites are spelled out in codes and in specifications set forth by local or national organizations.

Structural composites can range widely in performance from high-performance materials used in the aerospace industry down to wood-based composites, which have lower performance requirements. Within the wood-based composites, performance varies from multilayered plywood and laminated lumber to low-cost particleboard. Structural wood-based composites intended for indoor use are usually made with a lowcost adhesive, which is not stable to moisture, while exterior-grade composites use a thermosetting resin that is higher in cost but stable to moisture. Performance can be improved in wood-based as well as jute and kenaf composites by using chemical modification techniques, fire retardant, and decay control chemicals, etc.

7.17.6 Nonstructural Composites

As the name implies. nonstructural composites are not intended to carry a load in use. These can be made from a variety of materials such as thermoplastics, textiles, and wood particles, and are used for such products as doors. windows. furniture, gaskets, ceiling tiles, automotive interior parts. molding, etc. These are generally lower in cost than structural composites and have fewer codes and specifications associated with them.

7.17.7 Molded Products

The present wood-based composite industry mainly produces two-dimensional (flat) sheet products. In some cases, these flat sheets are cut into pieces and glued or fastened together to make shaped products such as drawers, boxes, and packaging. Flat-sheet wood fiber composite products are made by making a gravity formed mat of fibers with an adhesive and then pressing. If the final shape can be produced during the pressing step. then the secondary manufacturing profits can be realized by the primary board producer (Figure 7.12). Instead of making low-cost flat-sheet-type composites, it is possible to make complex-shaped composites directly using the long bast fiber.

In this technology. fiber mats are made similar to the ones described for use as geotextiles; except, during mat formation, an adhesive is added by dipping or spraying of the fiber before mat formation or added as a powder during mat formation. The mat is then shaped and densified by a thermoforming step. Within certain limits, any size, shape. thickness. and

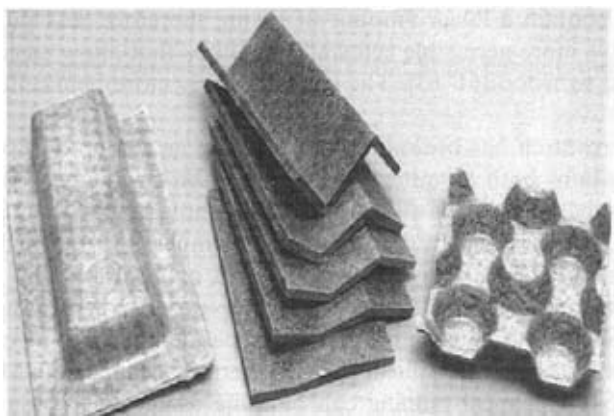


FIGURE 7.12 Three-dimensional composites made using a fiber web (USDA).

density is possible. These molded composites can be used for structural or nonstructural applications as well as packaging, and can be combined with other materials to form new classes of composites. This technology is described later.

7.17.8 PACKAGING

"Gunny" bags made from jute have been used as sacking for products such as coffee. cocoa. nuts. cereals. dried fruits. and vegetables for many years. Although there are still many applications of long fibers for sacking, most of the commodity goods are now shipped in containers. These containers are not made of agrofibers nowadays, but there is no reason why they cannot he made. Medium- and high-density jute and kenaf fiber composites can he used for small containers. for example, in the tea industry and for large sea-going containers for commodity goods. These composites can be shaped to suit the product by using the molding technology described previously or made into low cost, flat sheets and made into containers.

Jute and kenaf fiber composites can also he used in returnable containers where the product is reused several times. These containers can range from simple crease-fold types to more solid, even nestable, types. Long agrofiber fabric and mats can be overlayed with thermoplastic films such as polyethylene or polypropylene to he used to package such products as concrete, foods. chemicals. and fertilizer. Corrosive chemicals require the plastic film to make them more water resistant and reduce degradation of the jute and kenaf fiber. There are many applications for jute and kenaf tiher as paper sheet products for packaging also. These vary from simple paper wrappers to corrogated, mutifolded, multilayered packaging.

7.17.9 PULP AND PAPER

Using trees for the production of pulp and paper is much easier than using kenaf or jute as a source of fiber. Kenaf and jute must be harvested at a set time, collected, stored, cleaned, separated, and transported to a pulp mill. A tree can stand in the forest until needed, cut, transported, debarked, chipped, and then pulped. For some countries, however, trees are not available for pulping and so kenaf or jute are logical options. Kenaf can be harvested and put into piles that can be stored for 1 to 2 years without significant loss of quality. Trials have even been done to use a biopulping approach that reduces both the energy and quantity of chemicals needed in a later chemical pulping process [60].

Kenaf and jute contain a lower amount of lignin: therefore, less pulping chemicals are needed and they have more accessible cell wall structures that allow easier access to pulping chemicals compared to wood [61–63]. The stalk contains more hemicelluloses that result in faster hydration.

A great deal of research has been done to use kenaf as a source of pulp and paper [64]. Kenaf. like jute. contains both an outer layer of long bast fibers and a short fiber core. The bast. on a dry weight basis, contains about 20% of the whole stem with an average fiber length of approximately 2.6 mm. The 80% core fibers are much shorter with an average fiber length of only 0.6 mm. The bast gives a higher yield of pulp and the pulp produced has much higher strength properties compared to the pulp produced from the core.

Pulp has also been produced using the entire unseparated plant using chemical, chemithermomechanical (CTMP), chemimechanical (CMP), thermomechanical (TMP), and mechanical pulping processes [64]. Chemical pulping can be done using either soda or kraft processes. Chemical pulping of kenaf has been studied using a variety of pulping systems including keaft, soda, soda-anthraquinone, acidic sulfite, nitric acid, neutral sulfite, and organosolv [64].

The first commercial kenaf pulp mill was in Khon Kaen, Thialand, which started in 1982 with an annual capacity of 70.000 t [65].

The primary pulping process for kenaf is a CMP process using cold soda. The kenaf is steeped in a caustic soda solution for a short period of time and then fiberized in a disk refiner [64]. A 10% caustic soda cook of whole chopped and washed kenaf stalk cooked at 170°C for 3.5 h produces a good bleachable pulp [66, 67]. Kenaf stalk can also be pulped using a slightly modified kraft process to give a good pulp with good drainage, freeness, and strength properties similar to a softwood pulp [68, 69]. Whole stalk kraft pulping has also been done as reported by Mittal and Maheshwari [70]. They found a high percentage of bast fiber in the pulp resulting in a higher average fiber length and good physical properties in the paper. Table 7.17 shows the properties of kenaf pulped using either a soda or kraft process.

Thennomechanical pulping of whole kenaf was done, but the resulting pulp had very low strength properties [71]. Chemithermomechanical pulping has also been done using alkaline hydrogen peroxide [72]. Table 7.18 shows the properties of paper made from whole kenaf using either TMP and CTMP.

Han et al. pulped core and bast components separately using sodium sulfide in sodium hydroxide [73]. Table 7.19 shows the results of this work.

TABLE 7.17
Properties of Kenaf Paper Produced by Soda or Kraft Processes

Property	Soda	Kraft
Yield, %	62	55
Cellulose (alpha)	68	71
Pentosans, %	19	20
Kappa number	45	27
Yield bleached, % (Cl_2)	53	48
Burst factor, g/cm²/gsm	54	50
Tear factor, g/gsm	102	93
Breaking length, m	9,600	10,300

Soure : From Touzinsky, G.F. Laboratory paper machine runs with Kenaf thermochemical pulp, TAPPI, 1980, 63(3). 109: Touzinkky. G.F. Kenaf, In *Pulp and Paper manufacturing.* Vol. 3. Secondary fibers and non-wood pulping, Chapter 8, TAPPI Press, Atlanta, GA; 1987. 106.

TABLE 7.18
Properties of Paper Made Using Whole Kenaf Stalk Using Either TMP or CTMP

Property	TMP	CTMP
Brightness, %	65	70
Burst index, MN/kg	1.4	1.7
Tear index, Nm^2/kg	8.1	8.0
Breaking length, km	3.5	4.3
Apparent density, kg/m^3	318	388
Long fiber, %	36	33
Fines, %	49	53
Opacity, %	95	90

Soure: From Touzinsky, G.F. Laboratory paper machine runs with Kenaf thermochemical pulp, TAPPI, 1980, 63(3), 109: Touzinsky, G.F. Kenaf. In *Pulp and Paper Manufacturing*, Vol. 3., Secondary fibers and non-wood pulping, Chapter 8. TAPPI Press, Atlanta, GA: 1987, 106.

CMP produced from kenaf core using alkaline hydrogen peroxide gave a pulp yield of 80%, breaking length of over 4 km, brightness of 60%, and opacity of 92% [74].

Chemical and semichemical kenaf pulps are easy to bleach using a three-stage process including chlorination, caustic extraction. and hypochlorite stages [62]. Bleaching is done after removing shives and fines to reduce the consumption of bleaching chemicals.

Studies have been done on the recycling of kenaf paper [75]. The zero-span breaking length was not affected, but the freeness was significantly reduced. Tear strength increased on the first two recycles, but then decreased after the third cycle.

Jute has also been used to make paper, although the entire plant is rarely used [64]. Pulp mills generally buy old Jute sacks, cuttings, and waste wrapping material that are mainly bast fiber. Jute is usually pulped using either a chemical or by one of several chemimechanical processes. The Jute Technological Research Laboratory (JTRL) in Calcutta. India. has done

TABLE 7.19
Hand Sheet Paper Made from Wither Bast Fiber or Core Fiber Using Sodium Sulfate and Sodium Hydroxide

Test	Bast paper	Corepaper
Density. kg/m^3	571	906
Freeness, CSF (mL)	631	279
Caliper, mm	0.121	0.075
Strain (elongation), %	2.29	2.38
Tensile strength, kN/g	5.36	7.22
ISO brightness, %	25.3	20.5
Priming opacity, %	97.0	94.4
Burst strength, kPa	333.8	381.8
Burst index, $kPa.m^2/g$	4.92	5.71
Tear resistance, mN	1446.3	263
Tear index, $mN.m^2/g$	20.9	3.9
Smoothness, sheffield units	329.3	72.6
Fiber length, Kajaani, mm	2.8	0.81

TABLE7.20
Properties of Pulp and Paper from Jute Using Three Different Processes

Fiber	Pulping Process	Yield UB	B	Breaking Length (km)	Burst Factor	Tear Factor	Fold
Bast	Chemi-mech	8690	8285	7.3	30	130	250
	Soda	6567	6264	8.5	38	135	900
	Kraft	6870	6365	8.5	40	150	1077
Stick	Chemi-mech	7678	6870	5.0	20	51	78
	Soda	45	42	6.5	29	70	200
	Kraft	48	44	7.1	29	78	241
Whole plant	Chemi-mech	8082	7680	6.0	20	60	250
	Soda						
	Kraft	68	63	7.5	30	101	375

UB = unbleached. B = bleached (Young 1997).

the most research on pulping jute [8]. Using caustic soda (10 to 15%) prior to mechanical disintegration in a disc refiner produces good quality pulp. Jute bast and core can also be pulped using pure soda or a kraft process. Table 7.20 show the properties of pulp and paper produced using a chemimechanical. soda. or kraft process. Jute can also be pulped using fungal treatment prior to an alkaline pulping process and the pulp has higher strength properties than the pulp produced without the fungal pretreatment.

One mill in India uses a two-stage kraft process, where the first stags is run at low pressure and the second stage at high pressure [64]. The resulting pulp is washed and run through a beater. Jute can also he pulped using an alkaline sulfite or neutral sulfite anthraquinone process [76]. The process is carried out on jute bast fiber using sodium sulfite and sodium carbonate. Jute stick can also be pulped this way. but the strength properties are lower than when bast fiber is used.

Jute pulps are generally bleached using a 5 to 10% solution of sodium or calcium hypochlorite in a two-stage process. The process gives a brightness of 50 to 60. Jute pulp is used in cigarette papers, printing, bond and writing papers. but almost always in combination with other pulps.

7.17.10 PULTRUSION

Jute and kenaf bast fibers can be used to substitute for glass finer in pultrusion technology [77, 78]. The long bast fiber can be pulled through a bath of phenolic, polyester, or other thermosetting resin and molded to make a wide variety of stiff, strong profiles. After curing, the profiles can be cut to any length desired. Door frames. U-channels, and sports equipment have been successfully made using this procedure.

7.17.11 COMBINATIONS WITH OTHER RESOURCES

It is possible to make completely new types of composites by combining different resources. It is possible to combine, blend, or alloy leaf, bast and stick fiber with other materials such as glass, metals, plastics, and synthetics to produce new classes of materials. The objective is to combine two or more materials in such a way that a synergism between the components results in a new material that is much better than the individual components.

Jute and kenaf fiber–glass fiber composites can be made using the glass as a surface material or combined as a fiber with other lignocellulosic fibers. Composites of this type can have a very high stiffness to weight ratio. The long bast fibers can also be used in place of glass fiber in resin injection molding (RIM) or used to replace, or in combination with, glass fiber in resin transfer molding (RTM) technologies. Problems of dimensional stability and compatibility with the resin must be addressed. but this could also lead to new markets for property-enhanced jute and kenaf materials.

Metal films can be overlayed on to smooth. dimensionally stabilized fiber composite surfaces or applied through cold plasma technology to produce durable coatings. Such products could he used in exterior construction to replace all aluminum or vinyl siding—markets where jute and kenaf resources have lost market share.

Metal fibers can also be combined with stabilized fiber in a matrix configuration in the same way as metal fibers are added to rubber to produce wear-resistant aircraft tires. A metal matrix offers excellent temperature resistance and improved strength properties, and the ductility of the metal lends toughness to the resulting composite. Application for metal matrix composites could be in the cooler parts of the skin of ultrahigh-speed aircrafts. Technology also exists for making molded products using perforated metal plates embedded in a phenolic-coated fiber mat, which is then pressed into various shaped sections.

Bast or leaf fiber can also be combined in an inorganic matrix. Such composites are dimensionally and thermally stable, and they can he used as substitutes for asbestos composites. Inorganic bonded bast fiber composites can also be made with variable densities that can be used for structural applications.

One of the biggest new areas of research in the value-added area is in combining natural fibers with thermoplastics. Since the price of plastic has risen sharply over the past few years, adding a natural powder or fiber to plastics provides cost reduction to the plastic industry (and in some cases increases performance as well), but, to the jute and kenaf industry, this represents an increased value for the jute and kenaf component.

7.17.12 Fiber Thermoplastic Blends

Before 1980, the concepts of blends and alloys were essentially unknown in the plastic industry. Today, there are more than 1000 patents relating to plastic blends and alloys. and it is estimated that 1 out of every 5 kg of plastic sold in the United States is a blend or an alloy [79]. Blends and alloys have revolutionized the plastic industry, as they offer new materials with properties that were not available before and materials that can be tailored for specific end-uses. The jute and kenaf industries have the same opportunity to follow this trend and greatly expand markets for new materials based on blends and alloys with other resources.

Newer materials and composites that have both economic and environmental benefits are considered for applications in the automotive, building, furniture, and packaging industries. Mineral fillers and fibers are used frequently in the plastic industry to achieve desired properties or to reduce the cost of the finished article. For example, glass fiber is used to improve the stiffness and strength of plastics, although there are several disadvantages associated with the use of the fiber. Glass fibers need a great deal of energy to produce since processing temperatures can exceed 1200°C. They tend to abrade processing equipment and also increase the density of the plastic system. Jute and kenaf fibers have received a lot of interest for use in thermoplastics due to their low densities, low cost, and nonabrasive nature. The inherent polar and hydrophilic nature of the jute and kenaf fibers and the nonpolar characteristics of the polyolefins can lead to difficulties in compounding and result in inefficient composites. Proper selection of additives is necessary to improve the interaction and adhesion between the fiber and matrix phases.

Recent research on the use of jute and kenaf fiber suggests that these fibers have the potential use as reinforcing fillers in thermoplastics and a brief preliminary account was published earlier [80]. The annual growth of agricultural crop fibers such as kenaf has resulted in significant property advantages as compared to typical wood-based fillers and fibers such as wood flour. wood fibers. and recycled newspaper [81–85]. The results indicate that kenaf fiber–polypropylene (PP) composites have significant advantages over conventional inorganic filled and reinforced PP systems for certain applications. The low cost and densities and the nonabrasive nature of the fibers allow high filling levels. thereby resulting in significant cost savings. The primary advantages of using these fibers as additives in plastics are the following: low densities. low cost, nonabrasive nature, high-filling levels possible. low energy consumption. high specific properties, renewable, widely distributed. biodegradable, and improvement in the rural or agriculture-based economy.

The two main disadvantages of using jute and kenaf fibers in thermoplastics are the high moisture absorption of the fibers and composites [80] and the low processing temperatures permissible. The moisture absorbed by the composite and the corresponding dimensional changes can be reduced dramatically if the fibers are thoroughly encapsulated in the plastic and there is good adhesion between the fiber and the matrix. If necessary. moisture absorption of the fibers can be significantly reduced by the acetylation of the hydroxyl groups present in the fiber [86], although this is possible with some increase in cost. The disadvantage of the high moisture absorption of the composite can be minimized by selecting applications where the high moisture absorption is not a major drawback. For example, polyamide and its composites absorb large amounts of water, but applications are such that this deficiency is not of prime importance. The processing temperature of the lignocellosic fibers in thermoplastics is limited due to potential fiber degradation at higher temperatures. The plastics that can be used are limited to low-meltingtemperature plastics. In general, no deterioration of properties due to fiber degradation occurs when processing temperatures are maintained below about 200°C for short periods.

Kenaf bast fibers with a filament length longer than 1 m are common. These filaments consist of discrete individual fibers. generally 2 to 6 mm long, which are themselves composites of. predominantly, cellulose. lignin, and hemicelluloses. Filament and individual fiber properties can vary. depending on the source, age. separating techniques, and history of the fiber. Furthermore. the properties of the fibers are difficult to measure. so we have made no attempt to measure the properties of kenaf.

Kenaf filaments, about 15 to 20 cm long, a maleic anhydride grafted polypropylene (MAPP used as a coupling agent to improve the compatibility and adhesion between the fibers and matrix). and polypropylene were compounded in a high-intensity kinetic mixer where the only source of heat is generated through the kinetic energy of rotating blades. The blending was accomplished at 4600 rpm that resulted in a blade tip speed of about 30 m/s and then automatically discharged at 190°C.

The mixed blends were then granulated and dried at 105°C for 4h. Test specimens were injection molded at 190°C. Tensile tests were conducted according to ASTM 638–90, Izod impact strength tests according to ASTM D 256–90, and flexural testing using the ASTM 790–90 standard. The cross-head speed during the tension and flexural testing was 5 mm/min. Although all the experiments were designed around the weight percent of kenaf in the composites. fiber volumes fractions can be estimated from composite density measurements and the weights of dry kenaf fibers and matrix in the composite. The density of the kenaf present in the composite was estimated to be 1.4 g/cc. The results are shown in Table 7.21

To develop sufficient stress transfer properties between the matrix and the fiber, two factors need to be considered. Firstly, the MAPP present near the fiber surface should be

TABLE 7.21
Properties of Kenaf and Jute Reinforced Polypropylene Composites

Filler/reinforcement in PP	ASTM standard	None	Kenaf	Jute	Talc	$CaCO_3$	Glass	Mica
% filler by weight		0	50	50	40	40	40	40
% filler by volume (estimated)		0	39	39	18	18	19	18
Tensile modulus, GPa	D638	1.7	8.3	7.8	4	3.5	9	7.6
Specific tensile modulus, GPa		1.9	7.8	7.2	3.1	2.8	7.3	6.0
Tensile strength, MPa	D638	33	68	72	35	25	110	39
Specific tensile strength, MPa		37	58	67	28	20	89	31
Elongation at break, %	D638	≫10	2.2	2.3	×	×	2.5	2.3
Flexural strength, MPa	D 790	41	91	99	63	48	131	62
Specific flexural strength, MPa		46	85	92	50	38	107	49
Flexural modulus, GPa	D 790	1.4	7.8	7.7	4.3	3.1	6.2	6.9
Specific flexural modulus, GPa		1.6	7.3	7.1	3.4	2.5	5.0	5.5
Notched izod impact, J/m	D256A	24	32	31	32	32	107	27
Specific gravity		0.9	1.07	1.08	1.27	1.25	1.23	1.26
Water absorption % – 24 h	D570	0.02	1.05	×	0.02	0.02	0.06	0.03
Mold (linear) shrinkage cm/cm		0.028	0.003	×	0.01	0.01	0.004	×

strongly interacting with the fiber surface through covalent bonding and acid–base interactions. This means sufficient MA groups should he present in the MAPP so that interactions can occur with the –OH groups on the fiber surface. Secondly, the polymer chains of the MAPP should he long enough to permit entanglements with the PP in the interphase. Polar polymers that can develop hydrogen bonding between chains tend to reach mechanical integrity at lower molecular weights.

A small amount of the MAPP (0.5% by weight) improved the flexural and tensile strength, tensile energy absorption, failure strain, and unnotched Izod impact strengh. The anhydride groups present in the MAPP can covalently bond to the hydroxyl groups of the fiber surface. Any MA that has been converted to the acid form can interact with the fiber surface through acid–base interactions. The improved interaction and adhesion between the fibers and the matrix leads to better matrix to fiber stress transfer. There was little difference in the properties obtained between the 2 and 3% (by weight) MAPP systems. The drop in tensile modulus with the addition of the MAPP is probably due to molecular morphology of the polymer near the fiber surface or in the hulk of the plastic phase. Transcrystallization and changes in the apparent modulus of the bulk matrix can result in changes in the contribution of the matrix to the composite modulus and are discussed later. There is little change in the notched impact strength with the addition of the MAPP, while the improvement in unnotched impact strength is significant. In the notched test. the predominant mechanism of energy absorption is through crack propagation as the notch is already present in the sample. The addition of the coupling agent has little effect in the amount of energy absorbed during crack propagation. On the other hand, in the unnotched test, energy absorption is through a combination of crack initiation and propagation. Cracks are initiated at places of high stress concentrations such as the fiber ends, defects, or at the interface region where the adhesion between the two phases is very poor. The use of the additives increases the energy needed to initiate cracks in the system and thereby results in improved unnotched impact strength values with the addition of the MAPP. Entanglement between the PP and MAPP molecules

results in improved interphase properties and the strain to failure of the composite. There is a plateau after which further addition of a coupling agent results in no further increase in the ultimate failure strain. There is little difference in the tensile strength of uncoupled composites compared to the unfilled PP. irrespective of the amount of fiber present. This suggests that there is little stress transfer from the matrix to the fibers due to incompatibilities between the different surface properties of the polar fibers and nonpolar PP. The tensile strength of the coupled systems increased with the amount of fiber present and strengths of up to 74 MPa were achieved with higher fiber loading of 60% by weight or about 49% by volume. As is the case with tensile strength, the flexural strength of the uncoupled composites was approximately equal for all fiber-loading levels, although there was a small improvement as compared to the unfilled PP. The high shear mixing using the thermokinetic miser causes a great deal of fiber attrition. Preliminary measurements of the length of fibers present in the composite after injection molding show that few fibers are longer than 0.2 mm. The strength obtained in our composites was thus limited by the short fiber lengths. Higher strengths are likely if alternate processing techniques are developed that reduce the amount of fiber attrition while at the same time achieve good fiber dispersion.

The specific tensile and flexural moduli of 50% by weight kenaf coupled composites were about equivalent to or higher than the typical reported values of 40% by weight coupled glass–PP injection-molded composites [87]. The specific flexural moduli of the kenaf composites with fiber contents greater than 40% were extremely high and even stiffer than a 40% mica–PP composite. Table 7.21 shows some typical data of commercially available injection-molded PP composites and the comparison with typical jute and kenaf–PP composites. Data on the talc. mica. calcium carbonate, and glass composites were compiled from the Resins and Compounds (*Modern Plastics Encyclopedia*) [88], and Thermoplastic Molding Compounds (*Material Design*) [89]. The properties of kenaf-based fiber composites hare properties superior to typical wood (newspaper) fiber–PP composites. The specific tensile and flexural moduli of 50% by weight of kenaf–PP composites compares favorably with the stiffest of the systems shown, that of glass–PP and mica–PP. This technology has been used to make many products including decking shown in Figure 7.13.

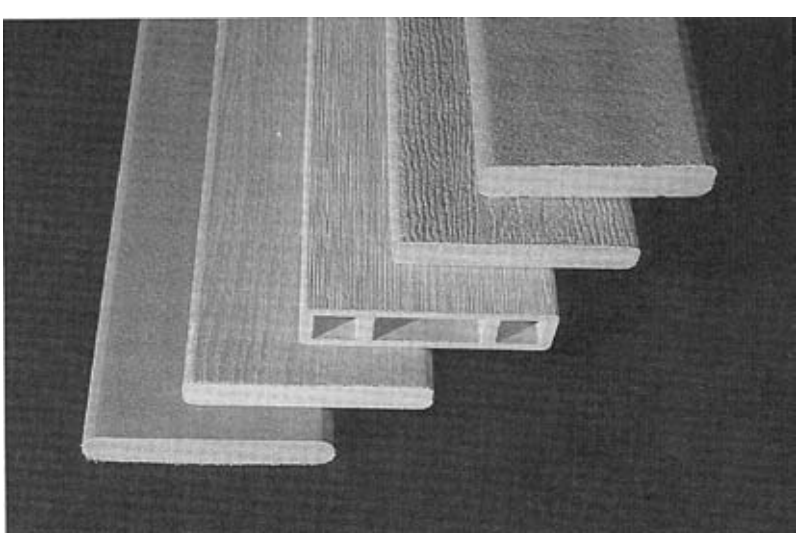


FIGURE 7.13 Extruded kenaf thermoplastic products (USDA)

The Failure strain decreases with the addition of the fibers. Addition of a rigid filler and fiber restricts the mobility of the polymer molecules to flow freely past one another. and thus causes premature failure. The addition of MAPP followed a similar trend to that of the uncoupled system. although the drop in failure strain with increasing fiber amounts was not as severe. There is a decrease in the failure strain with increasing amounts of kenaf for a coupled system. The stress–strain curve is not linear, which is due to the plastic deformation of the matrix. The distribution of the fiber lengths present in the composite can influence the shape of the stress–strain curve since the load taken up by the fibers decreases as the strain increases; detailed explanations are available elsewhere [90]. The tensile energy absorption and the integrated area under the stress–strain curve up to Failure behave in roughly the same manner as the tensile failure strain. The difference between the coupled and uncoupled composites increases with the amount of fibers present. although the drop in energy absorbed for the coupled composites levels off after the addition of about 35 vol.% of fiber.

The impact strength of the composite depends on the amount of fiber and the type of testing, i.e., whether the samples were notched or unnotched. In case of notched samples. the impact strength increases with the amount of fibers added until a plateau is reached at about 45% fiber weight, irrespective of whether MAPP is used or not. The fiber bridge cracks and increases the resistance of the propagation of the crack. The contribution from fiber pullout is limited since the aspect ratio of the fibers in the system is well below the estimated critical aspect ratio of about 0.4 mm [91]. In case of the unnotched impact values of the uncoupled composites, the presence of the fibers decreases the energy absorbed by the specimens. the addition of the fibers creates regions of stress concentrations that require less energy to initiate a crack. Improving the fiber–matrix adhesion through the use of MAPP increases the resistance to crack initiation at the fiber–matrix interface and the fall in impact strength with the addition of fibers is not as dramatic.

The two main disadvantages of using kenaf–PP as compared to glass-PP are the lower impact strength and higher water absorption. The lower notched impact strength can be improved by using impact modified PP copolymers and the use of flexible maleated copolymers. albeit with some loss in tensile strength and modulus, which will be discussed in a later paper. Care needs to be taken when using these fibers in applications where water absorption and the dimensional stability of the composites are of critical importance. Judicious use of these fibers makes it possible for jute and kenaf fibers to define their own niche in the plastic industry for the manufacture of low-cost, high-volume composites using commodity plastics.

An interesting point to note are the higher fiber volume fractions of the jute and kenaf composites compared to the inorganic filled systems. This can result in significant material cost savings as the fibers are cheaper than the pure PP resin, and far less expensive than glass fibers. Environmental and energy saving by using an agriculturally grown fiber instead of the high energy utilizing glass fibers or mined inorganic fillers are benefits that cannot be ignored. although a thorough study needs to be conducted to evaluate the benefits.

7.17.13 Fiber Matrix Thermoplasticization

There have been many research projects over the years studying ways to thermoform lignocellulosics. Most of the efforts have concentrated on film formation and thermoplastic composites. The approach most often used involves the chemical modification of cellulose. lignin. and the hemicelluloses to decrystallize and modify the cellulose and to thermoplasticize the lignin and hemicellulose matrix to mold the entire lignocellulosic resource into films or thermoplastic composites [92–97].

Jute and kenaf fibers are composites made up of a rigid polymer (cellulose) in a thermoplastic matrix (lignin and the hemicelluloses). If a nondecrystallizing reaction condition is

used. it is possible to chemically modify the lignin and hemicellulose, but not the cellulose. This selective reactivity bas been shown to occur if uncatalyzed anhydrides are reacted with wood fiber [98]. The god is to only modify the matrix of jute and kenaf fibers allowing thermoplastic flow, but keeping the cellulose backbone as a reinforcing filler. This type of composite should have reduced heat-induced deformation (creep), which restricts thermoplastic-based composites from structural uses.

The modification of the kenaf bast fibers using succinic anhydrides (SA) was performed using either solution reactions with xylene or solid-state reactions using SA in a melt state [99]. Since xylene does not swell the fiber. it is only a carrier for the reagent. The rate of reaction is fastest at higher concentration of SA in xylene and at temperatures above 140°C. The rate of reaction in the melt state has not been determined. It has also not yet been determined what level of modification is needed to give the desired thermoplasticity so it is not known what optimum reaction time is needed.

Thermal analysis (DSC) showed the first glass transition temperature decreased from 170°C to about 133°C [98].

Samples of reacted fiber were pressed into pellets using a powder pressing die consisting of a heavy-walled steel cylinder with a separate bottom and a ram (diameter 10.4 mm) to compress the fibers. Fiber was placed in the preheated cylinder and then compressed to a pellet thickness of 8.7 mm (target density 1.5g/cm^3, target volume 0.736 cm^3) for 10 min at 190°C.

Scanning electron micrographs (SEM) were taken of the pressed control and SA-reacted fiber specimens using a Jeol 840 scanning electron microscope [99]. Figure 7.14 shows the SEM of the hot pressed control and esterified kenaf fiber. The SA fiber is derived from a reaction done according to the solid-state reaction method and pressed at 190°C for 10 min. The weight percent gain due to esterification is 50. The control fiber (A) shows little tendency to thermally flow under the pressure of the hot press. whereas the esterified fiber (B) shows thermal flow at this temperature. Views A, B, and Dare taken from the top of the compressed

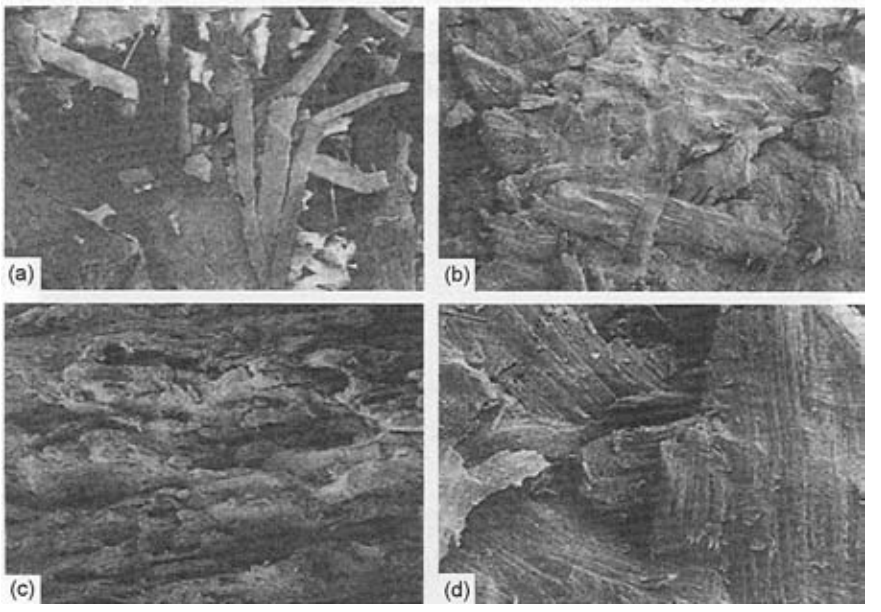


FIGURE 7.14 Scanning electron micrographs of pressed kenaf fiber: A, Control (30X), B, SA reacted (50 WPG, 30X), C, SA reacted (50 WPG, 50X), D, SA reacted (50 WPG, 100X) (USDA).

pellet, while Cis taken from the side of the pellet. The side view (C) shows a definite layering of the fiber has occurred and view D shows that fiber orientation is still evident.

The research done so far in this area shows that kenaf fiber can be reacted with SA to give high weight gains of esterification of the cell wall polymers either by solution or solid-state chemistry. The esterified fiber shows a reduced transition temperature from about 170°C down to about 135°C regardless of the weight gained. Electron microscopy of hot pressed fiber indicates matrix thermoplasticity with a rigid fiber structure still in existence.

7.17.14 Fiber Thermoplastic Alloys

Research to develop jute and kenaf fiber thermoplastic alloys is based on first thermoplasticizing the fiber matrix as described above, followed by grafting of the modified fiber with a reactive thermoplastic. This type of composite has the thermoplastic bonded onto the jute or kenaf so there is only one continuous phase in the molecule. This is done in one of two ways. In one case, the matrix is reacted with maleic anhydride that results in a double bond in the grafted reacted molecule. This can then be used in vinyl-type additions or in free radical polymerization to either build a thermoplastic polymer or graft one onto the jute or kenaf backbone. In the second method, the matrix is reacted with a bonded chemical and then reacted with a low-molecular-weight thermoplastic that has been grafted with side-chain anhydride groups.

The anhydride functionality in the compatibilization research described before may react with the lignocellulosic, but there is no evidence to support that at this time. A higher level of grafted anhydride on the polypropylene would be required for the alloy reactions, and it would be expected that the reaction between grafted thermoplastic and jute or kenaf would take place both on the matrix polymers (lignin and hemicelluloses) and in the cellulose backbone. Some decrystallization of the cellulose may be desired to give more thermoplastic character to the entire composite.

Preliminary results indicate that maleic anhydride reacts with the jute or kenaf matrix, both in liquid- and solid-state reactions, to similar weight gains as given for SA. Research in this area continues.

Combining jute and kenaf fibers with thermoplastics provides a strategy for producing advanced composites that take advantage of the enhanced properties of both types of resources. It allows the scientist to design materials based on end-use requirements within a framework of cost, availability, recyclability, energy use, and environmental considerations. These new composites make it possible to explore new applications and new markets in such areas as packaging, furniture, housing, and automotive.

7.17.15 Charcoal

Jute stick or core is often compressed and pyrolyzed into charcoal for cooking in India and Bangladesh. After the core has been compressed, it is heated for 2 h at 500°C in the presence of an inorganic salt to give a 35 to 40% yield of high-grade charcoal. The charcoal can also he used as a filler in vulcanized rubber and in the production of carbon disulfide [8].

7.18 FUTURE TRENDS

The main commercial developments in the jute industry have been concerned with the spinning and weaving technology, and considerable improvements in productivity have also taken place. However. it is time now to consider what new innovations would assist the spread of jute materials into textile uses outside the traditional fields of packaging and carpets.

Agricultural developments to breed Corchorus or Hibiscus plants containing fibers of significantly lower linear density would allow yarns of lower count to be spun than is feasible at present, and therefore enable lightweight fabrics to be produced. Such fabrics could have increased potential for decorative and furnishing use, especially if the constraint of instability of color could first be removed and some process then devised to produce additional elasticity on a more permanent basis than is done by the woolenizing process.

Kenaf is now being grown in several countries where the bast fiber is used for geotextiles and the pith is going into sorbents for oil spill clean up and animal litter. The production of pulp and paper from kenaf is growing, but it is only used for limited types of papers at present. The utilization of the whole plant of both jute and kenaf is under consideration for structural and nonstructural composites. Automotive interior door panels are now produced in Germany and the United States out of jute and kenaf bast fiber in combination with thermoplastics.

REFERENCES

1. R.H. Kirby, *Vegetable Fibers,* Leonard Hill (Books) Ltd., London (1963).
2. B.C. Kundu, K.C. Basak, and P.B. Sarkar, *Jute in India,* Monograph, Indian Central Jute Committee, Calcutta (1959).
3. W.A. Bell, *Sci. News,* **54,** 39 (1960).
4. R.P. Mukheriee and T. Radhakrishnan, *Tex. Progr.,* **4,** 1 (1972).
5. J.N. Mather, Carding—Jute and Similar Fibers. Iliff, London (1969).
6. R.M. Rowell, J.A. Young, and J.K. Rowell, eds., *Paper and Composites from Jute and Kenaf Resources,* CRC Lewis Publishers, Boca Raton, FL (1997).
7. T. Sellers, Jr and N.A. Reichert eds., *Kenaf Properties, Processing and Products,* Mississippi State University Press, Mississippi State, MS (1999).
8. S.N. Pandey and S.R. Anantha Krishnan, *Fifty Years of Research 1939–1989,* Jute Technological Research Laboratories, Hooghly Printing Co. Ltd, Calcutta, India (1990).
9. C.G. Jarman, FAO Agricultural Services Bulletin No. 60, Rome (1985).
10. E.P. Columbus and M.J. Fuller, *Kenaf Properties, Processing and Products,* Mississippi State University Press, Mississippi State, MS 83–89 (1999).
11. G. Fisher, *Proc. Sixth Annual International Kenaf Conf.,* New Orleans, LA 8–12 (1994).
12. G.N. Ramaswam, *Kenaf Properties, Processing and Products,* Mississippi State University Press, Mississippi State, MS 91–96 (1999).
13. E.P. Columbus and W.S. Anthony, *U.S. Cotton Ginning Laboratory Annual Report—CropYear 1994,* Stoneville, MS 198–201 (1995).
14. S.C. Barker, British Association for Advancement of Science, *J. Text. Inst.,* **30,** 273 (1939).

15a. A. Islam and A.M. Bhuyian, *Jute and Jute Fabrics No. 8,* Bangladesh (1978).

15b. J.S. Han and J.S. Rowell, Paper and Composites from Jute and Kenaf Resources, CRC Lewis Publishers, Boca Raton, FL, MS 83 (1997).

16. T.H. Soutar and M. Bryden, *J. Text. Inst.,* **46,** T521 (1965).
17. M. Manzoor-i-Khuda, A.S.M. Serajuddin, M.M.A. Islam, N. Am in, M. Bose, A.A. Khan, and Md. Shahjahan, *Pakistan J.* Sci. Ind. Res., *13, 153, 316, 321 (1970).*
18. C.G. Jar man and R.H. Kirby, *Colon, Plant Animal Prod.,* **5,** 281 (1955).
19. V. Ozsanlav, British Textile Technology Group, Cheshire, UK, Personal communication (1992).
20. H. Chatterjee. *J. Sci. and Ind. Research,* **18C,** 206 (1959).
21. A.C. Mukherjee, A.K. Mukhopadhyay, and U. Mukhopadhyay, *Textile Res. J.,* **56(9),** 562 (1986).
22. T.F. Clark and I.A. Wolff, *TAPPI,* **52(11),** 2606 (1969).
23. T.F. Clark, S.C. Uhr, and I.A. Wolff, *TAPPI,* **50(11),** 2261 (1967).
24. J.S. Han, W. Kim, and R.M. Rowell, International Kenaf Association Conference Proceedings, March 9–10, Irving, TX, (1995).
25. M.O. Baggy. *TAPPI,* **54.** 11 (1971).

26. M. Lewin, *TAPPI,* **41,** 403 (1958).
27. F. Stern and H.P. Stout, *J. Text. Inst.,* **45,** T896 (1954).
28. F. Stern, *J. Text. Inst.,* **48,** T21 (1957).
29. C.G. Jarman and V. Laws, *J.R. Microbiol. Soc.,* **84,** 339 (1965).
30. I.G. Cumming, D.F. Leach, and G.M. Smith, *Bull. Br. Jute Trade R. A.,* **10,** 74 (1964).
31. M. Kabir and N.G. Saha, *Pakistan J. Sci. Ind. Res.,* **14,** 162 (1971).
32. M. Kabir and N.G. Saha, *Bangladesh J. Sci. Ind. Res.,* **12,** 91 (1977).
33. J.N. Mather, *Bull. Br. Jute Trade R. A.,* **12,** 63 (1968).
34. H.P. Stout, *Fibre and Yarn Quality in Jute Spinning,* The Textile Institute, Manchester (1988).
35. R.M. Rowell, Commonwealth Forestry Bureau, Oxford, England, **6(12),** 363 (1983).
36. R.M. Rowell, *Handbook on Wood and Cellulosic Materials,* D.N.-S. Hon and N. Shiraishi, eds., Marcel Dekker, Inc., New York, NY, (1991).
37. H.J. Callow, *J. Indian Chem. Soc.,* **43,** 605 (1951).
38. M. Andersson and A.M. Tillman, *J. Appl. Polym. Sci.,* **37,** 3437 (1989).
39. R.M. Rowell, R. Simonson, and A.M. Tillman, European Patent 0213252 (1991).
40. R.M Rowell, International consultation of jute and the environment, Food and Agricultural Organization of the United Nations. ESC:JU/IC 93/15, 1 (1993).
41. R.M. Rowell and S.E. Harrison. *Proceedings, Fifth Annual International Kenaf Conference,* M.S. Bhangoo, ed., California State University Press, Fresno, CA, 129 (1993).
42. R.M. Rowell, G.R. Esenther, J.A. Youngquist, D.D. Nicholas, T. Nilsson, Y. Imamura, W. Kerner-Gang, L. Trong, and G. Deon, *Proceedings: IUFRO Wood Protection Subject Group,* Honey Harbor, Ontario, Canada. Canadian Forestry Service. 238 (1988).
43. American National Standard. Basic hardboard, ANSI/AHA 135.4. American Hardboard Association, Palatine, IL (1982).
44. C.B. Vick and R.M. Rowell, *Internat., J. Adhes. and Adhesives,* **10(4),** 263 (1990).
45. J. Compton, W.H. Martin, and R.P. Barber, *Text. Res. J.,* **25,** 58 (1955).
46. J. Compton, *Text. Res. J.,* **27,** 222 (1955).
47. T.E. Timell, *Pulp Paper Mag.,* Canada, **56,** 104 (1955).
48. T.E. Timell, *Text. Res. J.,* **27,** 854 (1957).
49. M. Lewin and J.A. Epstein, *Text. Res. J.,* **30,** S-20 (1960).
50. H. Muir (with W.A. Bell), Doctoral thesis, Edinburgh (1964).
51. M.M. Roy and I.K. Sen, *J. Text Inst.,* **43,** T396 (1952).
52. M. Kabir, M.S. Rahman, and M. Shahidullah, *Bangladesh J. Jute Fiber Res.,* **2,** 45 (1977).
53. W.A. Bell, *Bull Br. Jute Trade R. A.,* **12,** 154 (1969).
54. British Standard 1006, British Standards Institution, London.
55. I.G. Cumming, *Bull. Br. Jure Trade R. A.,* **8,** 240 (1961).
56. M. Lewin, M. Shiloh, and J. Banbaji, *Text. Res. J.,* **29,** 373 (1959).
57. J. Banbaji, *Text. Res. J.,* **30,** 798 (1960).
58. A.M. Bhuiyan, M.A. Salam, A. Sukur, and A.S.M.N. Ahsan, *Bangladesh J. Jute User Res.,* **2,** 85 (1977).
59. R.M. Rowell. Food and Agriculture Organization of the United Nations. ESC: JU/EGM 94/3 (1994).
60. H.S. Sabharwal, M. Akhtar, R.M. Blanchette, and R.A. Young, *TAPPI,* **77(12), 1** (1994).
61. T.F. Clark, *Pulp and Paper Manufacturing,* Vol. 2, 2nd ed., R.O. MacDonald, ed., McGraw-Hill, New York, NY 1 (1969).
62. D.K. Misra, Pulp and Paper, *Chemistry and Chemical Technology,* Vol. 1. 3rd ed., J.P. Casey, ed., Wiley-lnterscience, New York, NY 504 (1980).
63. A.M. Hunter. Non-wood plant fiber pulping, Progress Report No. 19. TAPPI Press, Atlanta, GA, 49 (1991).
64. R.A. Young, *Paper and Composites from Agro-Based Resources.* R.M. Rowell, J.A. Young, and J.K. Rowell, eds., CRC Lewis Publishers, Boca Raton. FL 135–248(1997).
65. V.P. Leehka and S.K. Thapar, Experience in kenaf pulping in Thailand, non-wood plant fiber pulping. Progress Report No. 14. TAPPI Press, Atlanta, GA (1983).
66. T.F. Clark, G.H. Nelson, H.J. Niechlag, and I.A. Wolff, *TAPPI,* **45(10),** 780 (1962).

67. T.F. Clark and I.A. Wolff, *TAPPI,* **45(10),** 786 (1962).
68. M.O. Bagby, Non-wood plant fiber pulping, Progress Report No. 9, TAPPI Press, Atlanta, GA 75 (1978).
69. A.J. Watson, G. Gartside, D.F. Weiss, H.G. Higgins, H. Mamers, G.W. Davies, G.M. Irvine, I.M. Wood, A. Manderson, and E.J.F. Crane, *Div. Chem. Technol,* Paper No. 7, CSIRO, Australia (1976).
70. S.K. Mittal and S. Maheshwari, *Proceedings Pulping Conference TAPI,* San Diego, 105 (1994).
71. G.F. Touzinsky. Laboratory paper machine runs with kenaf thermomechanical pulp. *TAPPI,* **63(3),** 109 (1980).
72. G.F. Touzinsky, Kenaf, In *Pulp and Paper Manufacturing,* Vol. 3., Secondary fibers and non-wood pulping, Chapter 8. TAPPI Press, Atlanta, GA 106 (1987).
73. J.S. Han, E.S. Miyashita, and S.J. Spielvogel, *Kenaf Properties,* Processing and Products, Mississippi State University Press, 267–283 (1999).
74. Y. Shuhui, H. Zhrivei, and L. Yorsen, *Proc. Seventh International Symposium on Wood and Pulping Chem.,* Vol. 3, Beijing, PR China, 317 (1993).
75. H. Pande and D.N. Roy, *Kenaf Properties, Processing and Products,* Mississippi State University Press, 315–320 (1999).
76. M. Shafi, A.F.M. Akhtaruzzamarn, and A.J. Mian, *Holzforschung* **47,** 83 (1993).
77. A.K. Rana and K. Jayachandran, *Mol. Cryst. and Liq. Cryst.,* **353,** 35 (2000).
78. R.M. Rowell, Final Report on Composites to the UNDP (1998).
79. V. Wigotsky, *Plast. Eng.,* Nov., 25 (1988).
80. A.R. Sanadi, D.F. Caulfield, and R.M. Rowell, *Plast. Eng.* April, 27 (1994).
81. R. Woodhams, T.G. Thomas, and D.K. Rodgers, *Polym. Eng. Sci.* **24,** 1166 (1984).
82. C. Klason and J. Kubat, *Composite Systems from Natural and Synthetic Polymers,* L. Salmen, A. de Ruvo, J.C. Seferis, and E.B. Stark, eds., Elsevier Science, Amsterdam (1986).
83. G. Myers, E.C.M. Clemons, J.J. Balatinecz, and R.T. Woodhams, *Proc. Annual Technol Conf.,* Society of Plastics Industry. 602 (1992).
84. B.V. Kokta, R.G. Raj, and C. Daneault, *Polym. Plast. Technol. Eng.,* **28,** 247 (1989).
85. A.R. Sanadi, R.A. Young, C. Clemons, and R.M. Rowell, *J. Rein. Plast. Compos.,* **13,** 54 (1994).
86. R.M. Rowell, A.M. Tillman, and R. Simonson, *J. Wood Chem. Tech.,* **6,** 427 (1986).
87. A.R. Sanadi, D.F. Caulfield, R.E. Jacobson, and R.M. Rowell, *Ind. and Eng. Chem. Res.,* **34,** 1889 (1995).
88. Resins and Compounds, Modern Plastics Encyclopedia, McGraw-Hill, NY, 269 (1993).
89. Thermoplastic Molding Compounds, *Material Design,* Material Selector Issue, Penton Publishing, OH, 184, (1994).
90. D. Hull, *An Introduction to Composite Materials,* Cambridge University, Cambridge (1981).
91. A.R. Sanadi, R.M. Rowell. and R.A. Young. AICHE Summer National Meeting, paper 24f (1993).
92. D.N.-S. Hon and N.-H. Ou, *J. Appl. Polym. Sci.*: *Part A*: *Polymer Chemistry,* **27,** 2457 (1989).
93. D.N.-S. Hon and L.M. Xing, Viscoelasticity of Biomaterials, W.G. Glasser, ed., Am. Chem. Soc., Washington, D.C. 118 (1992).
94. H. Matsuda, *Wood Sci. Techol.,* **21,** 75 (1987).
95. H. Matsuda and M. Ueda, *Mokuzai Gakkaishi,* **31(3),** 215 (1985).
96. N. Shiraishi, *Wood and Cellulose Chemistry,* D.N.-S. Hon and N. Shiraishi, eds., Marcel Dekker. Inc.. New York. NY. 861. (1991).
97. M. Ohkoshi, N. Hayshi, and M. Ishihara, *Mokuzai Gakkaishi,* **38(9),** 854 (1992).
98. R.M. Rowell, R. Simonson, S. Hess, D.V. Plackett, D. Cronshaw, and E. Dunningham, *Wood and Fiber Sci.* **26(1),** 11 (1994).
99. R.M. Rowell, J. O'Dell, and T.G. Rials, Proceedings, Second Pacific Rim Bio-Based Composites Symposium. Vancouver, Canada (1994).

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