FIBERS

1. Introduction

This overview of fibers and fiber products introduces the underlying concepts that govern the properties, manufacture, and utilization of these materials. For thousands of years in human history through the last century, fibers have been mainly used in constructing woven, nonwoven, knitted textiles for clothing, home and interior furnishing, and in papermaking. With the advent of polymer chemistry, fiber spinning technologies, product conversion processing, and the ever increasing demands for better quality goods, the field of fiber materials has evolved with new chemistry, processing technologies, and new product development strategies.

Over one-third of fibers today are being used in various industrial, civil, and consumer applications. These nontraditional uses of fiber have been referred to high performance textiles, technical textiles, or industrial textiles. These textiles were produced for their technical and performance properties rather than aesthetic characteristics or decorative functions (1). With the increasing use of fibers in nontraditional textile applications, new fiber types and processing technologies can be anticipated. Industrial textiles are used for manufacturing and in industrial settings, including those used, eg, as separation membranes, filters, abrasive pads, conveyer belts, acoustic and thermal insalation, electrical components, and cables. Others are sometimes referred to as technical textiles that were developed for medical, personal care products (hygiene, diapers, incontinent pads), performance-enhancement sportswear, structures (construction), transportation (vehicle interior, inflatable devices), geotextiles and civil engineering (separation, drain, stabilize, containment), projection media, reinforcement for composites, absorbents for industrial cleanup, seals and gaskets, packaging, marine, fishing and horticulture, and agriculture (containment, protection, packing). With greater expectations for performance, more fiber products are designed with both aesthetic and functional properties in mind.

2. Classification

A fiber is generally defined as a flexible, macroscopically homogeneous body having a high length/width ratio and a small cross-section. Fibers can be incorporated as whole or parts of materials and products of various forms and performance properties for wide-ranging applications. The unique combination of fibers characteritics determine not only how fibers can be put together and made into products, but also the performance of these products. For thousands of years, textile and paper have been the main products of fibers and the textile and paper industries are the prime converters of fibers. Generally, the manner by which fibers are processed into products is largely determined by the aspect ratio, or the length/width ratio of the fibers. Various yarn spinning technologies are available to physically align, bind, and twist fibers into yarns, the basic element of woven or knitted fabrics and stings or ropes. Yarn spinning typically requires fibers with higher aspect ratios, eg, 1000 or higher. Fibers having aspect ratios of 100 or less cannot be spun into yarns. Additional adhesion mechanisms are required to assemble such short fibers into continuous forms of products. Paper is made from aqueous suspension of short cellulose fibers held together by hydrogen bonding after water is removed. This secondary force mechanism of adhesion is the reason that paper desintegrates in water unless chemical adhesives are used. Pulp fibers for papermaking are typically from wood and other plants that contain 40–70% of cellulose. The nonwovens can be made from short or long fibers, employ physical entanglement, adhesives, and/or fusion to bind fibers together.

Textile fibers are traditionally classified according to their origin as follows:

Naturally occurring fibers
Plant: based on cellulose, eg, cotton, flax, hemp, jute, and ramie.
Animal: based on proteins, eg, silk, wool, mohair, vicuna, other animal hairs.
Mineral: eg, asbestos.

Regenerated fibers
Based on natural cellulose and proteins.
Rayon: regenerated cellulose.
Acetate: partially acetylated cellulose derivative.
Triacetate: fully acetylated cellulose derivative.
Azlon: regenerated protein.

Synthetic fibers
Based on synthesized organic polymers.
Acrylic: polyacrylonitrile (also modacrylic).
Aramid: aromatic polyamides.
Nylon: aliphatic polyamides.
Olefin: polyolefins.
Polyester: polyesters of an aromatic dicarboxylic acid and a dihydric alcohol.
Spandex: segmented polyurethane.
Vinyon: poly(vinyl chloride).
Vinal (or vinylon): poly(vinyl alcohol).
Specialty fibers: poly(phenylene sulfide) and polyetheretherketone.

Inorganic fibers
Carbon/graphite: derived from polyacrylonitrile, rayon, or pitch.
Glass, metallic, ceramic.

Natural fibers are those derived directly from the plant, animal, and mineral kingdoms. A significant segment of the world's agricultural activity is concerned with the growth and harvesting of natural fibers. With the exception of silk, which is extruded by the silkworm as continuous filaments, natural fibers are of finite length and are known as staple fibers. Natural fibers usually require certain levels of separation and cleaning before being used in the manufacturing of textiles and other fibrous products. The factors that affect the utility and quality of natural fibers for textile purposes are fineness, length, color, and spinnability. The latter term denotes the ability of a fiber to be spun economically into yarn by conventional textile processing procedures. Chemical properties, such as ability to absorb common dyes, thermal and environmental stability, and resistance to chemical degradation are also important.

Manufactured fibers, the other main category of textile fibers, are generated from natural polymers, synthesized polymers, and inorganic substances. Glass fiber is the main inorganic fiber in common use, although other ceramic and metallic fibers have been developed for niche specialized applications, particularly for use in high performance fiber-reinforced composites and high temperature applications. Regenerated and synthetic fibers, are generated from organic polymers of natural origins or organic syntheses via spinning processes. The term spinning has been used for describing the process for both yarn and fiber formation. Yarn spinning is the textile manufacturing operation where staple fibers are formed into continuous textile yarns by several consecutive attenuating and twisting steps. In the context of manufactured fibers, fiber spinning refers to the overall process of forming fibers from polymer liquids (solution or melt) by extrusion. The three principal fiber spinning methods are melt spinning, dry spinning, and wet spinning, although there are many variations and combinations of these basic processes.

A regenerated fiber is one formed when a natural polymer, or its chemical derivative, is dissolved and extruded as a continuous filament, and the chemical nature of the natural polymer is either retained or regenerated after the fiber formation process. Regenerated cellulose and cellulose derivatives are the first manufactured fibers to gain industrial and consumer acceptance. Cellulose is a nearly ideal polymer for the formation of fibers. The rigid glucosidic main chain structure facilitates orientation and crystallization and the hydroxyl side groups are capable of intermolecular and intramolecular hydrogen bonding. In fact, by changing the chemistry of the hydroxyl side groups, some of the celluose derivatives become either thermoplastic (cellulose acetate) or water soluble (carboxycellulose and cellulose ethers). Therefore, regenerated cellulose and their derivatives are available in a wide range of properties, making them suitable for textile and other products. Protein molecules contain a large number of amino acids leading to a more complex tertiary structure along the protein polymer chains. Reasembling such a tertiary molecular structure in the fiber formation process has been more technologically challenging, despite the fact that animal fibers, such as wool and hair, are ubiquitous. To date, almost all of commercially significant regenerated fibers are derived from cellulose.

Synthetic fibers are based on synthesized polymers and are mainly products of the worldwide petroleum chemical industry. Since their initial commercialization, synthetic fibers have not only revolutionized the textile production since early 1940s, but also expanded into many other industrial and consumer applications. The most widely used synthetic fibers are based on polyesters, polyamides, polyolefins, acrylics, polyurethanes, and polyaramids. A relatively small number of polymer types can produce synthetic fibers with wide ranges in fiber properties and characteristics because of the enormous versatility of fiber manufacturing processes. In the last three decades, numerous specialty high performance polymers have been synthesized, and some have been produced in fiber form. Among these are aromatic polyamides and polyimides, and ultrahigh molecular weight polyethylene, poly(phenylene sulfide) and polyetheretherketone (PEEK). The generic names of synthetic fibers are defined and controlled by the Federal Trade Commission.

The textile industry finds itself with an ever-increasing number of fibers from which to manufacture its products. Not only are there many more fiber types for the textile industry to use, but also it is recognized that many advantages are to be gained by blending the various fibers in an almost infinite number of combinations. Many current textile products are blends of natural and synthetic or conventional and new fibers that incorporate the desirable attributes of both.

3. Fiber Properties

The most significant fibers properties are the geometric, physical, and chemical categories.

3.1. Geometric Properties. These properties pertain primarily to staple fibers and include various aspects of fiber dimensions and form such as length, width, cross-sectional area, cross-sectional shape, and crimp. They are of particular importance in processing and for product quality. For example, machine settings in yarn spinning operations are based on fiber length, and the efficiency of processing is related to length uniformity. In general, the content of fibers shown to be shorter than average fibers have more adverse effects on yarn processing.

Fiber cross-sectional area or fineness also affects textile processing efficiency and the quality of the end product. To produce fine fabrics requires fine yarns. Yarn spinning is only possible with a certain minimum number of fibers. With a minimum number of fibers, the finer the fibers, the finer the yarns. However, fibers with too small a cross-section cannot be processed efficiently. The number of fibers in a cross-section, of yarn of a given size determines yarn properties. The smaller the fiber size or cross-section, the more fibers can be packed in the yarn. The yarns would be more compact and denser in appearance. Other factors being equal, yarn strength increases as the number of fibers in the yarn cross-section increases.

The linear density, namely, mass per length in terms of denier and tex, is often used to describe the size or fineness of fibers or yarns. Denier is the weight in grams of 9000 m of fibers, whereas tex is the weight in grams of 1000 m of the same. Therefore, one-denier fibers weigh 1 g with a total length of 9000 m. Common cotton and wool fibers are 5–8 deniers. The finest cotton and wool fibers are 1–3 deniers. Nylon fibers used in fine stockings are 10–15 deniers.

The cross-sectional shape of fibers is an important characteristic that influences many end use properties. The cross-sectional shape of cotton fibers is essentially that of a flat ribbon, although there are cotton fibers that have circular cross-sections. Wool fibers are elliptical in shape, although again nearly circular shapes can be found. The earlier synthetic fibers were generally circular in cross-sectional shape, but it is now possible to produce fibers with modified cross-sections. This is accomplished by designing the shape of the spinneret orifice used in melt spinning. Fibers (primarily nylon, polyester, and polypropylene) can be melt spun into trilobal, multilobal, flat, triangular, and a variety of other shapes. These noncylindrical shaped fibers have differential surface curvatures that reflect and scatter light differently, thereby creating special optical effects such as luster and brightness. These shapes also have more surface areas and can be useful in modifying the mechanical properties of textile products. Hollow fibers, produced by special fiber extrusion processes, have external and internal surfaces of different curvatures. They have more specific surface and exhibit unique optical properties.

Crimp is a form factor that describes the waviness of a fiber or its longitudinal shape. Crimp of a fiber can be quantified either in geometric terms, such as wave height, wave amplitude, and frequency, or in energy terms, such as the force or energy required to uncrimp a fiber. A certain level of fiber crimp is essential in order for a fiber to be processible on conventional textile manufacturing equipment. All natural fibers have crimps, particularly animal fibers. Synthetic fibers must be crimped artificially to be processible into spun yarns. Crimp is imposed on the filaments by various mechanical means often coupled with heat, usually in the tow stage before cutting into staple. In certain fibers, it has been possible to develop a structurally based crimp. In these cases, the crimped configuration is a reflection of molecular structure and may be considered the equilibrium state.

The economic value of natural fibers is highly dependent on the level and uniformity of these properties. The geometric properties of the natural fibers are highly variable from fiber to fiber, both within a given lot and among lots of the same fiber type. In the synthetic fibers, the geometric properties can be highly uniform in view of the production control possible in a chemical plant, but not in an agricultural product. The cross-sectional area or fineness is controlled by the fiber spinning (extrusion) process, and the amount of attenuation in drawing. The length is simply set to the desired value, and length uniformity is always high. Similarly, the amount of crimp imposed on a fiber can be specified.

3.2. Physical Properties. Thermal and light properties are among the primary physical properties of fibers. Since fibers are frequently subjected to elevated temperatures, it is necessary that they have high melting or degradation points. It is also necessary that other fiber properties be relatively constant as a function of temperature over a useful temperature range. For textile applications, fibers should be optically opaque so their refractive indexes need to be significantly different from those of their most common environments, namely, air and water. Luster and color are two optical properties that relate to a fiber's aesthetic quality and consumer acceptance. Textile fibers are always used in aggregates of a large number of single fibers that are caused to interact with each other through their surfaces. The surface characteristics of fibers, therefore, are of singular importance. Interfiber friction and geometric roughness or rugosity are two surface properties that relate directly to processibility and product performance.

Electrical properties also affect fiber utility. In view of their chemical structure, most textile fibers are nonconducting and their high resistivities readily classify them as insulators. Fibers are subject to static electrification and some means of discharging them needs to be employed in high speed manufacturing processes and in certain end uses. In fibers that absorb water vapor from the atmosphere, water molecules increase electric conductivity whereby dissipating the electric charges. Static electrification is a particular problem with hydrophobic fibers that do not absorb moisture. By blending electrically conductive fibers, a number of antistatic finishes have been developed to reduce the static charge generated during textile processing and end use.

3.3. Chemical Properties. The ability of fibers to interact with water is among the most significant chemical property. Interaction of fibers with water in the vapor phase involves moisture absorption whereas that with liquid water is water wetting. The ability of fibers to absorb moisture or to be wetted by water ranges from hydrophilic, to those that are essentially hydrophobic (2). All natural and regenerated fibers and some synthesized fibers are hygroscopic, ie, they are capable of absorbing moisture from the atmosphere. This water vapor absoption property is directly related to the chemical structure of the polymers and the molecular arrangement of the polymers within the fibers. For fibers to absorb water vapor, the molecular structure of the polymer has to allow the formation of hydrogen bonds with water molecules. The arrangement of the polymer chains has to allow space for water molecules to diffuse into the fibers. Hydrogen bonding, by definition, is when a hydrogen atom is bond to two electronegative atoms, one by a covalent bond and the other by a hydrogen bond. In order for water molecules to form a hydrogen bond with a polymer, the polymer molecule must contain electronegative atoms, such as oxygen and nitrogen. Cellulose contains oxygen and protein, contains both oxygen and nitrogen. These natural fibers absorb moisture readily. Those synthetic fibers whose chemical compositions resemble hydrocarbons, such as polyolefins (polyethylene and polypropylene), do not absorb any moisture whereas polyamides (nylons and polyaramids) typically absorb some moisture, but much less than the natural and regerated fibers.

Wool fibers have the most distinct qualities of absorbing highest quantities of vapor and liquid water. With absorption of water vapor and liquid, heat is generated. For liquid water, the heat of sorption (H_1) is expressed as

$$H_1 = 0.256 \log h_1/h_2(T_1T_2/T_1 - T_2)$$

where h_1 and h_2 are the relative humidity at temperature T_1 and T_2. Wool absorbs as high as 30% w/w moisture, the highest among fibers. For moisture absorption, the latent heat of condensation (2450 kJ/kg at 20°C) that is three times the heat of sorption from liquid water has to be added. The heat generated from sorption of water and moisture in wool is much higher in the initial sorption process than when sorption approaches saturation. This excellent moisture absorbing capacity coupled with much higher heat of absorption make wool an excellent thermal insulation material, especially in high humidity (Table 1).

Table 1. **Heat of Sorption (kJ/kg) of Wool at Varying Relative Humidity**

relative humidity, %	0	10	20	30	33
liquid wetting	101	38.1	10.0	1.13	0
moisture sorption	854	431	159	41.9	33.5

Moisture sorption follows the Langmuir isotherm, ie, the extent of sorption of water vapor increases with the increasing partial pressure of water vapor in the atmosphere in a sigmoidal shape (Fig. 1). The moisture sorption properties of textile fibers are generally expressed as the moisture content (based on total mass of fiber and moisture) or the moisture regain (based on dry fiber mass) under a given set of conditions. Mechanical and other fiber properties of moisture absorbing fibers vary as a function of moisture content, and therefore need to be evaluated under controlled and specified atmospheric conditions, usually at 65% relative humidity (RH) and 21°C. It is also necessary, at times, to determine fiber properties under other atmospheric conditions to which they may be subjected or used.

The sorption of molecular species other than water from the atmosphere or from solution must also be considered. Paramount among general sorption properties of textile fibers are their dyeing characteristics, which describe the rate and extent of dye sorption. In order for fiber to have substantial textile use, its ability to absorb and retain at least one of the common classes of dyes is essential. The fiber–dye complex must be colored to an acceptable depth and must be capable of withstanding exposure to washing, light, mechanical abrasion, dry cleaning, and other influences under use situations. These abilities are called fastness. Wash- and lightfastness are particularly important; these and other

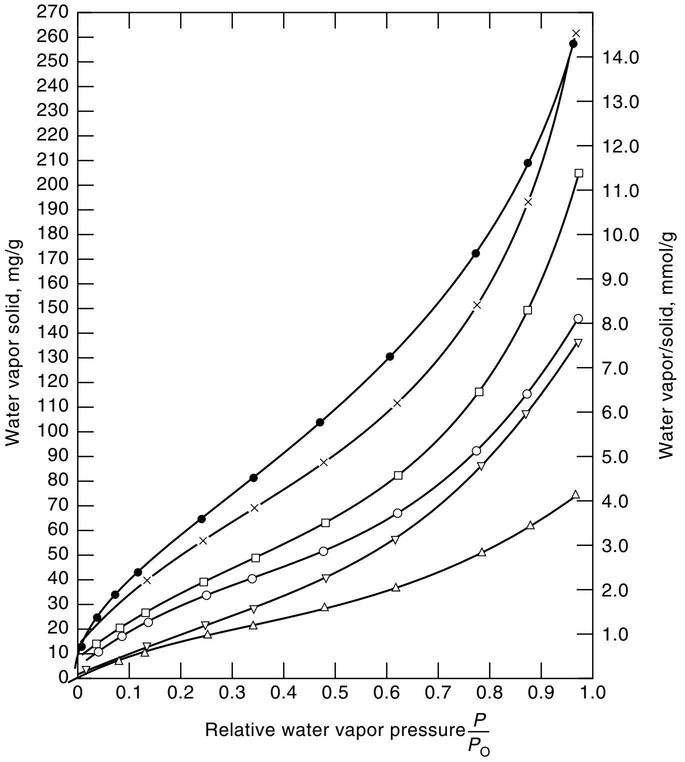


Fig. 1. Sorption isotherms of water on textile fibers at 25°C: •, wool; × viscose; □, silk; ○, cotton; ▽, acetate; Δ nylon.

fastness characteristics are properties of the fiber–dye complex and not of the dye alone. Dyeability is dependent on the chemical structure of polymers in the fiber, such as the presence of functional groups that are capable of interacting with the dye. These interaction can be the strongest covalent bonds to secondary forces such as strong ionic and hydrogen bonds to the very weak van der Waals forces. The affinities of various dyes for textile fibers are thermodynamic quantities that depend only on the chemical structures of the dye and the fiber, and should not be confused with the rate of dyeing. The rate of dyeing is related to the fiber's supramolecular organization or molecular packing, and the ability of a dye to penetrate and diffuse into the internal regions of the fiber. Rate of dyeing is also strongly influenced by dye concentration in the external solution (or vapor phase), temperature, pH, and degree of dye aggregation in the external solution and in the fiber. The effects of these and other variables on the rate of dyeing, as well as other aspects of the physical chemistry of dyeing, have been summarized (3,4).

Swelling is a chemical property closely related to a fiber's sorption characteristics. It may be defined as the reversible dimensional changes that occur when fibers undergo an absorption process. Since fibers are structurally anisotropic, they invariably undergo greater transverse (diametrical) than longitudinal swelling. The swelling of fibers in aqueous systems or in atmospheres of high relative humidity is of particular importance since fibers are frequently subjected to these environments. The dimensional stability of textile fabrics in laundering is related to fiber swelling phenomena, although other factors such as altered mechanical properties of fibers in the wet state are known to be important in this instance. True thermodynamic swelling of a fiber is reversible. Sometimes, the absorption of certain molecular species causes a disruption of the internal fiber structure and the dimensional changes accompanying this process are not reversible in the accepted sense. More commonly, swelling at the fiber level impose much greater impact at the yarn and fabric structures that, due to the geometric constraints, are irreversible. It is important, although frequently quite difficult, to differentiate between reversible thermodynamic swelling and irreversible alterations in fiber structure.

Fibers must be resistant to the effects of acids, alkalies, reducing agents, and oxidizing agents, as well as to electromagnetic and particulate irradiation. Resistance to these degradative systems is required for both short-term exposure to large doses or concentrated reagents, and for long-term exposure to weak or dilute systems.

4. Fiber Morphology

Fiber structure is described at three levels of molecular organization, each relating to certain aspects of fiber behavior and properties. First is the organochemical structure, which defines the chemical composition and molecular structure of the repeating unit in the base polymer, and also the nature of the polymeric link. This primary level of molecular structure is directly related to chemical properties, dyeability, moisture sorption, and wetting characteristics, and indirectly related to all physical properties. The chemical structure also determines the magnitude of intermolecular forces, which is important in terms of overall molecular arrangement in the fiber and many physical properties. The macromolecular level of structure describes the chain length, chain-length distribution, chain stiffness, molecular size, and molecular shape. The supramolecular organization is the arrangement of the polymer chains in three-dimensional (3D) space. The physical properties of fibers are strongly influenced by the organization of polymeric chains into crystalline and noncrystalline domains, and the disposition of these domains with respect to each other. In the case of natural fibers, a further level of structural organization related to the natural growth and development of the fiber must be considered. This morphology is quite complex, with fibrils, microfibrils, and similar structural subunits frequently surrounded by a matrix material in a composite configuration.

Polymeric fibers can be differentiated from other polymeric materials, such as films and powders, on the basis of geometric form. Fibers are also different from rubbers and some plastics because of their physical properties. It is, however, more instructive to differentiate fibers from other polymeric substances on the basis of structure. Certain underlying structural features are fiber forming, ie, the ability to assume the special supramolecular organization characteristic of fibers. All polymers that can be made into fibers for common textile and engineering applications must be capable of being oriented, and in most cases, Crystallized by drawing. In the crystalline regions, the polymeric chains are in near perfect registry so that the laws of X-ray diffraction are obeyed. In other regions of the fiber, the molecular chain segments are not perfectly ordered and may approach random coil configurations. This is the simplest two-phase crystalline–amorphous model of the structure of semicrystalline polymers that was for a long time was used to describe fiber structure and to interpret fiber properties.

The original two-phase model, with sharp boundaries between crystalline and amorphous regions, was replaced by various models postulating gradual transitional regions. One formulation of this idea is the concept of a lateral-order distribution, according to which structural regularity varies from the perfectly ordered or crystalline state to the completely disordered or amorphous state in a continuous manner. Other formulations of the gradual transition from crystalline to amorphous regions are the fringed micelle structure and the fringed fibril structure. Another model considers fibers to be fully crystalline, and associates regions of higher reactivity and accessibility (previously the amorphous regions or regions of low lateral order) with imperfections and defects in the crystalline system. These imperfections and defects may be associated with molecular dislocations, chain ends, and chain folds. In many cases, such models have been postulated for specific fiber types.

All models of fiber structure picture a fiber as a polymeric substance with a high degree of 3D structural regularity, leading directly to the concept of the degree of crystallinity, ie, the fractional crystalline content of a partially crystalline polymeric material. The degree of crystallinity is difficult to evaluate. X-ray diffraction techniques probably provide the best estimates, but unsolved questions remain because the degree of crystallinity is actually a composite value that reflects not only the fractional quantity of ordered material, but also the size or dimensions and the perfection of the crystallites. Thus, a highly ordered polymer may be evaluated by X-ray diffraction as being of low crystallinity if the crystallites are either highly imperfect or so small that well-resolved diffraction patterns cannot be obtained. Other methods of crystallinity evaluation depend on the fact that the polymer chains in the crystalline domains are more densely packed and less accessible to penetrants than the chains in the noncrystalline domains. Measurements of density and moisture sorption are frequently used to estimate degree of crystallinity in polymeric fibers, as are other specialized techniques such as differential thermal analysis, infrared (ir) spectroscopy, chemical reactivity, and deuterium exchange.

Attention must also be focused on the noncrystalline domains. Many important properties of fibers can be directly related to these noncrystalline or amorphous regions. For example, absorption of dyes, moisture, and other penetrants occurs in these regions. The crystalline domains contain most orderly arranged and densely packed chains and cannot be penetrated by most reagents, although reagents may be adsorbed on crystallite surfaces. The extensibility and resilience of fibers is also directly associated with the noncrystalline regions.

Noncrystalline domains in fibers are not structureless, but the structural organization of the polymer chains or chain segments is difficult to evaluate, just as it is difficult to evaluate the structure of liquids. No direct methods are available, but various combinations of physicochemical methods, such as X-ray diffraction, birefringence, density, mechanical response, and thermal behavior, have been used to deduce physical quantities that can be used to describe the structure of the noncrystalline domains. Among these quantities are the amorphous orientation function and the amorphous density, which can be related to some of the important physical properties of fibers.

Fiber structure is a complex mix of oriented and crystallized polymer chains. Neither a completely amorphous structure nor a perfectly crystalline structure provides the balance of physical properties required in fibers. The formation and processing of fibers is designed to provide an optimal balance in terms of both structure and properties. Excellent discussions of the structure of fiber-forming polymers and general methods of the structure characterization are available (5).

5. Production of the Major Commodity Fibers

5.1. Cotton.

Cotton fibers have economic significance in the global market because of their large share ($> 50\%$) among fibers for apparel and textile goods. The most essential cotton fiber qualities related to dry processing (yarn spinning, weaving, and knitting) are length, strength, and fineness. For wet processing such as scouring, dyeing, finishing, fiber structure related to maturity or the level of development, plays a major role. Knowledge of cotton fibers has been derived mainly from studies of dried and matured fibers of different varieties. There is, however, little understanding regarding the relationship between cell wall development and fiber structure and properties.

Cotton fibers are composed mostly of α-cellulose (88.0–96.5%) and are nature's purest form of cellulose. The noncellulosics including proteins (1.0–1.9%), waxes (0.4–1.2%), pectins (0.4–1.2%), inorganics (0.7–1.6%), and other

(0.5–8.0%) substances are located on the outer layers and inside the fiber lumens. The specific chemical composition of cotton fibers varies by their varieties and growth conditions. The matured fibers are flat twisted ribbon forms. The twist or convolution were resulted from concentric layers of fibrillar spirals whose direction reverse frequently along the fibers. The number of twists in cotton fibers varies between 3.9 and 6.5/mm and the spiral reversal changes 1–3 times/mm length. The convolution angle has been shown to be variety dependent. Reversal frequencies have been observed among different species and varieties of cotton, between lint and fuzz on the same ovule, and along a single fiber (6,7). The reversals in cotton fibers are related to the orientation of the secondary wall microfibrils whose organization is critically important to fiber strength. The orientation angles and shifts of microfibrils along the fiber axis change with cell-development stages.

5.2. Wood. *Wood fibers* are much shorter and contain less cellulose than cotton. Wood fibers are derived from trees and categorized by the tree types (8). Fibers from most softwood, ie, *Gyomnosperns* or evergreens, are average 3–3.6 mm in length and 25–60 mm wide. Fibers from certain southern pines are longer, up to 7 mm in length. Hardwood fibers from *Angiosperms* or deciduous trees are in shorter lengths of 0.1–1.5 mm. Both contain cellulose, hemicellulose, xylans, lignin, extractives, and ash. Softwood fibers contain slightly higher cellulose (45–50%), hemicellulose (20–25%) and xylans (25–35%) than hardwood (40–50% cellulose, 2–5% hemicellulose, 18–25% lignin). The cellulose in wood fibers is $\sim$50–70% crystalline, less than the native cellulose found in cotton.

More than one-half the world's wood supply is burned as fuel source. While the global demand for fuel wood and charcoal rose by nearly 80%, the demand for the remaining share of wood for saw logs, veneers, pulp for papermaking and other industrial forms rose by nearly 50%. Rising demand for industrial wood has encouraged widespread planting of industrial plantations that supply nearly 25%, the rest comes from old-growth or secondary-growth forests. Demand for industrial wood fiber is projected to rise by between 20 and 40% by 2010. Most forestry analysts expect that demand will be met at the global level with some regional shortfalls.

5.3. Wool. Wool is the hair (fleece) of various breeds of sheep (*Ovis areis*). However, the term wool has been used more generally, sometime to describe the hair of all animals, including goat (cashmere and angora "mohair"), camel, alpaca, rabbit, yak, and vicuna. Depending on the breeds, environment, individual animals and body location on each animal, wool fibers vary significantly in their physical and performance properties. Wool fibers have complex chemical compositions and morphological structures; both have been well documented (9). Each fiber consists of bilaterally aligned cortexes, the orthocortex (60–90%) and paracortex (10–40%). The proteins in wool are α-keratins that are organized in a very specific conformation and structural levels to form fibrils in the cortical cells. Over 24 amino acids have been identified in wool, with the majority carrying polar side groups of basic amine, acidic carboxylic, and neutral hydroxyl groups. The highly polar nature of these constituent amino acids are responsible for one of wool fibers' most distinct qualities of water absorption. The disulfide bonds from the sulfur-containing cystine provides the cross-links that give additional chemical stability. The paracortex cells have higher cystine content and are more resistant to chemicals and microbial attacks.

World wool production is categorized into three general groups: merino, crossbred, and half-bred, which accounted for 43, 32, 25%, respectively, in 1998. Over 60% of world wool production is from Australia (31%), New Zealand (13%), China (11%), and Russia (6%). Australia wool is highly concentrated on the Merino breed and accounts for about one-half of the world supplies of fine wools. New Zealand wools are ~75% crossbred and constitute 30% of the crossbred wool in the world.

5.4. Silk. Silk fibers are spun from the glands of adult silkworms *Bombyx mori* (10). Each of the two glands of a worm produces a single strand of silk and are bound together by sericin. The silk filaments wrap around to form the protective cocoon for it chrysalis, the intermediate stage between larva and moth. Silk is the thinnest and longest natural fibers, this unique combination of characteristics putting it in a class of fibers all by itself. The fineness of the silk fibers yields soft hand. Silk's triangular cross-section and smooth surfaces offer excellent light reflection and a lustrous appearance. The protein in silk is fibroin, which consists of 70% alanin and glycine, whereas sericin consists of 30% serine and 15% of alanin and glycine. Although the chemical composition and structure of silk fibers are well characterized, the process in which the sericin-fibroin proteins are combined from the silk worm is still to a large extent not well understood.

Silk originated from China and today remains the main producer. Silk was spread to India through Bhutan in Chinese Turkistan ~140 BC, to Korea in 1200 BC, then to Japan ~300 BC. Currently, silk accounts only for <0.2% of global fiber production.

5.5. Manufactured Fibers. Manufactured fibers, with the exception of glass, asbestos, ceramic, and the specialty metallic fibers, are organic polymers. The major *regenerated* fibers are cellulosics, ie, rayon, lyocell, and cellulose acetates. *Synthetic* fibers are spun from fiber-forming polymers. Fiber-forming polymers are linear polymers that can be oriented and partially crystallized under the spinning conditions. Fiber spinning is the engineering process by which polymer solutions or melts are mechanically forced or extruded through spinnerets followed by drawing to finer, orientated and stronger fibers. The ability of certain polymers to form fibers can be traced to several structural features at different levels of organization rather than to any one particular molecular property. The major fiber-forming synthetic polymers are step and chain polymers. Step polymers are those synthesized by the slower step-wise polymerization reactions. Polymer chains are lengthed gradually in condensation reactions, such as esterification, transesterification, amidation, and transamidation. The most common step polymers are polyesters, polyamides, and polyurethanes. Chain polymers, on the other hand, are synthesized by the faster chain-building reactions, such as free-radical and ring-opening polymerization reactions. The vinyl polymers, such as the olefins (polyethylene, polypropylene) and acrylics (polyacrylonitrile and its copolymers), are among the most common chain polymers for fibers.

To a large extent, the structural characteristics of polymers that allow them to crystallize under appropriate conditions have been summarized as follows.

Regularity, the polymer chains must be uniform in chemical composition and stereochemical form. *Shape and interaction*, the shape of the polymer chains must allow close contact or fit to permit effective and strong intermolecular interaction. This is generally achieved by linear macromolecules with no bulky side groups or with side groups that are regularly spaced along the backbone chain. *Repeat length*, the ease of crystallization decreases with increasing length of the polymer repeating unit. *Chain directionality*, since certain polymer chains have a directionality, the mode of chain packing in a crystallite can take either parallel or antiparallel configurations. *Single-chain, conformation*, crystallization is favored if the chain conformation is compatible with its form in the crystallite. *Chain stiffness*, an optimal stiffness of the polymer is necessary.

In fiber spinning, polymer solutions or melts are mechanically forced or extruded through spinnerets that are dies with many small orifices that may be varied in diameter and shape. In melt spinning the polymer is heated above its melting point and the molten polymer is extruded. The jet of molten polymer emerging from each orifice in the spinneret is pulled to a cooling zone where the polymer solidifies to complete the fiber formation process. In dry spinning the polymer is dissolved in a suitable solvent, and the resultant solution is extruded under pressure through a spinneret. The jet of polymer solution is guided to a heating zone where the solvent evaporates and the filament solidifies. In wet spinning, the polymer is also dissolved in a suitable solvent and the solution is forced through a spinneret that is submerged in a coagulation bath. As the polymer solution emerges from the spinneret orifices in the coagulating bath, the polymer is either precipitated or chemically regenerated. In most instances, the filaments formed by melt, dry, or wet spinning are not suitable textile fibers until they have been subjected to one or more successive drawing operations. Drawing is the hot or cold stretching and attenuation of fiber filaments to achieve an irreversible extension and size reduction. Drawing induces a molecular orientation with respect to the fiber axis and develops a fiber fine structure. This fine structure is generally characterized by a high degree of crystallinity and by an orientation of both the crystallites and the polymer chain segments in the noncrystalline domains.

The fine structure and physical properties of synthetic textile fibers are frequently further modified by a variety of thermomechanical annealing treatments, including processes known as texturing. Texturing provides crimp to the filaments, and bulk and softness to textile products manufactured from them. In the case of melt spinning, the two-step process of spinning (extrusion) and drawing (structure development) is increasingly being combined in a single high speed spinning process. Bicomponent fibers, where two different polymers are extruded simultaneously in either side-by-side or skin/core configurations, are also an important category of melt-spun fibers.

6. Economic Aspects

For centuries upto the first quarter of the twentieth century, the textile industry relied exclusively on the natural fibers, particularly cotton, flax, wool, and silk. Commercialization of manufactured fibers began with regenerated cellulose ("artificial silk" by Chardonnet in 1891) and cellulose derivatives (cellulose acetate, Celanese Company in 1924) (11). With since the onset of the petroleum industry development, synthetic fibers development followed with nylon (1939), modacrylics (1949), olefin (1949), acrylic (1950), polyester (1953), spandex (1959), aramids (1961) and PBI (1983). With the commercialization of manufactured fibers, starting with those based on natural polymers in the mid-1920s, and then with those based on synthetic polymers in the mid-1940s, the use of fibers has expanded not only for the textile industry, but also in many other areas of applications.

The 1990 total world production of fibers amounted to ~40 million metric tons, distributed among the principal types of fibers. This reflects not only an increasing world population, but also an increasing per capita consumption of textile fibers. World population has increased in the past several decades at an average annual rate of ~2% to its current level of nearly 5.0 billion. The average per capita fiber consumption increased from 5.6 kg in 1965 to 7.3 kg in 1986 (12). Because of variations in climate and socioeconomic conditions, there are large variations in the per capita fiber consumption for different regions of the world.

Global production of manufactured fiber was 36.0 million metric tons in 2002. The average annual growth in the last two decades is ~2%. Of the manufactured fibers, the overwhelming majority is the synthetics, ie, 94%, and the remaining are the cellulosics. Polyester has maintained a strong lead in growth and share (58%), whereas the olefins have shown strong growth and now surpass nylon (11%) and acrylic (8%) and cellulosics (6%) fibers at a share of 17%.

Nearly all regions of the world are involved with fiber production. The current major producers of cotton are China, the United States, and Australia. The major wool producers are Australia and New Zealand. Global synthetic fiber production has shifted from North America and Europe to Asia. In 2002, synthetic fibers produced in Asia accounted for 65% (20.0 million metric tons) of the global production compared with 14% (4.7 million metric tons) in North America and 13% (3.4 million metric tons) in Europe. The growth of the synthetics is expected to be much higher in Asia with the upcoming quota-free regime in textile trade.

7. Uses

7.1. Fibrous Materials.

Fibers are used in the manufacture of a wide range of products that can generically be referred to as fibrous materials. This brief overview of the types of fibrous materials is intended to indicate the broad range of materials that can be produced from fibers. Since the properties of fibrous materials depend both on the properties of the fibers themselves and on the spatial arrangement of the fibers in the assembly, a given type of fiber may be used in many different end products. Similarly, a given end product can be produced from different fiber types.

Fibrous materials are distinguished primarily on the basis of fiber organization or the geometric arrangement of the component fibers in the structure. The isotropic assemblies, at one extreme, consist of completely randomly arranged fibers with no preferred orientation in any of the three principal spatial axes.

For such an isotropic fiber assembly, the physical properties are independent of the test direction, and indistinguishable from another unit volume space within the assembly. Some paper and nonwoven products approach isotropic fiber arrangement by exerting various forces to overcome the tendency for preferred orientation. High aspect-ratio fibers are rarely made into isotropic fiber assemblies because the high aspect-ratio fibers tend to align themselves in a stress field, thereby creating a preferred orientation of the fibers in the processing direction. Therefore, various anisotropic fibrous materials are more common with the fibers arranged in well-defined spatial patterns.

Most manufacture fibers, ie, regenerated and synthetic, are obtained in continuous form or filaments. Frequently, it is desired to obtain fibers in finite lengths for subsequent manufacture into spun yarns by conventional textile spinning operations. In this case, thousands of continuous filaments are collected together into a continuous rope of parallelized filaments called a tow. The tow is converted into staple length fiber by simply cutting it into specified lengths. The staple length produced in this conversion process depends on the system of yarn manufacture to be used. The cotton yarn manufacturing system requires lengths of ~1.5 in. (3.8 cm), whereas the woolen or worsted systems require lengths between 3 and 5 in. (7.6–12.7 cm). When synthetic fibers are produced in staple form for blending with natural fibers, dimensional properties such as length and fineness are matched to the natural fiber that is to be used in the blend.

Textile yarns and several preliminary linear structures, such as roving and sliver, are typical of those structures where there is a high degree of fiber orientation with respect to the principal axis of the material (13). The degree of fiber parallelization and orientation varies from one type of yarn to another, and can be controlled by variation in the fiber type, in the fiber geometric properties, and in the processing conditions used in the yarn production process. The high degree of structural anisotropy of textile yarns is reflected in large differences between axial and transverse physical properties. The structural anisotropy of yarns, and of the individual fibers, imparts a unique combination of high strength and low bending rigidity to textile yarns.

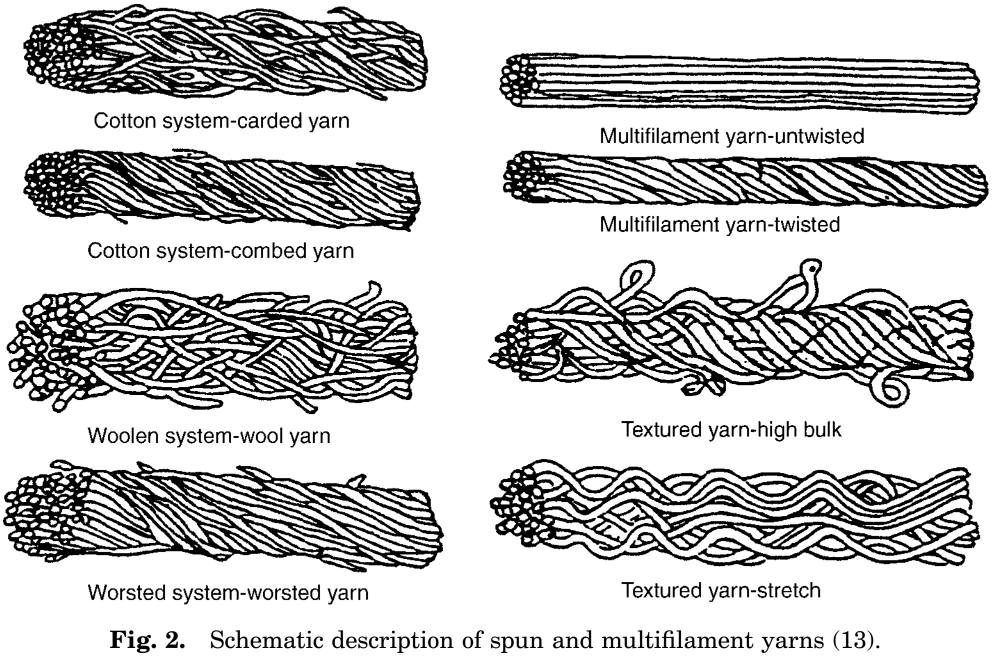
Textile yarns are produced from staple (finite length) fibers by a combination of processing steps referred to collectively as yarn spinning. After preliminary fiber alignment, the fibers are locked together by twisting the structure to form the spun yarn that is continuous in length and uniform. Depending on the specific processing conditions, the degree of fiber parallelization and surface hairiness can vary over a considerable range that strongly influences yarn physical properties. Sorption properties in particular are strongly affected by the fiber organization in a spun yarn. The staple fibers may be either natural fibers, such as cotton or wool, or any of a number of synthetic fibers.

Textile yarns are also produced from continuous filament synthetic fibers. When several such filaments are combined together and slightly twisted to maintain unity, the product so obtained is called a multifilament yarn. Multifilament yarns may contain 100 single filaments and are characterized by nearly complete filament alignment and parallelization with respect to the yarn axis. The degree of twist introduced into a multifilament yarn is usually quite low and just adequate to produce some level of interfilament cohesion. Such yarns are quite compact and smooth in appearance. Individual filaments, considerably larger in cross-section than those used in multifilament yarns, may also be used in certain applications as monofilaments. A variety of processes have been developed to introduce bulk and texture in multifilament yarns. These processes are designed to disrupt the high degree of filament alignment and parallelization and to produce yarns with properties generally associated with spun yarns. Schematic representations of typical yarns are given in Figure 2.

Yarns are used principally in the formation of textile fabrics either by weaving or knitting processes (14). Fabrics are a form of planar fibrous assembly where the high degree of structural anisotropy characteristic of yarns is minimized, but not totally eliminated. In a woven fabric, two systems of yarns, known as the warp and the filling, are interlaced at right angles to each other in various patterns of arrangements. The woven fabric can be viewed as a planar sheet-like material with pores or holes created by the yarn interlacing pattern. The dimensions of the fabric pores are determined by the yarn structure and dimensions, and by the weaving pattern. The physical properties of woven fabrics are strongly dependent on the direction of fabric tested.

Knitted fabrics are produced from one set of yarns by looping and interlocking processes to form a planar structure. The pores in knitted fabrics are usually not uniform in size and shape, and again depend largely on yarn dimensions and on the numerous variables of the knitting process. Knitted fabrics are normally quite deformable, and again physical properties are strongly dependent on the test direction.

The term nonwoven simply suggests a textile material that has been produced by means other than weaving, but these materials really represent a rather unique class of fibrous structure (15,16). In nonwoven processess, the fibers are laid into a planar sheet-like fabric structure, bypassing the intermedi-



Cotton system-carded yarn

Multifilament yarn-untwisted

Cotton system-combed yarn

Multifilament yarn-twisted

Woolen system-wool yarn

Textured yarn-high bulk

Worsted system-worsted yarn

Textured yarn-stretch

Fig. 2. Schematic description of spun and multifilament yarns (13).

ate stage of yarn formation, and then either bonded through fusion, chemical bonding, or mechanical interlocking (or two of the above) to achieve a cohesive fabric such as shown in Figure 3. Typically, staple length fibers are dispersed in a fluid (liquid in the wetlaid process of manufacture or air in the dry-laid process of manufacture) and deposited in sheet-like planar form on a support base prior to bonding or interlocking. The papermaking process is a well-known example of a wet-laid nonwoven process that utilizes short paper (pulp) fibers. The spunbond process differs from the dry- and wet-laid processes in that continuous length filaments are extruded, collected in a randomized planar network, and bonded together to form the final product. Spunbonded nonwovens are generally thin, strong, and almost film-like in appearance.

Within the plane of a nonwoven material, the fibers may be either completely isotropic or there may be a preferred fiber orientation or alignment usually with respect to a machine or processing direction. In the case of thicker dry-laid nonwovens, fiber orientation may be randomized in the third dimension, ie, that dimension perpendicular to the plane of the fabric, by a process known as needle punching (17). This process serves to bind the fibers in the nonwoven material by mechanical interlocking.

The type of nonwoven material that is produced depends largely on the fiber type used and on the method of manufacture. Generally, air-laid nonwovens are

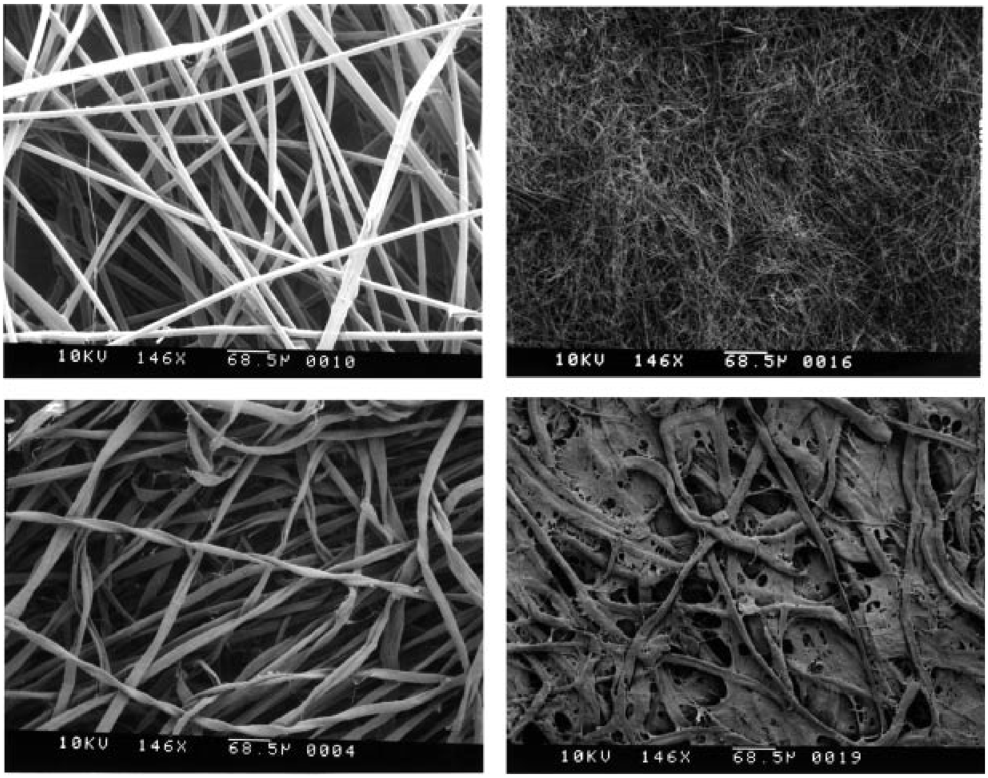


Fig. 3. Scanning electron microscopy of nonwoven materials (new SEM to be provided by Y.-L. Hsieh).

less dense and compact and tend to be softer, more deformable, and somewhat weaker. Wet-laid or paper-like nonwovens are more dense, but brittle. However, nonwovens by either process can be made into a wide variety of products with a broad range of physical properties. The methods used for bonding and for interlocking the constituent fibers to form the nonwoven material may be as important as the method used for producing the initial nonwoven web. The degree of bonding or interlocking also has a critical influence on the final properties. In general, strength increases, extensibility decreases, softness decreases, and sorptive capacity decreases with an increasing degree of bonding or interlocking. When thermoplastic fibers are used the nonwoven, thermal, or heat bonding is generally preferred to the use of chemical binding agents.

7.2. Properties of Fibrous Products. *Chemical Finishing.* Fibrous products are often chemically modified to enable more efficient processing and/or better performance. Most fibrous products are colored. Coloration not only serves an essential aesthetic function, but can be critical for certain functional properties such as protecting fibers from weathering, heat control, and identification. Coloration of textiles or fibrous products is commonly accomplished by either dyeing or printing processes. Chemical pretreatments are often necessary to prepare fibers for dyeing and other chemical finishes. Cleaning pretreatment, commonly called *scouring*, is to remove any natural or added substances that can interfere with the coloration and/or finishing processes and to optimize the ability of the fibers to take in the dyes and chemical reagents. Scouring of cotton involves a hot alkaline, usually 4% (w/w) NaOH, treatment followed by a hot wash to remove the hydrophobic waxes and fatty acids. Wool grease, suint, and dirt must be removed before coloration. Conventional methods employ scouring in hot alkali solutions to remove wool greases in emulsion, suint in solution, and dirt in suspension. The vegetable matter in raw wool is removed by carbonizing, which consist of the following steps: scouring, acidizing (4.5–7.5% sulfuric acid), and neutralizing. The serum gum on silk is removed by hot water. Another common pretreatment for natural fibers is bleaching to reduce yellowness and achieves a higher level of whiteness for better coloration, especially for pale colors. Hydrogen peroxide under alkaline conditions is most common for commercial bleaching, although sodium hypochlorite (basic) and other oxidizing agents such as peracetic acid or sodium chlorite (acidic) can also work. Size, a water-soluble polymer such as poly(vinyl alcohol), is usually applied to yarns to provide a coating to reduce friction for processing and to increase strength. All sizes must be removed before dyeing and finishing, thus desizing. Mercerization, in cold alkaline solutions of 18–24% NaOH, swell cotton fibers to a more rounded cross-sectional shape and give a smoother and added shine to fine cotton fabrics.

Colorants for fibers consist of dyes, pigments, and fluorescent brightening agents. Dyes are organic molecules containing chromophores that absorb visible light of specific wavelengths so that the light scattered is perceived as colors. Chromophores are conjugated structures of single and double bonds. Azo, nitro, and carbonyl groups are among the most commonly structures found in dyes. Natural dyes can be derived from plants and insect, whereas synthetic dyes are mainly aromatic compounds produced from petroleum. Dyes are classified by either their chemical structures or dyeing processes, ie, how they are applied to fibers. Most dyes structures contain either diazo or anthraquinone groups.

The dyeing processes classify dyes into acid (for wool, silk, and polyamides), basic (for acrylics and aramids), direct (cellulosics, proteins), reactive (cellulosics, proteins), and disperse (for polyesters, polyamides, cellulose acetates, polypropylene, aramids). Dyes are applied by either batch (exhaust) or continuous pad-fixation, or printing processes. Pigments are water insoluble coloring compounds that can be either organic or inorganic. They are applied as a suspension of fine particles; some may be soluble in organic solvents. Fluorescent brightening agents are organic compounds that absorb in the shorter wavelength ultraviolet (uv) light region and emit in the longer wavelength blue-violet region of the visible light, giving a lighter or whiter appearance.

Mechanical Properties. Because textile fibers are used primarily as elements of construction, a sound engineering approach to their mechanical properties is necessary. The mechanical properties of fibers describe the response of a fiber to deforming loads under conditions that induce tension, compression, torsion, or bending. Torsional deformations are normally analyzed in terms of shearing stresses, whereas bending may be considered to produce simultaneous tensile and compressive stresses around a neutral fiber axis. Mechanical properties are usually evaluated under standard conditions of temperature and humidity (21°C, 65% relative humidity), and under closely specified conditions of load application. Since textile fibers are exposed to a variety of chemical environments in the normal course of manufacturing and processing into yarns and fabrics, as well as during their ultimate use by the consumer, it is frequently important to evaluate mechanical properties in relation to a fiber's chemical environment. Not only do such measurements make possible a more probable prediction of fiber behavior under other than standard conditions, but also it may be possible to deduce important information about fiber structure.

The mechanical properties of fibers or of any other material may be described in terms of six factors: strength, elasticity, extensibility, resilience, stiffness, and toughness. Information about these mechanical properties is obtained from stress–strain or load-deformation curves that are graphical records of tensile, compressive, or shearing stresses as a function of deformation. In view of a fiber's geometric shape and dimensions, these curves are usually evaluated under uniaxial tension. The procedure for obtaining a load-deformation curve is to subject the fiber to increasing loads while recording the extension. Alternatively, the fiber can be subjected to controlled extension while recording the force generated by some suitable device. Several commercial constant rate of loading and extension tensile testers are available with sufficient sensitivity to permit the accurate evaluation of a fiber mechanical properties.

The load-extension curves obtained on these devices must be normalized by the fiber cross-sectional area so that the stress–strain curve may be derived. In fiber science, the initial cross-sectional area of a fiber is used for normalization of the load-extension curve. Thus, by not taking into account the fiber attenuation during extension, the true stress–strain curve is not obtained. However, the nominal or engineering stress–strain curve obtained reflects the number of stress-bearing units in the initial fiber cross-section, and thus provides significant information. The nominal or engineering stress can be easily converted into true stress by multiplying the nominal stress at any given value of the strain by the factor $(1 + \epsilon)$.

It is difficult to determine the cross-sectional area of a fiber. Direct observation and measurement of a cross-section under a microscope is the most accurate method. This is a destructive test that does not allow subsequent study of fiber mechanical properties, and is slow and tedious. Also, it does not take into account any variations in the cross-sectional area along the fiber length. Measurement of fiber diameters from microscopic observations of longitudinal views is somewhat easier, but the ellipticity of the cross-section in certain fibers can lead to serious errors.

The more usual method of designating fiber size is by its linear density in units of mass per unit length. If the bulk density (mass per unit volume) is known, then the cross-sectional area can be computed by dividing the linear density by the bulk density. In fiber and textile terminology, three special linear density units are used: denier, grex, and tex. The tex system has been adopted by the American Society for Testing and Materials (ASTM) as the standard unit for designating the linear density of textile fibers and yarns, although the denier unit continues to be widely used. The tex is also acceptable as part of the Systems International (SI) system, although rigorously, the SI unit is kg/m. The tex as a measure of fineness or linear density is defined as 1 g/1000 m (10^{-6} kg/m). Denier is defined as 1 g/9000 m (1.111×10^{-7} kg/m); 1 denier = 0.1111 tex. A grex is 0.1 tex.

Typical textile fibers have linear densities in the range of 0.33–1.66 tex (3–15 denier). Fibers in the 0.33–0.66 tex (3–6 denier) range are generally used in nonwoven materials as well as in woven and knitted fabrics for use in apparel. Coarser fibers are generally used in carpets, upholstery, and certain industrial textiles. A recent development in fiber technology is the category of microfibers, with linear densities <0.11 tex (1 denier) and as low as 0.01 tex. These fibers, when properly spun into yarns and subsequently woven into fabrics, can produce textile fabrics that have excellent drape and softness properties as well as improved color clarity.

Normalized fiber mechanical properties are expressed in terms of unit linear density. For example, in describing the action of a load on a fiber in a tensile test, units of N/tex or gram force per denier (gpd) are generally used. If this is done, the term tenacity should be used in place of stress. The true units of stress are force per unit cross-sectional area, and the term stress should be reserved for those instances where the proper units are used.

The linear density of fibers is determined by direct weighing of a known length of fiber or by means of a vibroscope. Direct weighing is a feasible method in the case of continuous synthetic filaments where a sufficient length for accurate weighing can be obtained. Direct weighing of staple fibers, either natural or synthetic, is not practicable in view of the uncertainties involved in the length measurement and in the weighing. The vibroscopic method of determining linear density is well suited to fibers of all lengths. The vibroscope consists of a system for applying an oscillatory force of known frequency to a fiber while it is held under tension, and also a means of detecting mechanical resonance under the applied oscillatory force. From the values of frequency, tension, and fiber length, the linear density can be computed from the classical vibrating string formula. Corrections taking into account fiber stiffness, cross-sectional shape, and nonuniformity along the length of the fiber have been developed.

A schematic stress–strain curve of an uncrimped, ideal textile fiber is shown in Figure 4. It is from curves such as these that the basic factors that define fiber mechanical properties are obtained.

The strength of a fiber, which measures the ability of the fiber to withstand a load, is expressed in terms of the stress required to produce rupture in units of mass per unit cross-section. In more common fiber and textile terminology, strength is expressed in terms of the tenacity at break or ultimate tenacity in units of N/tex or gram force per denier. Extensibility describes the deformation of the fiber produced by a given stress. It is quantitatively defined by the ultimate strain, which is the fractional increase in length of a fiber when subjected to a stress that causes it to rupture. The units for extensibility or strain are length per unit length, which may be expressed in percentage units. Stiffness describes the resistance of the fiber to deformation. This is measured by the elastic stiffness, which is the ratio of the stress–strain at the yield point. The elastic stiffness constitutes the slope of the initial Hookean region of the stress–strain curve where the stress and strain are directly proportional. The elastic stiffness is equivalent to the elastic modulus or Young's modulus of elasticity, and carries the units of stress per unit strain. In textile terminology, where tenacity is used in place of stress, the units for stiffness are gram force per unit linear density. On the assumption that the stress–strain curve of a textile fiber is essentially linear, fiber stiffness may be approximated by the average stiffness, which is the ratio of the breaking stress to the breaking strain.

The resilience of a fiber describes its ability to absorb work or mechanical energy elastically, ie, without undergoing permanent deformation. This property is related to the area under the Hookean portion of the stress–strain curve, which can be considered as the energy of elastic deformation. Rigorously, resilience must be defined as the ratio of the energy of recovery to the energy of deformation in a cyclic loading experiment that may be carried to any given

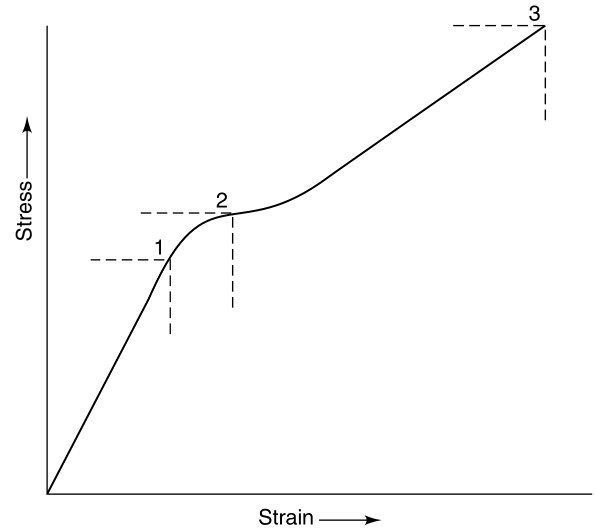


Fig. 4. Idealized stress–strain curves of an uncrimped textile fiber; point 1 is the proportional limit, point 2 is the yield point, and point 3 is the break or rupture point.

value of load or extension. Frequently, resilience may be evaluated in terms of dimensional recovery from a given deformation. Resilience is dimensionless and is usually expressed in percentage units.

The elasticity of a fiber describes its ability to return to original dimensions upon release of a deforming stress, and is quantitatively described by the stress or tenacity at the yield point. The final fiber quality factor is its toughness, which describes its ability to absorb work. Toughness may be quantitatively designated by the work required to rupture the fiber, which may be evaluated from the area under the total stress–strain curve. The usual textile unit for this property is mass per unit linear density. The toughness index, defined as one-half the product of the stress and strain at break also in units of mass per unit linear density, is frequently used as an approximation of the work required to rupture a fiber. The stress–strain curves of some typical textile fibers are shown in Figure 5.

When an ideal fiber is subjected to a deformation within the Hookean region of the stress–strain curve, the extension is recoverable upon removal of the load. In this region of the stress–strain curve, the ideal fiber behaves as an elastic body. When a fiber is subjected to a load that places it under a stress higher than its yield value, the fiber does not return completely to its original length upon removal of the deforming load. The fiber in this case develops a permanent set. Not all of the original deformation is retained as permanent set; some of it is recoverable. Recovery from deformation may be divided into two components (19). The first takes place immediately upon removal of the deforming load and is called the immediate elastic deflection. The other is the delayed deflection, which can be further subdivided into a time dependent recoverable component and a nonrecoverable component. The latter is also known as permanent set or secondary creep. Permanent nonrecoverable deformation is a manifestation of plasticity or internal stress-induced plastic flow. The tensile recovery behavior of a large number of textile fibers has been studied (20).

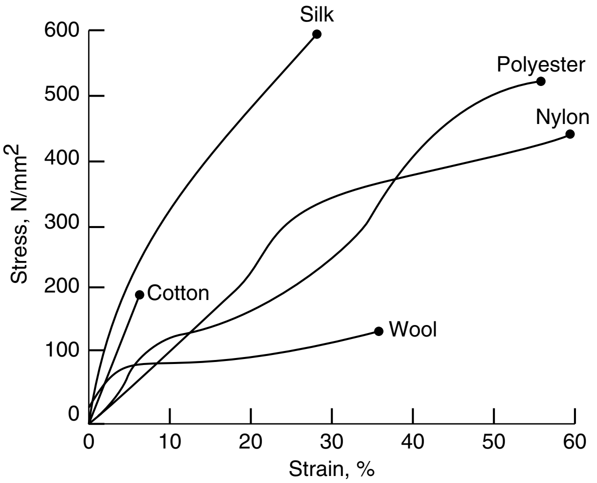


Fig. 5. Stress–strain curves of some textile fibers (18). To convert N/mm^2 to psi, multiply by 145.

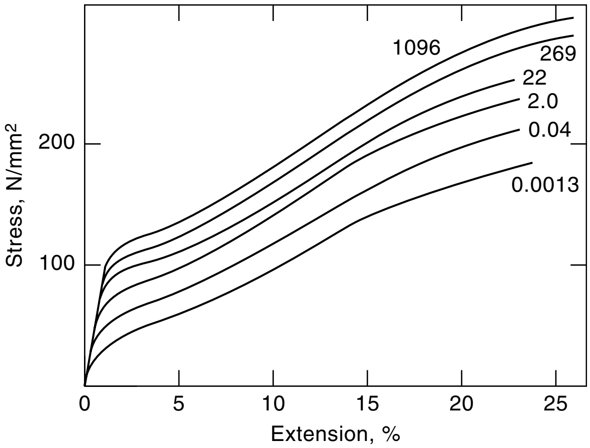


Fig. 6. The effect of rate of extension on the stress–strain curves of rayon fibers at 65% rh and 20°C. The numbers on the curves give the constant rates of extension in percent per second (21).

Another aspect of plasticity is the time dependent progressive deformation under constant load, known as creep. This process occurs when a fiber is loaded above the yield value and continues over several logarithmic decades of time. The extension under fixed load, or creep, is analogous to the relaxation of stress under fixed extension. Stress relaxation is the process whereby the stress that is generated as a result of a deformation is dissipated as a function of time. Both of these time dependent processes are reflections of plastic flow resulting from various molecular motions in the fiber. As a direct consequence of creep and stress relaxation, the shape of a stress–strain curve is in many cases strongly dependent on the rate of deformation, as is illustrated in Figure 6.

The resistance to plastic flow can be schematically illustrated by dashpots with characteristic viscosities. The resistance to deformations within the elastic regions can be characterized by elastic springs and spring force constants. In real fibers, in contrast to ideal fibers, the mechanical behavior is best characterized by simultaneous elastic and plastic deformations. Materials that undergo simultaneous elastic and plastic effects are said to be viscoelastic. Several models describing viscoelasticity in terms of springs and dashpots in various series and parallel combinations have been proposed. The concepts of elasticity, plasticity, and viscoelasticity have been the subjects of several excellent reviews (22).

An important aspect of the mechanical properties of fibers concerns their response to time-dependent deformations. Fibers are frequently subjected to conditions of loading and unloading at various frequencies and strains, and it is important to know their response to these dynamic conditions. In this connection, the fatigue properties of textile fibers are of particular importance, and have been studied extensively in cyclic tension. The results have been interpreted in terms of molecular processes. The mechanical and other properties of fibers have been reviewed extensively (23,24).

8. New Fiber Properties

New fibers and new properties can be created by either chemical or physical means. Changing fiber geometries, specifically reducing fiber size or fineness is among the simplest fiber modification approaches to create significant changes to fiber properties and product performance. Current melt and solution spinning technologies are capable of producing fibers with diameters typically in the 20 μm range and higher at relatively high speeds and with good uniformity. Through the development of new fiber spinning technologies, fibers <1 denier have been generated from polyester, nylon, rayon and most recently acrylic. *Micro-denier* fibers, also called microfibers, are finer than any naturally- occurring fibers. Thus, these-synthetic fibers have the advantage for development of high performance products. Ultrasuede developed by the Japanese nearly 20 years ago is the better-known early example.

The fine fiber sizes of microfibers give them soft hand (low stiffness) and silk-like texture, drape and hand. Such properties make microfibers desirable for fine clothing such as blouses, dresses, evening wear, tailored suits, hosiery, intimate apparel, luxurious bedding, and upholstery fabrics. Microfibers also allow dense packing of fibers and yarns in fabrics for wind- and water-resistant outerwear. Additional finishes such as sanding and sueding can enhance the look and feel of microfibers to give a velvety hand, or a leather look. The high specific surface, high surface curvature, and reduced interfiber void spaces are desirable for applications such as wiping cloths, high performance filters, artificial blood vessels, sanitary, and towel products. Microfibers can be blended with other fibers including cotton, linen, wool, rayon, and Lycra spandex to enhance the appearance, hand, drape, and other performance properties of the fabrics. Usually, a minimum of 35–40% of microfibers is required to retain the desired hand and performances.

Submicrometer size fibers have also been generated by electrospinning technologies. In these processes, polymer melts or solutions are charged to high voltage to overcome their surface tension forces to form fine jets and, upon solidification, fine fibers. The process is similar to electrostatic atomization and spraying of liquid jets that have found industrial applications, such as aerosol spraying, atomization in the charged droplets, and formation of particles. Although the concept of electrospinning to form fine fibers was patented in 1934, interest has surged in the last two decades. Most work to date has focused on the formation of fibers from a wide varieties of polymers (25). Electrospinning presents many advantages to fiber formation. It is versatile for forming fine fibers from a wide range of polymers, some of which cannot be converted into fibers via conventional fiber spinning processes. It requires very small quantities of polymer, as low as submilligram levels, making it possible to transform research-quantity polymer to fibers. However, technologically demanding issues such as generating fibers with diameters <100 nm, or on a continuous basis, and with commercially viable efficiency, remain to be addressed.

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