Chapter 6
Kapok Fiber: Structure and Properties

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Abstract Due to the development of sustainable technology, green renewable resources have attracted increasing interests in recent years. Kapok fiber belongs to a typical cellulosic fiber, which is obtained from the seed hairs of kapok trees (*Ceiba pentandra*). Kapok fiber possesses the features of thin cell wall, large lumen, low density, and hydrophobic–oleophilic properties. This chapter focuses on the structure and properties of kapok fiber.

Keywords Kapok fiber • Structure • Properties

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6.1 Introduction

Kapok fibers are obtained from the fruits of kapok trees (*Ceiba pentandra*) which belong to the family of Bombacaceae and are growing in Asia, Africa, and South America. Their color is yellowish or light brown with a silk like luster. Kapok fiber is odorless, fluffy, nontoxic, nonallergic, and resistant to rot. Traditionally, kapok fiber is used as the stuffing for pillows, bedding, and some soft toys. Owing to excellent buoyancy and air-filled lumen, kapok fiber is also utilized as the buoyant material (such as life preservers) and insulation materials against sound and heat. As a kind of natural biodegradable fibers, kapok fiber is now receiving more attention in scientific researches.

6.2 Structure of Kapok Fiber

As a kind of natural fiber, kapok fiber shows the highest hollowness and the lowest specific mass that any microchemical fiber is incomparable. Kapok fibers consist of natural microtubules with fine tube structure (ca. 8–10 μm in diameter and ca. 0.8–1.0 μm in wall thickness) (Chung et al. 2008), and the hollow ratio can reach 97 %. One end of the fiber that tapers to one point is closed, and the other end is bulbous shape and may be closed tightly (Xiao et al. 2005). As a single-cell fiber, cotton fiber looks like ribbons, rolled in a helicoidal manner around the axis, while kapok fiber is not convoluted. Figure 6.1 shows the SEM micrographs of longitudinal and cross-sectional view of kapok fiber. A longitudinal view of kapok fiber shows smooth cylindrical surface, while a cross section reveals a wide open lumen (Mwaikambo and Bisanda 1999). Kapok fiber shows a unique hollow structure, and this feature is expected to enlarge its specific surface area, endowing the fiber with outstanding moisture transfer property and making it an ideal environment-friendly natural thermal fiber (Feng et al. 2006).

From the fine structure of the walls of kapok fiber, five layers, i.e., cuticle (S), primary wall (W1), secondary wall (W2), tertiary wall (W3), and inner skin (IS), have been clearly observed in lateral and longitudinal cross sections. The W1 is characterized by an interlaced fibril-like network (Xiao et al. 2006), while the fibrils of W2 and W3 are arranged angled or parallel to the fiber axis. The thickness of W1 is about 200 nm, and this thickness seems the same for W2 and W3 (ca. 500 nm). The cuticle S is the protective layer of kapok fiber and shows the highest packing density. In addition, the fibrils of W1 and W3 are closely packed and accordingly, the structure of them is more compact than that of W2. However, the structure of IS is relatively loose, and the fibrils are easily escaped from IS and then dispersed in the lumen. Between the adjacent layers, a transition layer with the low packing density is present. In transitional layers, the interactions between the fibrils are weaker than those in the individual layers. As for different walls, the variety in the fibril size from protofibrils to fibrils is observed for the smallest structural units. The smallest fibril size is found to be 3.2–5.0 nm in different walls (Shi et al. 2010).

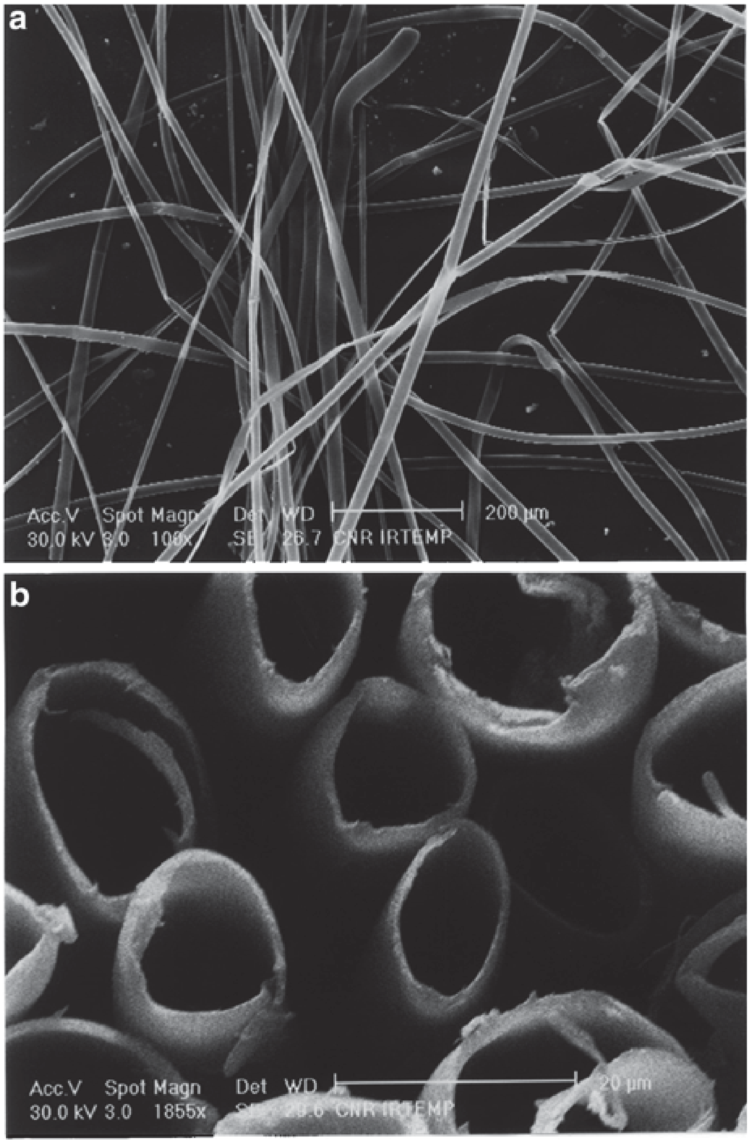

Fig. 6.1 SEM micrographs of longitudinal (**a**) and cross-sectional (**b**) view of kapok fiber (Mwaikambo and Bisanda 1999) (Copyright 1999, reproduced with permission from Elsevier)

The main components of kapok fiber are cellulose, lignin, and xylan (Fengel and Przyklenk 1986; Gao et al. 2012). The outer cell wall layer contains less lignin and more of the minor polysaccharides mannan and galactan and more proteins than the main part. There is a high mineral content in the outer layer which obviously influences the surface properties of the kapok fiber. Kapok fiber includes a high ratio of syringyl/guaiacyl units (4–6) and a high level of acetyl groups (13.0 %) as compared with normal plant cell walls (about 2–4 %) (Chung et al. 2008). The bulk density of the kapok fiber is 0.30 g/cm^3, the crystallization degree is 35.90 %, and the specific birefringence is 0.017 (Xiao et al. 2005). The kapok fiber shows the well-resolved spectrum of cellulose I, and the crystallinity is lower than cotton fiber (Cao et al. 2010).

To enhance the intrinsic properties or alter the surface characteristics, natural kapok fiber is usually pretreated including (1) chemical treatment, such as alkali/acid treatment, solvent treatment, oxidation treatment and acetyl treatment, and

(2) physical treatment, such as ultrasonic treatment and radiation treatment, by which the surface impurities can be removed and the interfacial properties will be improved.

Solvent treatment is a popular method to change the surface property of kapok fiber. Previous studies have shown that the kapok fiber has lost their silky luster after solvent treatment. By comparing the spectra of untreated and solvent-treated kapok fiber, the increase in absorption bands at 3,410 and 2,914 cm^{-1} can be observed, and this information is an indication of the removal of plant wax from the surface of kapok fiber. Except for the above absorption bands, there is no significant variation in other bands for water-treated and chloroform-treated kapok fiber. But for NaOH-treated fiber, the absorption bands at 1,740 and 1,245 cm^{-1} show a remarkable reduction in their intensities. This is ascribed to the fact that the alkali treatment can remove all the esters linked with aromatic ring of lignin, resulting in a significant de-esterification of kapok fiber. For $NaClO_2$-treated kapok fiber, the absorption bands around 1,602 and 1,504 cm^{-1} nearly disappear, owing to the cleavage of the aromatic ring in lignin (Wang et al. 2012a).

Furthermore, for untreated, water-treated, HCl-treated, NaOH-treated, $NaClO_2$-treated, and chloroform-treated fiber, the crystallinity index is determined to be 35.34 %, 33.93 %, 22.17 %, 32.00 %, 26.97 %, and 27.17 %, respectively. This result implies that the crystalline region of lignocellulose in kapok fiber shows no remarkable change for water-treated kapok fiber, while HCl, $NaClO_2$, and chloroform treatment will change the aggregate structure and expand the proportion of amorphous region of kapok fiber. But for NaOH-treated kapok fiber, there appears no remarkable reduction in the crystallinity when compared to $NaClO_2$ treatment, even though a significant de-esterification occurs for kapok fiber during this process (Wang et al. 2012a).

Liu and Wang (2011) investigated the effect of mercerization on microstructure of kapok/cotton yarns, with the findings that the chemical compositions of fiber showed no appreciable changes after mercerization treatment, but this treatment could decrease the crystallinity of kapok/cotton yarns, transforming partial cellulose I to cellulose II. Chen and Xu (2012) found that the ultrasonic treatment with water had little influences on the morphological structure and chemical component of the kapok/cotton-blended yarns, except for some loss of kapok flocks. Via the combination process of chlorite–periodate oxidation, kapok fiber was found to harbor a certain amount of polysaccharides, together with lowered lignin content. Although a distorted hollow shape and rough surface were observed, the characteristic fine hollow shape was still maintained in all of the chemically oxidized kapok fiber (Chung et al. 2008). To provide the functions or facilitate further modification, some polymerizable monomers had been grafted onto the kapok fiber by Co^{60} γ-ray radiation-induced graft copolymerization, such as styrene, glycidylmethacrylate (GMA), and acrylic acid (AA) (Cho et al. 2007; Kang et al. 2007).

6.3 Properties of Kapok Fiber

6.3.1 Spinning Property

Kapok fiber is known as the soft gold in plants for its finest and lightest quality, highest hollowness, and most warm nature. Due to their wide lumen filled with air, their smooth surface, and low strength, kapok fibers are considered unfit for textile fabrics in the early years (Fengel and Wenzkowski 1986). With the development of technology, the spinning of 100 % kapok fibers beyond lap formation stage is not possible, but kapok yarn property and weavability could be improved through sizing or blended spinning (Yang and Jin 2008). To resolve the problem of pure kapok yarn such as low strength, much hairiness, poor wear resistance, and difficult to weave, sizing experiment of 27.8 tex pure kapok yarns was carried out in order to improve yarn performance and meet the requirements of weaving. According to the characteristics of kapok yarns, a mixed size composed of acid-modified starch and poly(vinyl alcohol) (PVA) was selected to size kapok yarns. The results show that low solid content helps size penetration and facilitates yarn strength and elongation improvement (Yang 2010). Furthermore, the spinning of kapok fiber blended with cotton fiber is largely successful. With an increase in kapok content in the blend, the yarn regularity and tenacity decrease, while the yarn extensibility increases. It is considered that kapok fiber can be blended with cotton for spinning yarn, but the content of kapok fiber should not be more than 50 %, or the blended yarn property and weaving processing will be effected (Dauda and Kolawole 2003; Yang et al. 2013). Also, the total cost of production of the yarns decreases significantly as the kapok content increases in the blend.

6.3.2 Dyeing Property

Owing to large hollow structure and waxy surface, kapok fiber shows the hydrophobic–oleophilic characteristics. The higher surface tension (7.2×10^{-4} N cm^{-1} at 20 °C against air) will drive out the water droplets, leading the surface of kapok fiber cannot get wet with the water droplets (Chung et al. 2008), making this fiber show poor affinity to hydrophilic coloring agents or dyes. For kapok fiber, the dyeing efficiency is relatively low, and the dyeing property of kapok fiber is worse than that of cotton fiber (Lou 2011). Pretreatment of kapok fiber is thus important to enhance the dyeing property of this fiber, but up to now, no mature processing or pretreatment techniques have been established except for the mercerization. Compared with cotton fiber, the alkali resistance of kapok fiber is rather poor, and accordingly, mild alkali treatment conditions are generally expected for kapok fiber in dyeing and finishing processes.

6.3.3 Mechanical Properties

According to the tested data of four types of kapok fibers, the average breaking strength and breakage elongation of kapok fibers are 1.44–1.71 cN and 1.83 %–4.23 %, respectively. By comparing with cotton fiber, kapok fiber has the lower tensile elongation, similar breaking tenacity and initial modulus, while easily fragile due to the fineness and softness of kapok fiber (Xu et al. 2009). Comparing kapok fiber with cotton and some synthetic fibers, the bending rigidity of a single kapok fiber is lower. However, its relative bending rigidity is much higher (Xu et al. 2011). As reported, the average bending rigidity of a single kapok fiber is found to be 0.823×10^{-5} $cN \cdot cm^2$, whereas its relative bending rigidity is determined to be 21.06×10^{-4} $cN \cdot cm^2 \cdot tex^{-2}$. The compression test is an indirect evaluating method of kapok fiber hollowness and manufacturing technology of kapok products, with the finding that the compression elasticity of dry kapok fibrous assemblies is better than that of wet kapok fibrous assemblies (Fang et al. 2012). For the kapok-/cotton-blended yarns, the mercerization treatment will produce some impressive influences on their mechanical properties. When NaOH concentration increases from 180 to 250 g/L, the strengths of kapok-/cotton-blended yarns increase and elongations at breaking decline, and up to 280 g/L, the strengths of kapok-/cotton-blended yarns exhibit a dramatic drop and elongations at breaking present a gradual increase with an increase in kapok fiber content (Liu and Wang 2011).

6.3.4 Hydrophobic–Oleophilic Property

Kapok fiber contains the pectin and wax substances that contribute to its hydrophobic–oleophilic characteristic. On the glass slide coated with kapok extract, the diesel drop and water drop will show a different spreading radius and contact angle. The diesel drop can spread out rapidly, and in contrast, the water drop cannot spread out on the glass slide. As a result, a large spreading radius and small contact angle are observed for diesel drop, whereas a large contact angle is visualized for water drop, demonstrating that the oil is a wetting liquid for kapok fiber and the water is a non-wetting liquid for kapok fiber (Lim and Huang 2007). The static and dynamic contact angle of kapok fibers with different kinds of liquids such as vegetable oil, used oil, and engine oil is also investigated. It is found that kapok fiber is an excellent oleophilic and hydrophobic fiber with the contact angle of kapok fiber to water of 139.55°, but is less than 60° to various kinds of oil. The contact angle of kapok to water is constant as time flies. All the oil liquids on the kapok fibers have the quick spread rates, and the spread curves are similar though the spread rates varied with viscosity and surface tension of the liquids (Sun et al. 2011). This hydrophobic–oleophilic characteristic can be tuned by solvent treatments. Our study reveals that for untreated and $NaClO_2$-treated kapok fiber, different wetting phenomenon can be observed using water drops, with a large contact angle of 116° and a large spreading

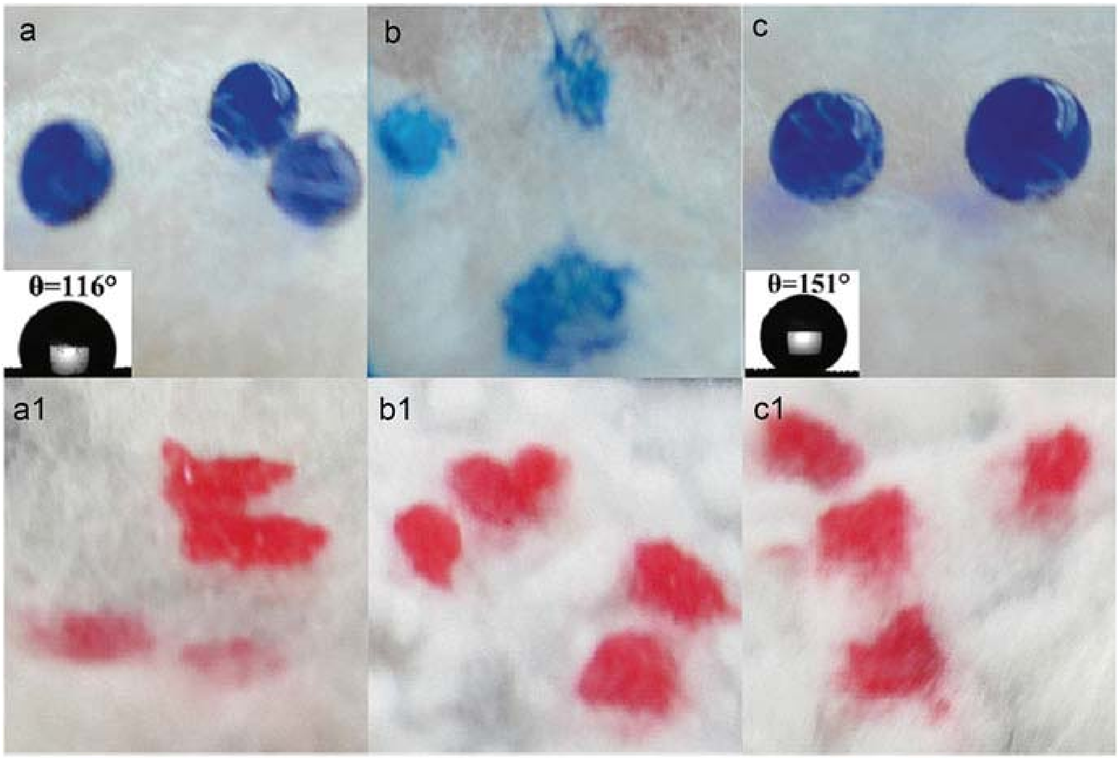

Fig. 6.2 Pictures of water droplet (dyed with methylene blue) on (**a**) raw, (**b**) treated, and (**c**) superhydrophobic kapok fiber surface; oil droplet (dyed with oil red O) on (**a1**) raw, (**b1**) treated, and (**c1**) superhydrophobic kapok fiber surface (Wang et al. 2012b) (Copyright 2012, reproduced with permission from Elsevier)

radius for untreated and $NaClO_2$-treated kapok fiber, respectively (Fig. 6.2) (Wang et al. 2012b). Here, another observation should also be mentioned. Before and after collecting the oils from water, the kapok fiber may float steadily on the water surface due to its light density and hydrophobic–oleophilic properties, a useful characteristic for oil spills cleanup. In addition to the thin hydrophobic plant wax layer covered on the surface of kapok fiber, the hydrophobic–oleophilic characteristic is also related to its micro–nano-binary structure (Zhang et al. 2013).

6.3.5 Adsorption Property

The water is a non-wetting liquid for kapok fiber due to the formation of large contact angle (>90°) between water and kapok fiber. Therefore, the water is not accessible to the large lumen of kapok fiber. Then, the kapok fiber should experience a chemical or physical pretreatment to be hydrophilic for further application as the adsorbent for removing different kinds of pollutants from aqueous solution. Wang et al. (2012b) found that after $NaClO_2$ treatment, the water drop can form a large spreading radius on the corresponding fiber surface, suggesting that by $NaClO_2$ treatment, the surface of kapok fiber has been transformed from intrinsic hydrophobic–oleophilic to hydrophilic. In addition, $NaClO_2$ treatment can lead to the de-esterification of kapok fiber, thus reducing the aggregate structure and expanding the proportion of amorphous region in kapok fiber (Wang et al. 2012a). In this case, Liu et al. (2012a) investigated the adsorption behaviors of a cationic dye methylene blue from aqueous solution using $NaClO_2$-treated kapok fiber as the adsorbent. In order to alter the hydrophobicity to hydrophilicity, a series of chemical modifications on the kapok fibers via the combination processes of chlorite–periodate oxidation have also been carried out (Chung et al. 2008). When treated with $NaClO_2$ for lignin degradation and $NaIO_4$ for sugar degradation, the chemically oxidized kapok fibers retained their hollow tube shape and evidenced elevated ability to adsorb heavy metal ions, with the adsorption rates of 93.55 %, 91.83 %, 89.75 %, and 92.85 % for Pb, Cu, Cd, and Zn ions, respectively. This enhanced adsorption of heavy metal ions onto the chemically oxidized kapok fibers can be attributed to the generation of -COOH groups during the oxidation process. When the kapok fiber is washed with dichloromethane to remove the botanic wax and further treated with NaOH solution, the resultant fiber can be modified with diethylenetriamine pentaacetic acid (DTPA). The resultant kapok-DTPA shows a fast adsorption for the metal ions with the adsorption equilibrium being reached within 2 min for Pb^{2+} and Cd^{2+}, and 5 min for Cu^{2+}. Maximum adsorption capacities of kapok-DTPA are 310.6 mg/g for Pb^{2+}, 163.7 mg/g for Cd^{2+}, and 101.0 mg/g for Cu^{2+}, respectively (Duan et al. 2013).

6.3.6 Microbiological Properties

Because of high lignin content, kapok fiber is not easily attacked by ordinary cellulolytic bacteria (Nilsson and Björdal 2008) and shows better antibacterial property (Han 2010). Liu et al. (2007) investigated the anti-moth, anti-mite, and antibacterial properties of kapok battings. The results of anti-moth test showed that the mean value of weight loss of kapok batting was smaller than reference sample obviously, and the damage grade of surface of kapok batting was 2A. In the anti-mite test, the mite expelling rate was 87.54 %, which proved the anti-mite property of kapok batting. For antibacterial test, kapok batting was confirmed to possess both the bactericidal effect and bacteriostatic effect on *Escherichia coli*. But in contrast, it did not have these effects on *Staphylococcus aureus*.

6.4 Conclusions and Future Perspective

As the “low-carbon” concept prevails, abundant kapok fiber has received increasing attention as an eco-friendly textile material for its intrinsic superiorities such as finest and lightest quality, highest hollowness, and most warm nature. With the focus on this green cellulosic fiber, more studies will be carried out to expand the application fields for kapok fiber by combining its higher hollowness and hydrophobic–oleophilic characteristics.

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