THE FINE STRUCTURE OF DEVELOPING COTTON FIBERS

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Abstract

Single fiber breaking force (in gram force) and tenacity (in g/tex) of developing SJ-2 cotton fibers have been studied. Wide angle X-ray diffraction (WAXD) techniques provide crystalline structural information of dried cotton fibers at the same development stages. The increased crystallinity and crystallite sizes and perfection offer only partial explanation to the strength of cotton fibers. Other structural factors including orientation of microfibrils, inter-crystallite and inter-fibril hydrogen bonding, and inter-crystallite and inter-fibril stress can also contribute to single fiber strength.

The properties of cotton fibers depends on their genotypes and growing conditions. Performance properties such as strength and dyeability depend strongly on fiber structure. The mechanical properties of cotton fibers have been studied and reviewed extensively.[1,2] It is generally agreed that the strength of cotton fibers is attributed to the rigidity and the high molecular weight of the cellulose chains, the extensive intermolecular and intramolecular hydrogen-bonding, and the highly fibrillar and crystalline structure of the fibers. Cotton fiber strength has also been shown to be associated with molecular weight of the cellulose, crystallinity, and reversal and convolution characteristics of the fibers. These relationships are, however, not well defined due in part to the variability of cotton fibers, even within a genotype and under well-defined growing conditions. These relationships can also be complicated by the method of analysis. In the case of crystallinity, values ranging from 50% to nearly 100% has been reported, depending upon the measurement techniques.

For polymeric fibers, it is commonly recognized that fiber strength is largely dependent on the structural uniformity and regularity in the fibers. Recent advances in polymer physics have shown that defects and irregularities of the polymeric chains lead to low strength whereas optimized chain orientation and crystallization can enhance strength. The structural elements that lack of uniformity and regularity are part of so called noncrystalline domains in semicrystalline polymers. The noncrystalline domains include molecular segments that are excluded from the crystals during crystallization and may contain chain ends, entangled chains, tie-chains, and randomly configured chain segments. It has been demonstrated that increase in crystalline content and improvement of structural regularity in non-crystalline regions of the fiber structure are among the successful strategies to produce high strength and high modulus fibers.

The micro-structure and macro-structure of cotton fibers are more complicated in comparison to manufactured fibers. During cotton fiber cell development, the secondary cell wall microfibrils are laid down at a range of angles in layers inwards from the primary cell wall. The highly rigid cellulose chains are organized into crystalline microfibrils. These microfibril angulation reverse along the fiber axis and form the winding helicals. The reversals of these helical microfibrils causes the fiber cells to collapse into twisted ribbons upon dehydration.

Single fiber breaking force (in gram force) and tenacity (in g/tex) of developing SJ-2 cotton fibers have been studied.[3] The maximum breaking strength or tenacity of the SJ-2 cotton fibers is reached at 21 dpa. The absolute forces required to break individual fibers continue to increased with fiber development beyond 21 dpa without further increases in fiber tenacity. Dried seed fiber weight, fiber thickness, lengths between adjacent twists, and linear density (tex) have shown close relationships with the developmental stages.

The crystalline structure of dried cotton fibers at varying development stages has been investigated using wide angle X-ray diffraction (WAXD) techniques.[4] The cellulose **I** crystalline structure has been confirmed on dried SJ-2 Acala cotton fibers collected at varying developmental stages and at maturity. The cellulose **I** crystalline structure is clearly evident at the early developmental stage of 21 days post anthesis (dpa) (Figure 1). The crystal system remains unchanged during the cotton fiber biosynthesis and at maturity. The degree of crystallinity and crystallite dimensions in the cotton fibers increase with cell development (Table I). The most significant increments are observed during the first half of the secondary wall thickening process. These increases coincide with the largest increase in forces to break single fibers. The unit cell sizes slightly decrease and thus the crystal densities increase with fiber development. Among the crystal lattice planes, the alignment of the glucosidic rings in respect to the 002 planes improves most significantly with fiber cell development.

The strength and modulus of cotton fibers are far from any of the theoretical values predicted by the assumed native cellulose crystalline structure. The increased crystallinity and crystallite sizes and perfection offer only partial explanation to the strength of cotton fibers. Other structural factors can also contribute to single fiber strength including orientation of microfibrils, inter-crystallite and inter-fibril hydrogen bonding, and inter-crystallite and inter-fibril stress. Fibril orientation is determined by the biosynthesis of cellulose and may experience changes from

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the drying process. Inter-crystallite and inter-fibril stress and hydrogen bonding, on the other hand, may be largely resulted from the cell collapsing and dehydration process. The relationship between single fiber strength and fine structure of cotton fibers and the significant discrepancy between the practical and theoretical strengths of cotton fibers are crucial questions remained to be addressed.

References

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Table I. Crystallite parameters of developing SJ-2 cotton fibers

Parameters	21 dpa	27 dpa	34 dpa	48 dpa	60 dpa
d_{101}, nm	0.610	0.601	0.594	0.592	0.589
d_{101^-}, nm	0.535	0.531	0.529	0.523	0.528
d_{002}, nm	0.392	0.391	0.389	0.390	0.388
a, nm	0.834	0.812	0.806	0.804	0.802
b, nm	1.032	1.042	1.034	1.032	1.036
c, nm	0.790	0.787	0.784	0.784	0.781
β, deg	82.48	82.97	83.36	83.65	83.75
density, kg/m^3	1595	1616	1658	1664	1670
Crystallinity	30	45	54	56	58