2
PROPERTIES OF FIBERS AND YARNS

2.1 INTRODUCTION

The utilization and serviceability of textile materials, other than industrial or technical textiles, are determined by their physical and mechanical properties, which include softness, pliability, good handle, feel, and drape [1]. The pliability of a textile structure is attributed to the fact that it is composed of a number of individual elements, commonly referred to as yarns. These yarns are made up of either staple or filament fibers, having sufficient degree of freedom of movement within the fabric structure without causing distortions. The softness and pliability of textile fabrics are due to this freedom of movement of constitutional elements, i.e., the fibers and yarns. The yarns are generally formed by twisting a bundle of fibers together. Though the process of twisting generates transverse pressures to prevent slippage of fibers, especially in staple yarns under axial tension, the yarns still retain flexibility because of the inherent flexibility of textile fibers. Obviously, it implies that the properties of textile structures will depend substantially upon the properties of fibers, which are the true building units.

The process of woven fabric manufacturing is neither simple nor accomplished in one step. The conversion of raw materials (fibers) into finished products (fabrics) involves many different steps, broadly categorized as spinning of a yarn, weaving of a fabric, and finishing. Each of these steps in turn involves many intermediate processes to perform well-defined specific functions. The process of spinning staple yarns involves preparatory steps such

as opening and cleaning of cotton fiber stock, or only opening for synthetic fibers, optimal blending of different fibers, carding, combing, drawing, and twist insertion. The process of weaving is preceded by preparatory steps of winding, warping, and slashing (more commonly known as sizing).

The processes of spinning and weaving have undergone many developments due to the proliferation of high-speed production technologies. In today's market-based economy, the scale and speed of spinning and weaving operations are decisive factors. The quality of yarns and warp preparation processes, such as winding, warping, and sizing, are prerequisites for the success of newer high-speed weaving technologies. To keep pace with changing weaving technologies, the process of sizing and ingredients used for sizing have also changed. The success of the sizing operation, on which the success of weaving and to some extent the quality of woven fabric are based, is influenced by the quality and properties of the warp yarns. Before discussing the process of sizing it is important to know the properties of fibers used in the making of various types of yarns. The fiber type and characteristics have a profound influence on the geometry and other properties of staple yarns spun on various spinning systems [2]. The mechanical behavior of staple yarns is strongly dependent on the properties of the constituent fibers and their disposition in the body of the yarn [2].

2.2 FIBERS

A staple fiber is a long, thin, and flexible material, very similar to human hair, having macroscopic dimension along its length but microscopic transverse dimension [1,3]. The ratio of length to thickness of fibers, defined as slenderness ratio, is usually of the order of 1000 and above [3,4]. The inherent attributes of flexibility, fineness, and a high length-to-width ratio of fibers make them suitable for producing soft and flexible fabrics. The ease of converting fabrics into garment greatly depends upon the ability of the fabrics to conform to three-dimensional shapes such as the human body. Table 2.1 illustrates the typical dimensions of some natural fibers.

Besides slenderness ratio, the other most important property of textile fibers is elasticity. The breaking extension of an ideal textile fiber should be between 5 to 50% depending upon the actual end-use application [5]. The extensibilities of glass and crystalline solids are below 5%, and those of rubbers are above 50%, which makes them very difficult to process during subsequent spinning and weaving operations. These fibrous materials having suitable extensibility for successful textile processing are all partially oriented, partially

Table 2.1 Length-to-Diameter Ratios of Natural Textile Fibers

Fiber	Typical length (mm)	Typical diameter (μm)	Slenderness ratio
Cotton	25	17	1500
Wool	75	25	3000
Cashmere	40	18	2200
Mohair	55	28	1900
Flax	25	20	1250
Jute	2.5	15	170
Hemp	40	25	1600
Ramie	150	50	3000

Source: Refs. 4 and 5.

crystalline (usually linear polymers), and similar to some naturally available cellulosic and protein fibers.

2.2.1 Classification of Textile Fibers

Textile fibers are broadly classified into two major groups: (1) natural and (2) manmade, depending upon the nature of their origin. Natural fibers still account for a major share (some 45%) of the total textile fiber consumption around the world. The term ''manmade'' applies to all fibers that include those regenerated from natural products as well as those that are synthesized from basic chemicals. There are a variety of texts dealing with the general classification, properties [4–7], and chemical compositions of textile fibers and the synthesis of manmade fibers [7,8]. In recent years, the original list of manmade fibers has been supplemented by a variety of newly synthesized fibers, engineered specifically for high performance end uses, such as aramid, polysulfide, and polybenzimidazole to name a few. Table 2.2(A) gives the classification of textile fibers [4–9].

Natural fibers are further subdivided into (a) animal, (b) vegetable, and (c) mineral. The fibers from animal sources can be further subdivided into silk, wool, mohair, cashmere, and hair. Vegetable fibers are subdivided into (i) seed fibers (e.g., cotton); (ii) bast fibers (e.g., flax, hemp, jute, and ramie); (iii) leaf fibers (e.g., manila, sisal, and abaca); and (iv) fruit fibers (e.g., coir).

Manmade fibers are divided into two main categories, as shown in Table 2.2(B):

A. Natural polymer fibers in which the fiber-forming polymer is of natural origin, referred to as regenerated fibers.

Table 2.2A Classification of Fibers

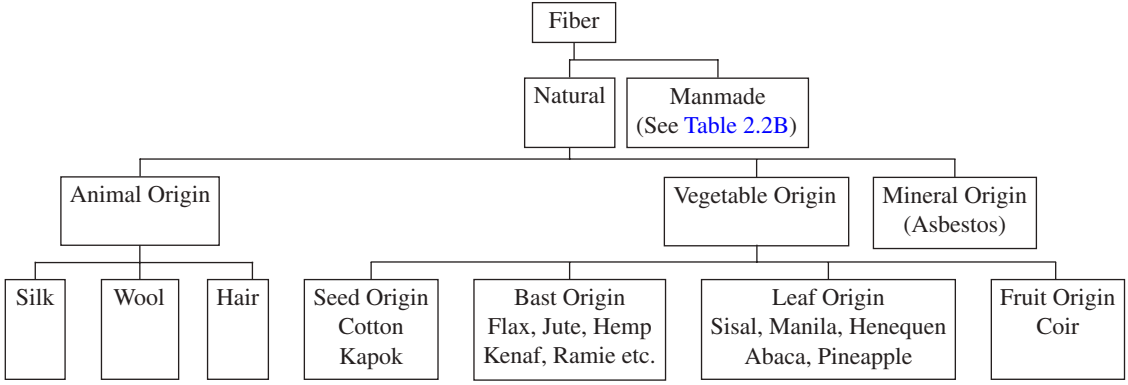

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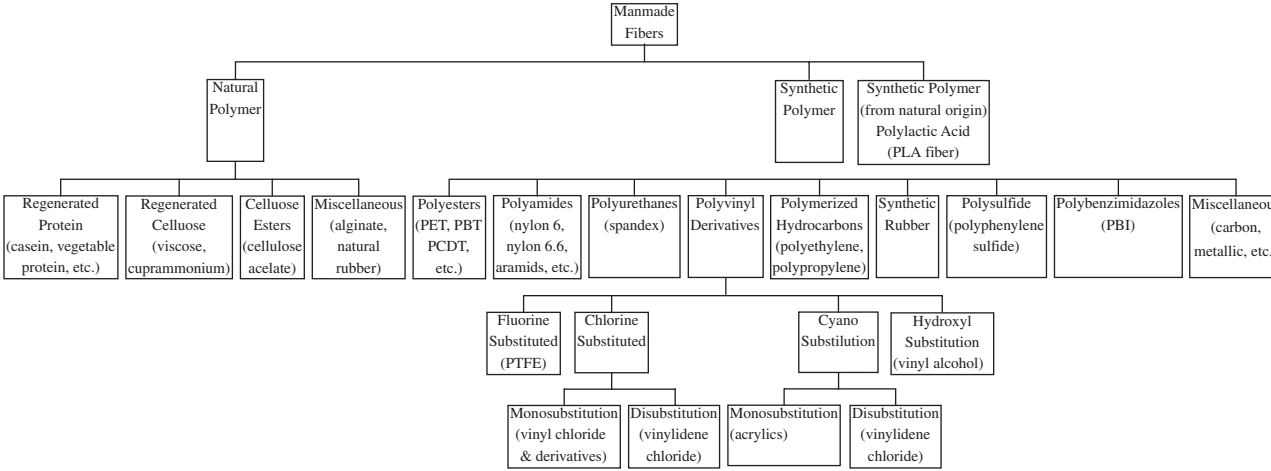
Table 2.2B Classification of Manmade Fibers



Source: Refs. 7–9.

B. Synthetic fibers in which the fiber-forming material(s) is from basic chemicals. There is now also a new class of synthetic fibers, those produced from material derived from a natural renewable origin, such as corn, known as polylactic acid or polylactide (PLA).

Regenerated fibers derived from natural polymers are further subdivided into four groups, namely,

a. Cellulose fibers (e.g., viscose, polynosic, cuprammonium rayons, and Tencel® or lyocell)
b. Protein fibers (e.g., casein)
c. Cellulose esters (e.g., acetate and triacetate)
d. Miscellaneous fibers (e.g., alginate and natural rubbers)

It is more convenient to classify synthetic fibers according to their chemical structure. They fall into the following ten subdivisions:

i. Polyurethanes (e.g., Spandex®)
ii. Polyamide (e.g., nylon 6, nylon 6.6, etc.)
iii. Polyesters (e.g., Dacron®)
iv. Polyvinyl derivatives:
    a. polytetrafluoroethylene (PTFE)
    b. polyvinylchloride (PVC)
    c. polyvinylidene chloride
    d. polyacrylonitrile (PAN)
    e. polyvinylidene dinitrile
    f. polyvinyl alcohol (PVA)
    g. polystyrene
    h. miscellaneous polyvinyl derivatives
v. Polyolefins (e.g., polyethylene and polypropylene)
vi. Polysulfide (e.g., PPS)
vii. Aramids (e.g., Kevlar® and Nomex®)
viii. Novoloid (e.g., Kynol®)
ix. Miscellaneous (e.g., glass, metallic, carbon, and ceramics)
x. Polylactic acid or polylactide (PLA)

2.2.2 Essential Properties of Textile Fibers

The choice of textile fibers to be used as raw materials in a specific application depends upon a unique combination of different properties. The most essential and desirable properties may be broadly categorized as

Dimensional or geometric
Physical
Mechanical
General

Table 2.3 lists various essential properties of textile fibers.

Dimensional Properties

The longitudinal and transverse dimensions, i.e., fiber length and fineness, respectively, are two of the most important dimensional properties that influence processing performance and the final end-use properties. Both these dimensional properties of natural fibers vary considerably depending upon the

Table 2.3 Essential Properties of Textile Fibers

A. Dimensional
   1. Length
   2. Diameter
   3. Cross-sectional shape
B. Physical Properties
   1. Density
   2. Crimp
C. Mechanical Properties
   1. Strength
   2. Elongation
   3. Elasticity
   4. Recovery
   5. Bending stiffness
D. General Properties
   1. Frictional
   2. Softness
   3. Light fastness
   4. Thermal stability
   5. Resistance to chemicals, organic solvents
   6. Pliability
   7. Durability
   8. Abrasion resistance
   9. Dimensional stability
   10. Wearing comfort

Source: Refs. 5 and 6.

type and origin of the materials. The relationships between the fiber length and fineness of different natural fibers of different types have been reported in the literature [10,11]. The length and diameter of manmade fibers can be accurately determined and controlled during extrusion (spinning). Consequently, manmade fibers are far more uniform in their longitudinal and transverse dimensions than natural fibers.

Length. The actual length of textile fibers may be infinite for continuous filament and finite for all staple fibers. Staple length is defined as the most commonly occurring fiber length in the population. The shortest staple fiber length that can be satisfactorily processed on known spinning machines should not be less than about 6–7 mm (0.25 in.) [4] since it is not possible to twist very short fibers to impart the necessary cohesion required to spin the yarns. The inherent variability in the length of natural fibers is quite diverse, depending upon the type and origin. For example, Sea Island cotton is much longer than the American Upland cotton because of differences in the genetic variety and cultivating conditions. Climatic conditions, natural fertility of soil, and fertilizer application also affect the quality of cotton. These natural factors affect the variation in fiber length not only between fibers of different types and origins, but also within the same type. The inherent length variability in terms of the coefficient of variation may be as high as 40% for cotton and as high as 50% for wool, irrespective of their types [10]. This poses a formidable problem of deriving a unique length value to characterize the given fiber sample. In textiles, therefore, the measurement of staple fiber length is usually supplemented by an index of length variation, namely, the coefficient of variation (CV) of length. The coefficient of variation for manmade staple fibers is usually relatively low (about 10%). The variation in staple length of manmade fibers is due to machine wear and attendant errors involved in cutting machines and due to fiber breakage occurring during extrusion and spinning. However, more often the manmade fibers are blended with natural fibers to optimize the properties of the resulting yarns. Hence, the length to which a manmade staple fiber is produced is also influenced by its blending component, i.e., the length of natural fiber, since they have to be processed on spinning machines originally designed for natural fibers of specific length and fineness characteristics.

For the methods, instruments, and techniques used for characterizing fiber length, readers are referred to other standard texts [5,11].

Fiber Fineness. Fiber fineness is a measure of the transverse dimension of textile fibers; included in this definition are fibers which have various forms and cross-sectional shapes. The technical significance of fiber fineness can be

appreciated by, for example, considering its effect on yarn irregularity. The unevenness of staple yarns is dependent upon the average number of fibers in a yarn cross section. For a given linear density of a staple yarn, the irregularity is reduced by having a larger number of fibers in the cross section [12,13]. The average number of fibers in the cross section of a yarn of specific linear density will in turn depend upon the fineness of the fibers being used; the finer the fiber, the greater the number of fibers which can be packed into the cross section of a yarn of a given linear density, and hence the lower is the yarn irregularity [12,13]. The spinning value or spinnability of fibers is determined, for all practical purposes, by their fineness. However, there is a limit to the fineness of a yarn that can be spun commercially on spinning systems such as ring, rotor, and air-jet, even if the fineness of the constituent fibers is reduced to the lowest value practically possible. Table 2.4 gives the minimum number of fibers required to spin a yarn on different spinning systems. Thus the spinning limit of fibers is largely determined by the fiber fineness: for coarser fibers the spinning limit is low, and vice versa. The bending behavior of a fiber is influenced by its fineness because the bending rigidity is inversely proportional to the square of the radius. Finer fibers are easier to bend; therefore resulting yarns are also flexible, and the fabrics made from such fibers exhibit soft handle, graceful drape, and flexibility. During the process of spinning a staple yarn, the fibers are twisted to impart the necessary cohesion. The finer fibers offer lower torsional and bending resistance and are therefore easier to twist and spin. Furthermore, yarns spun from finer fibers require lower twist factors because the finer the fiber, the greater the total fiber surface area available for interfiber cohesion. High and super twisted yarns used in certain applications (e.g., Swiss voiles and crepe fabrics), made from finer fibers, do not produce kinks and snarls because of lower bending and torsional stiffness of such fine fibers. The luster of fabric is also affected by the fineness of fibers. A fabric woven from yarns made from finer fibers (greater number of fibers in the yarn cross section) is more lustrous due to the greater reflection of incident light without significant distortion resulting from a higher number of reflecting surfaces per unit area of the fabric. The rate of dyeing (in other words, time required for the exhaustion of the dye bath) is also dependent upon the total available specific surface area of fibers. Finer fibers and those with irregular cross sections exhibit better dyeing affinity than those observed for an equal amount of coarser and smooth cylindrical fibers.

The task of measuring fiber fineness is not made any easier by the fact that variations in cross-sectional shape and size exist not only between different fiber types, but also within the same fiber type. The classical method of measuring the fiber fineness of wool known to have a reasonably circular cross section,

Table 2.4 Minimal Number of Fibers Required to Spin a Yarn

Spinning system	Number of fibers[a]
Ring spinning	60
Rotor spinning	120
Open-end friction spinning	100
Air-jet spinning	70
Filament wrap spinning	40

[a]For 100% polyester yarn from 1.5 denier, 38 mm polyester fiber.
Source: Refs. 90 and 110.

in terms of fiber diameter [14,15], is rarely valid for cotton which has a flat ribbonlike longitudinal shape and an irregular kidney bean shape cross section, as shown in Fig. 2.1. The degree of development of the cell wall of cotton fibers depends upon various natural factors. A fiber with a well-developed cell wall is considered a mature fiber. Besides its fineness, the maturity of a cotton fiber is also important because it significantly affects the subsequent processing performance, particularly nep formation and dyeing. The variety of methods and instruments used for measuring fiber fineness is outside the scope of this present volume, but readers are referred to standard texts [5,11] for detailed information.

Cross-sectional Shapes. The cross-sectional shape of fibers varies widely, from irregular shapes such as kidney bean for cotton and reasonably circular for wool to cylindrical in general for manmade fibers. The form and extent of cross-sectional variation is higher in the case of natural fibers. The degree of development of the cell walls of all natural fibers of vegetable origin (e.g., cotton, flax, jute, and sisal) varies considerably. Mature fibers with well-developed cell walls exhibit somewhat different shapes than immature fibers that do not have fully developed cell walls. The cross-sectional shape of a textile fiber has significant influence on its processing behavior as well as on the properties of the ultimate fabrics. Fibers with a circular cross section often have a good handle and feel. The warmth-retaining property of wool fiber is due to this nearly circular cross section and natural crimp, which allow a large amount of air space between the fibers in a yarn. The flatter ribbonlike cross section of cotton fibers provides better covering power than that of fibers with circular cross sections. The luster of silk is attributed to its cross section, which is triangular with rounded angles in shape.

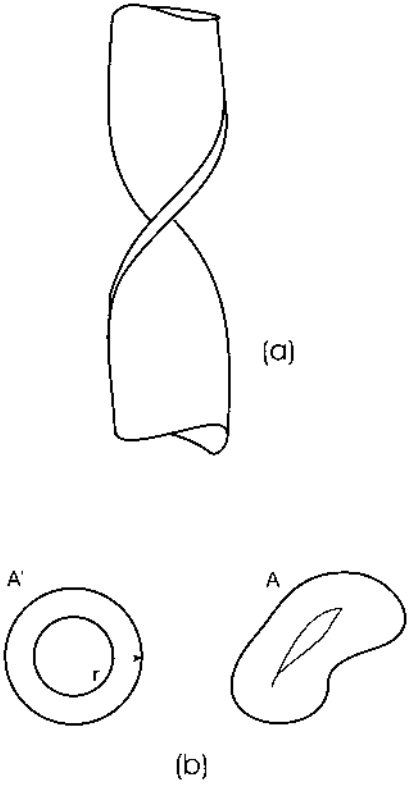


Fig. 2.1 (a) Schematic diagram of longitudinal view of a cotton fiber. (b) Cross section and degree of thickening of a cotton fiber. (From Ref. 5.)

The cross-sectional shapes of manmade fibers, though in general circular, can be independently controlled by using a suitable shape of holes in the spinneret. To achieve some of the desirable properties related to cross-sectional shapes of natural fibers, the manmade fibers are often also produced with noncircular cross sections. For example, the trilobal cross section of some manmade fibers, such as polyester and nylon, is produced to simulate the luster of natural silk fiber and also to impart soil-hiding capacity in yarn.

Physical Properties of Fibers

The density of textile materials plays an important role in processing behavior and the ultimate fabric properties. Crimp is another important property of

textile fibers, especially those of natural origin, but is not that common in the case of other solid materials. The manmade fibers are usually crimped before processing on the textile equipment.

Fiber Density. Fiber density is defined as the ratio of fiber mass to fiber volume. The measurement of fiber mass can be readily obtained by a suitable weighing balance. The task of measuring fiber volume for a given mass by a classical method of displacement of liquid in a measuring cylinder is complicated because of entrapped air and the absorption characteristics of textile fibers. The density column method, which is most widely used, utilizes liquids that neither swell nor affect the fibers being tested. A number of methods for measuring the density of textile fibers and their limitations have been reported in the literature [16–19]. The readers are referred to various published works [16–19] and standard texts [5,11] for more detailed information.

The density of textile fibers directly affects the weight and bulk of fabrics. The fabrics made from yarns containing low density fibers will have a fuller and bulkier appearance than those made from high density fibers. Typical values of the densities and specific volumes of dry fibers at 65% relative humidity are given in Table 2.5. The densities of fibers more commonly used for apparel applications vary from 0.9 for polypropylene, 1.14 for nylon, 1.30 for wool, and 1.38 for polyester to 1.55 for cotton. Lighter (lower density) fibers such as polypropylene and polyethylene have densities of 0.91 and 0.92, respectively. Consequently, they float on water. Some heavier fibers, such as polytetrafluoroethylene and glass, are used for specialized industrial applications.

Fiber Crimp. Fiber crimp is a natural attribute of all staple fibers defined as ''waviness'' in general for all practical purposes [20]. Because of this natural crimp in fibers they are capable of entangling together even under small transverse pressure which facilitates many processing operations. The interfiber forces in a card web, though relatively small, hold all fibers together and prevent the disintegration of the web. This is attributed particularly to the crimp of textile fibers. The manmade fibers, if not crimped during manufacturing, are difficult to separate during opening and carding because they cling to one another. The fibers with higher crimp (i.e., more waviness) tend to make bulkier yarns and fabrics as a consequence of an increase in specific volume. The elasticity of textile yarns and fabrics under low uniaxial tensile load is also partly attributable to the rigidity of the crimped form of the constituent fibers.

The crimp in textile fibers is usually considered to have two dimensions, namely, wavelength along the fiber axis and the amplitude along the transverse dimension (i.e., diameter) of the fiber as shown in Fig. 2.2a. If the length of

Table 2.5 Fiber Densities

Fiber	Density (g/cm^3, Mg/m^3 Dry	Density (g/cm^3, Mg/m^3 65% RH	Specific volume (cm^3/g) Dry	Specific volume (cm^3/g) 65% RH
Cotton (lumen filled)	1.55	1.52	0.64	0.66
Viscose rayon	1.52	1.49	0.66	0.67
Secondary acetate, triacetate	1.31	1.32	0.76	0.76
Wool	1.30	1.31	0.77	0.76
Silk	1.34	1.34	0.75	0.75
Casein	1.30	1.30	0.77	0.77
Nylon 6.6, nylon 6	1.14	1.14	0.88	0.88
Terylene (and other polyester fibres)	1.39	1.39	0.72	0.72
Orlon (and other acrylic fibres)	1.19	1.19	0.84	0.84
Polypropylene	0.91		1.09	
Polyethylene, low density	0.92		1.09	
Polyethylene, high density	0.85		1.05	
Dynel (modacrylic)	1.29	1.29	0.78	0.78
Teklan (modacrylic)	1.34		0.75	
Polyvinyl chloride	1.4		0.71	
Polytetrafluorethylene	2.2		0.45	
Glass	2.5	2.5	0.40	0.40

Source: Refs. 5 and 6.

a crimped fiber placed on a flat plane is l_o and the length of the same fiber when the crimp is removed by applying a tension is l, then the crimp is given by [5,20,21]

$$\text{crimp}(\%) = \frac{l - l_o}{l_o} \times 100$$

Besides this scientific representation of crimp, sometimes crimp is also specified in terms of a number such as 4 crimps/cm.

Mechanical Properties

The mechanical properties of textile materials are measured in terms of their resistance to deformation under applied stresses or loads. The nature of loads applied may be tensile, shear, bending, compressive, etc. The tensile behavior

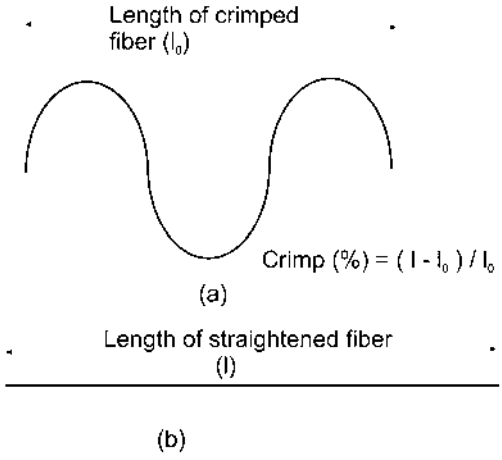


Fig. 2.2 Fiber crimp dimensions. (From Refs. 5 and 20.)

of a textile fiber has a very profound influence on subsequent processing behavior and the ultimate fabric behavior. The tensile properties under forces applied along the fiber axis are therefore most widely studied.

To express the behavior of a fiber under gradually increasing tensile load, a load–elongation curve up to the rupture point is usually plotted. Figure 2.3 shows a typical load–elongation curve of a fiber. The parameters used to describe the tensile properties of fiber are

1. Strength
2. Elongation at break
3. Initial modulus
4. Breaking energy or work of rupture
5. Elasticity and recovery

Strength. This is the measure of the force required to break a fiber and is usually expressed in newtons or gram force. In the load–elongation curve of an individual fiber, the strength of the fiber is its breaking load. However, to compare different fibers having different linear densities, specific stress at break, more commonly known as tenacity, is used. The tenacity, or specific strength, is given by

$$\text{tenacity} = \frac{\text{force at break (N)}}{\text{linear density (tex)}}$$

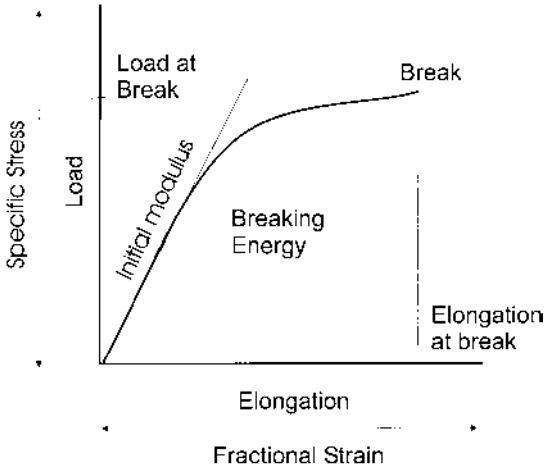


Fig. 2.3 Typical load–elongation curve of a fiber. (From Refs. 5 and 6.)

For comparing strengths of different engineering materials on the basis of area of cross section, the stress at break, termed ultimate stress, is used. However, textile fibers generally do not have well-defined geometric cross sections. Therefore, expressing the strength of fibers in terms of ultimate tensile stress is susceptible to error.

Elongation at Break. The actual increase in the length of the fiber under applied axial tension is known as elongation. The elongation of a fiber at the break point is termed elongation at break or breaking elongation. For comparing different fibers in terms of their elongation properties, a more commonly used quantity is the fractional or percent strain at break, which is expressed as

$$\text{strain} = \frac{\text{breaking elongation}}{\text{gauge length}} \times 100$$

Another quantity of practical interest is the breaking extension, defined as the percentage increase in length of fiber at the break point. If L_g is the gauge length and L_b is the length of fiber at break expressed in percentage, then

$$\text{breaking extension } (\%) = \frac{L_b - L_g}{L_g} \times 100$$

Initial Modulus. A close analysis of the stress–strain curve of a fiber reveals that the relationship is fairly linear, at least in the initial region, until a point is reached where the yielding begins. The slope of the stress–strain curve of an initially straight fiber at the origin is defined as initial modulus, as shown in Figure 2.3. However, the natural crimp in textile fibers will tend to change the initial part of the load–elongation curve. When a crimped fiber is subjected to axial tension, an extremely small load is registered until all the crimp present in the fiber is removed [20–22], as shown in Fig. 2.4. To calculate the initial modulus in such a case, the origin of the curve is shifted to a point O, where the fiber is assumed to be straight. The point O, an artificial origin, is located by extrapolating the initial slope of the curve. The slope of the initial part of the curve (before the straight line) determines the crimp rigidity of the fiber.

The initial modulus is a measure of initial resistance to deformation of the fiber. A fiber having higher initial modulus will have a low initial extensibility and vice versa.

Breaking Energy. The energy required to break the fiber is known as breaking energy or work of rupture. It is also called ''toughness''. It can be calculated by estimating the area under the load–elongation curve of a fiber, as shown in Fig. 2.3. However, the variability of length, linear density, and strength of individual fiber makes it difficult to compare work of rupture of different materials. Therefore, a more commonly used quantity, namely, specific work of rupture, is used, which is given by

$$\text{specific work of rupture} = \frac{\text{work of rupture}}{\text{linear density} \times \text{initial length}}$$

Elasticity and Recovery. The elasticity is the measure of the property of a fiber by which it tends to recover its original length after deformation when the applied axial tension is completely removed. The initial part of the stress–strain curve, as shown in Fig. 2.5, is linear (on OA), indicating that the strain is proportional to applied stress. A is a yield point beyond which this proportionality of stress–strain does not exist and the fiber stress–strain behavior follows a plastic deformation. If a fiber is allowed to recover from the deformation by removing the applied load before the yield point, the fiber gradually snaps back to its original dimensions. The deformation is completely reversible and it is termed as elastic deformation. When the fiber is allowed to recover from point B, which is well beyond the yield point but before the fiber breaks, the recovery follows the line BC. OC is the nonrecoverable

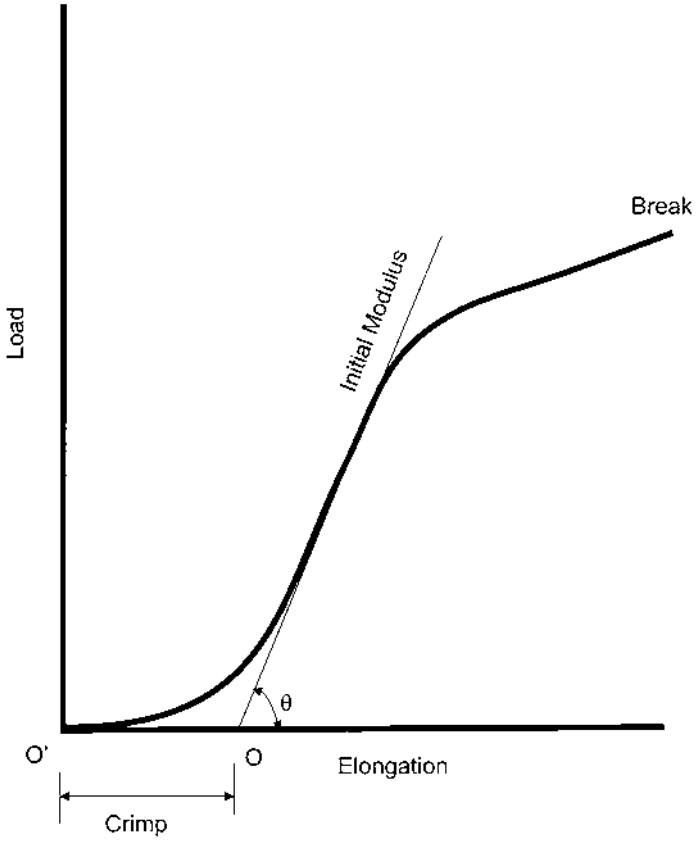


Fig. 2.4 Load–extension curve of a crimped fiber. (From Ref. 22.)

deformation known as plastic extension, and CD is the recovered deformation known as elastic extension.

The study of fiber elasticity and recovery under applied stresses has great technical importance because the knowledge of the extent to which a fiber is permanently deformed is essential for subsequent processing and for designing fabrics for special end uses to attain the desired properties. The perfect elasticity as discussed in the previous paragraph is a special case of the general hysteresis effect, as shown in Figure 2.6, commonly observed in viscoelastic materials, which form the basis of most textile fibers [23]. Such

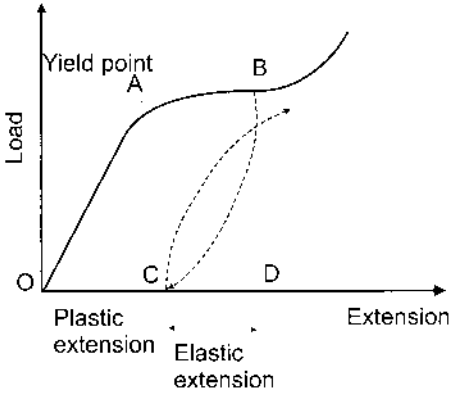


Fig. 2.5 Elastic and plastic recovery. (From Refs. 5 and 23.)

materials are considered to be completely elastic but not perfectly elastic. Besides the hysteresis effect, the tensile properties of textile fibers also exhibit time dependence. The time effect on extension under an applied load is known as creep, and the time effect on stress under constant extension is known as stress relaxation. This is shown in Figs. 2.7 and 2.8. For detailed information on the time dependence and viscoelasticity of textile fibers, readers are referred to various research publications [24–26] and standard texts [5,27,28].

General Properties

In addition to the dimensional, physical, and mechanical properties of fiber discussed in the foregoing sections, several other general fiber properties are

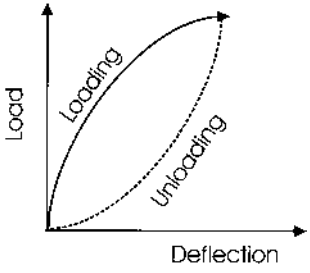


Fig. 2.6 Hysteresis effect. (From Refs. 5 and 23.)

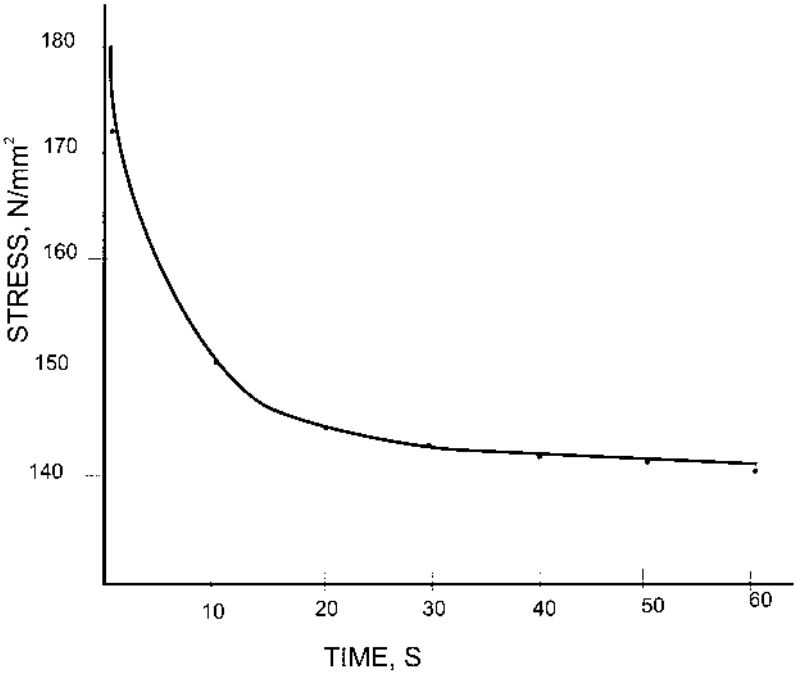


Fig. 2.7 Stress relaxation in viscose rayon. (From Refs. 26 and 27.)

of significant importance. A list of all the important general properties discussed in the following sections is presented in Table 2.3.

Friction. The frictional properties of textile fibers are of great technical importance. It is by virtue of the interfiber frictional forces that the fibers are held together in a spun yarn and the fibers or yarns, when interwoven into a fabric, maintain their position in the interlaced form and prevent fabric distortion. The fibers having very low frictional coefficients lead to poor yarn strength due to the easy slippage of such fibers. The high frictional coefficient of fibers hinders processing and when they are spun into a yarn becomes a hindrance during further processing, such as when the yarn passes over a guide at high speed. The coefficient of friction of the same yarn increases with an increase in yarn winding speed [29].

Moisture. The ability of fibers to absorb moisture from the atmosphere is usually expressed in terms of either the moisture regain (R) or the moisture content (M), expressed as follows:

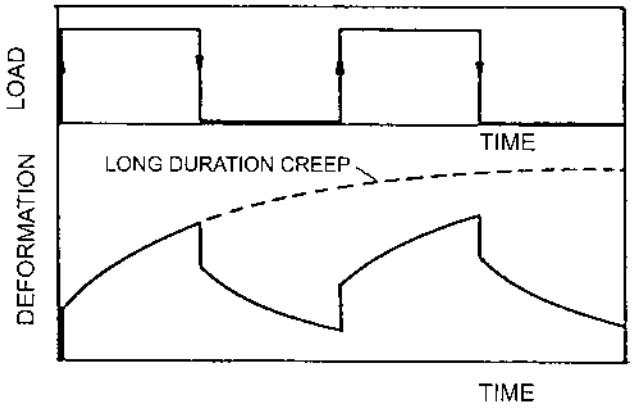


Fig. 2.8 Creep behavior under cyclic loading and unloading. (From Ref. 5.)

$$R = \text{moisture regain (\%)} = \frac{\text{weight of water absorbed within specimen}}{\text{weight of oven dry specimen}} \times 100$$

$$M = \text{moisture content (\%)} = \frac{\text{weight of water absorbed within specimen}}{\text{weight of undried specimen}} \times 100$$

It can be shown that these two quantities are interrelated by the equation

$$M = \frac{R}{1 + \frac{R}{100}}$$

The moisture sorption characteristics of a textile fiber are an important feature for comfort and warmth retention behavior of clothing. The hygroscopic textile fibers keep the human skin dry and protect against sudden temperature changes at the skin [30]. Moisture absorption causes swelling of fibers [31,32], which eventually changes size, shape, bending stiffness, strength, elasticity, and permeability of yarns and fabrics [33].

Thermal Properties. The thermal properties of textile fibers are of great practical importance because they determine the usefulness of fibers in view of the end-use application in the textile field. The maximal processing temperature that the fibers can withstand without deterioration, decomposition, and softening often dictates the end-use application. Heating of fibers at elevated temperatures causes a weakening of the fiber structure due to molecular changes.

The thermal response and the characteristics of different fibers are diverse. For example, when subjected to heat, wool begins to decompose without melting; polypropylene and regenerated acetate soften and subsequently melt before decomposition; and cotton becomes yellowish brown and subsequently diffuses before decomposition. Many of the newer synthetic fibers are thermoplastic in nature and soften when heated and eventually melt. The decomposition characteristics of textile fibers are important in view of their flammability behavior. Natural fibers, such as cotton, wool, and linen, do not cause severe burn injuries since they do not soften and melt at high temperatures. The softening and melting tendency of some synthetic and regenerated acetate fibers may cause severe burn injuries if they stick to the skin.

Like other engineering materials, textile fibers also show reversible changes in dimensions with temperature. Synthetic fibers have a thermal memory. When subjected to tension at high temperatures and allowed to cool down in a deformed state, some synthetic fibers have a tendency to ''set'' in this new form [34]. This attribute of the thermoplastic synthetic textile fibers, for example, nylon and polyester, has been advantageously exploited in the process of texturizing to impart bulk and handle. The application of heat causes certain changes in the physical and mechanical properties of textile fibers. Some synthetic fibers show an irreversible contraction on heating. For example, for nylon the shrinkage in boiling water is usually about 10%, and more rapid shrinkage occurs as the melting point is approached [35].

Resistance to Sunlight. Almost all textile fibers are affected by prolonged exposure to sunlight, which contains ultraviolet and infrared radiation. The rate of loss in tensile strength and changes in color due to exposure to sunlight determine the serviceability of textile fibers and fabrics. Some fibers have a reasonably good light fastness, and therefore they are used in certain special applications such as drapes, furnishings, awnings, transport fabrics, and other structural uses.

The degree of loss in tensile strength and visual deterioration depends on the type of fiber, fiber fineness, and the extent to which the fibers are protected by the neighboring fibers; presence of dyes, finishes, and chemical agents; and on the intensity of radiation [5]. Table 2.6 shows the effect of sunlight on the mechanical properties of some textile fibers [35].

Electrical Properties. The electrical properties of textile fibers are important when they are used for insulation purposes in electrical components. The generation of static electric charges during processing and in use of most of the synthetic fibers has led to many investigations of the electrical properties of textile fibers [36–38]. The static electricity is produced by the friction

Table 2.6 Relative Loss in Strength Due to Exposure to Sunlight

Exposed behind glass		Exposed outdoors
Bright Orlon		Bright Orlon
Semidull Orlon		Semidull Orlon
Bright Dacron		Bright acetate, bright Dacron, bright nylon, type 680 dull nylon, bright rayon, cotton
Semidull Dacron		
Bright acetate, bright nylon, type 680 dull nylon, bright rayon, cotton		Semidull Dacron
Silk and most other semidull fibers		Silk and most other semidull fibers
Most dull fibers excluding dull Dacron or those with a light-degradation inhibitor, such as type 680 nylon		Most dull fibers excluding dull Dacron or those with a light-degradation inhibitor, such as type 680 nylon

Decreasing Resistance

Source: Ref. 5.

between the yarns or fabrics and the surfaces of the processing equipment, which may lead to serious difficulties by entangling or misaligning yarns.

The production of static charge is affected by the moisture content in the fibers. Figure 2.9 shows the drop in static charges with the increase in moisture regain of various fibers as reported by Keggin et al. [39]. When the fibers are relatively dry the charges in all fibers are high and nearly constant; however, the charge drops rapidly at increasing moisture regain. From the points corresponding to 65% relative humidity marked on the graph in Fig. 2.9 it appears that the static charge generation under the same atmospheric conditions vary from one fiber to another. The processing difficulty encountered will therefore depend upon the fiber type.

The electrical conductivity—resistance to electrical current—property of fibers is of less technical importance for fibers in normal textile applications, such as apparel and furnishings.

Resistance to Microorganisms. Natural cellulosic fibers, such as cotton are susceptible to attack by microorganisms such as certain molds and bacteria. Such microorganisms cause the decomposition of the cellulose fibers, leading to a degraded product. Cotton fiber is susceptible to attack by bacteria and microorganisms when stored in warm and damp conditions. Synthetic fibers are resistant to attack by bacteria and mildew.

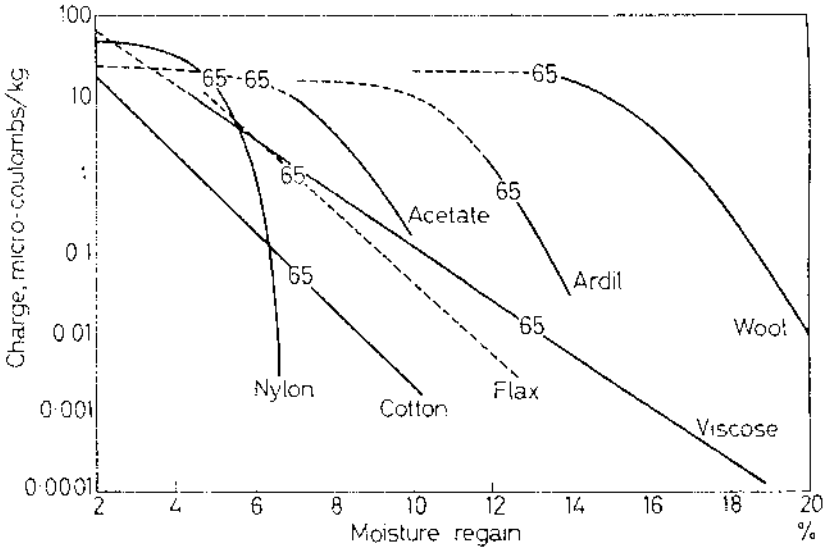


Fig. 2.9 Relationship between static charges and moisture regain. (From Ref. 39.)

Resistance to Chemicals, Acids, Alkalies, and Organic Solvents. The processing and use of textile materials usually involves a variety of chemical materials. For example, peroxide-based bleaching agents, dyestuffs, and other dyeing auxiliaries; detergents for washing; alkaline scouring agents; and finishing chemicals. The fibers, therefore, need to be resistant to a variety of chemicals without decomposition and deterioration. Most textile fibers are affected by very strong acids and alkalies; however, many are resistant to moderate concentrations of a variety of chemicals used in processing. During dry cleaning of garments, some organic solvents, such as carbon tetrachloride and trichloroethylene, are used; most natural fibers are insoluble in such organic solvents, but some synthetic fibers do suffer some damage.

2.2.3 Natural Fibers

Out of a large number of natural fibers of animal, vegetable, and mineral origins, the most important ones used for apparel and similar end-use applications are cotton, flax, wool, and silk. These fibers have certain natural attri-

butes, such as comfort, strength, flexibility, crimp, etc., which make them excellent raw materials in many textile applications. Other natural fibers, such as jute, hemp, ramie, sisal, and kapok, are used for certain special applications. Except silk, which is continuous, all other natural fibers are staple fibers. The staple fibers are usually divided into two categories, namely, short and long staple. The staple fibers shorter than about 50 mm (2 in.) are described as short staple and those over 50 mm are designated long staple. For example, cotton is a short staple fiber (12.5–38 mm long) since the staple length rarely exceeds 38 mm (1.5 in.), whereas wool is generally referred to as a long staple fiber as its length varies from 50 to 175 mm (2 to 7 in.). In case of jute, flax, and bast fibers, the ultimate length is of the order of 2.5 mm (0.1 in.); however, they are processed and used in the strand form varying in length from 25–46 cm (10–18 in.).

Cotton

Cotton is a natural fiber of vegetable origin which grows on the seed of a plant belonging to the *Gossypium* family. The cotton fibers are formed on the plant itself as long thin hairs attached to the seeds inside the boll. As the plant grows, the cotton fiber matures and eventually the boll opens up and the cotton appears as a soft fluffy wad of fine fibers, as shown in Fig. 2.10. The cotton boll itself is a fruit, which is formed when the flowers wither and drop from the cotton plant. The full length of a cotton fiber, about two to three thousand times its diameter, is developed inside the boll. During the initial period the cotton fibers grow into a thin-walled hollow tube of cellulose with one end attached to the seed and the other end closed. The fiber at this stage is filled with protoplasm and liquid nutrients drawn from the plant. Once its lengthwise growth ceases the development of the internal structure begins. Figure 2.11 shows a schematic of the gross internal structure of a cotton fiber. The growth of this internal structure is attributed to the deposition of cellulose layers one after the other as a thin cellulose membrane from the inside of the cell. Each growth ring so deposited day by day during the development of the internal structure has two layers, one is compactly packed solid and the other is porous. Figure 2.12 shows a daily development of growth rings in a single fiber swollen and stained for clear visibility. The deposition of cellulose chains is in the form of spiral fibrils. A mature cotton fiber therefore consists of several thousands of fibrils of bundles of cellulose chains arranged in a spiral configuration. Until the cotton boll opens, the fibers remain in their tube-like shape with a circular cross section. The opening of the cotton boll occurs at the completion of the ripening process, when the fibers come in contact with air; consequently, they

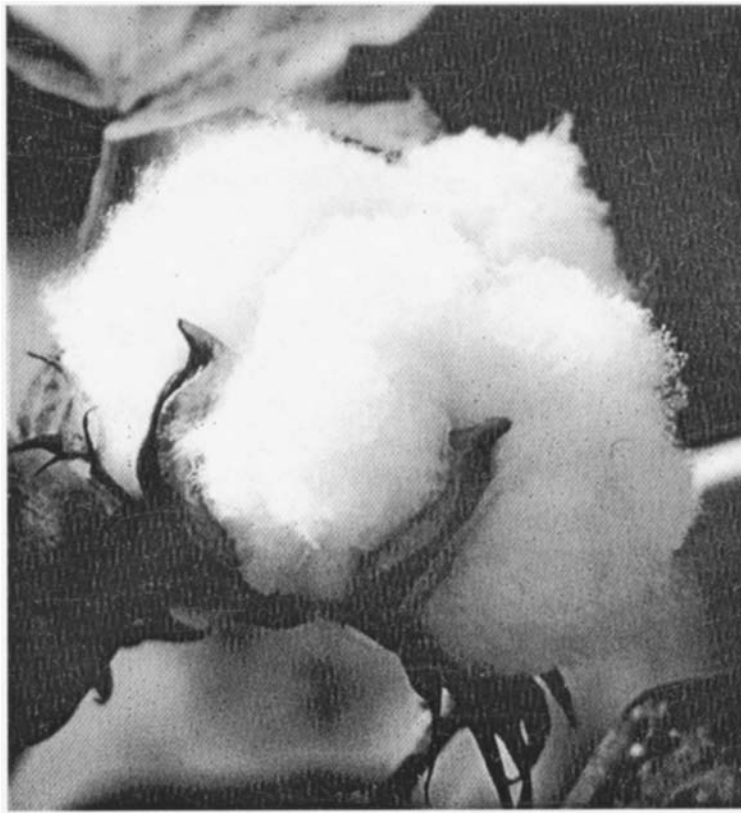


Fig. 2.10 The cotton boll.

lose moisture and the drying causes the collapse of the cell wall. The fiber collapses into a convoluted ribbon form and attains the kidney bean shaped cross section, as shown in Fig. 2.13.

The growth and basic characteristics of numerous varieties of cotton fibers grown all over the world vary inherently due to the genetics (cultivars), environmental conditions, and methods of cultivation. Fiber properties such as length, fineness, and maturity are affected by these factors. Therefore, cotton fibers grown in different parts of the world generally have different properties.

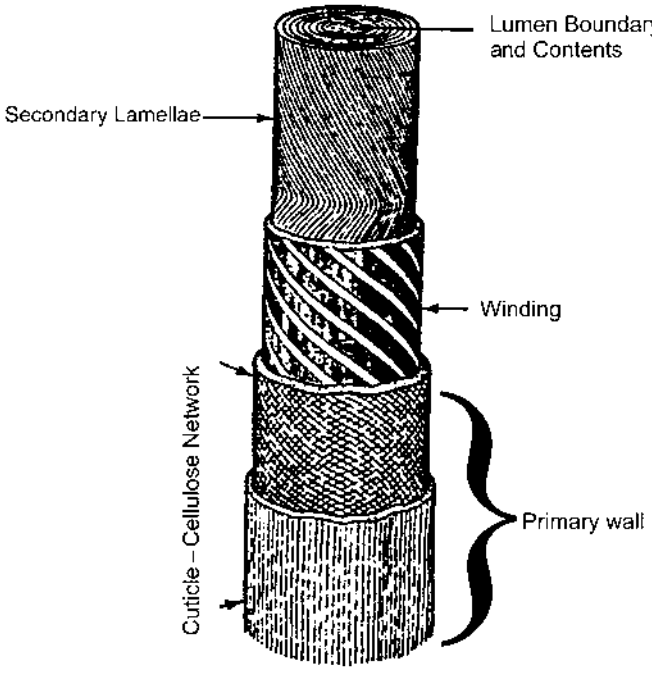


Fig. 2.11 Schematic diagram showing the gross internal structure of a cotton fiber. (From Ref. 57.)

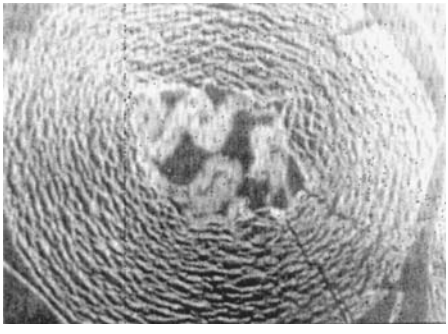


Fig. 2.12 Photomicrograph of a cross section of a single cotton fiber showing the development of growth rings. (From Ref. 40.)

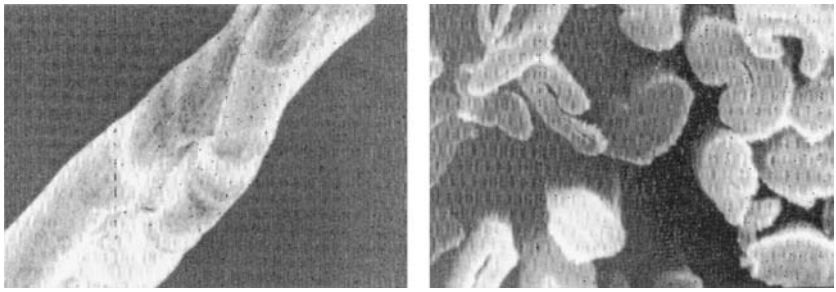


Fig. 2.13 Longitudinal and cross-sectional views of cotton fibers. (From Ref. 40.)

The proportions of short and immature fibers in a cotton variety are two of the many criteria used in determining its quality. Both these properties are important in view of the subsequent processing behavior of cotton fibers. The incidence of an excessive amount of short fibers indicates a poor growth in the early phase of development of the cotton fiber boll. Many fibers with thin walls (immature) indicate interrupted or retarded development of the cell wall during the second phase. The immature fibers, due to lack of cellulose deposition, exhibit poor dyeing affinity, lower strength, and higher flexibility than the mature fibers. Relatively easy bending of the immature fibers gives rise to nep formation. The measurement of the maturity of a cotton fiber is usually made in terms of the degree of cell wall thickening. The maturity ratio is a measure of the degree of development of the cell wall and is expressed as θ, the ratio of the actual cross-sectional area of the cell wall, A, to the area of the circle with the same perimeter, A' [43], as shown in Figure 2.1b.

$$\text{maturity ratio } (\theta) = \frac{A}{A'} \tag{2.1}$$

where

$$A' = \pi r^2 \tag{2.2}$$

By multiplying the Eq. (2.2) by 4π, we get

$$A' = \frac{4\pi^2 r^2}{4\pi} = \frac{p^2}{4\pi}$$

where p is the perimeter of the circle.

Therefore,

$$\theta = \frac{A}{A'} = \frac{4\pi A}{p^2}$$

The indirect measurement is the immaturity ratio, which is the reciprocal of the maturity ratio θ [44,45]. In spite of the large research effort that is being expended all over the world in improving cotton quality through better cultivation methods, many of the fibers in a cotton boll still remain in an immature state. The maturity count of most commercial cottons varies between 68 to 76%, and cottons with maturity counts below 67% are regarded as immature [4] and are not fit for spinning.

Like maturity and fineness, it is inevitable that not all cotton fibers in a boll achieve the same length. The inherent length variation of cotton fibers has a significant technical importance both in judging its quality and its efficient performance during subsequent processing. The efficiency of spinning machines and the quality of yarn produced depend largely upon the judicious setting of the optimal spacing between rollers in roller drafting. These spacings are governed by the staple length of the fibers being processed. Staple length is defined as the most commonly occurring fiber length in a population. The early estimation of staple length was made by expert judgment of classers, graders, or spinners. The classers usually use the hand stapling technique. The fibers are straightened by hand doubling and drafting to prepare an approximately 12.5-mm-wide tuft of parallel fibers. This tuft is then laid on a flat black background, and the staple length is measured as the distance between the two well-defined edges of the tuft. The well-defined edges are determined by feeling the most rapid changes in the density of the tuft, which is obviously dependent on an individual classer's personal judgment. Because of the recourse to manual measurement, the exact statistical distribution of length estimation could not be made, and therefore staple length could not be distinctly defined. This manual method of estimating staple length, being partly subjective, was prone to variation.

The first noteworthy approach to quantitatively evaluate the staple length was carried out by Clegg [46], who outlined a Baer Sorter diagram, as shown in Figure 2.14, and defined a geometrically derived quantity termed *effective length*.

The effective length is the upper quartile of the fiber length distribution obtained by ignoring short fibers whose length is below half the effective length [47]. However, the elimination of short fibers for deriving the effective

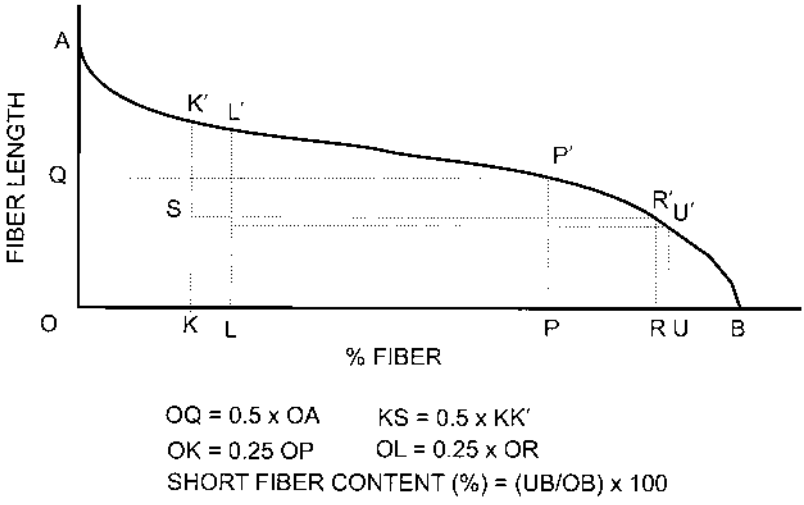


Fig. 2.14 Analysis of Baer Sorter diagram. (From Ref. 11.)

length is a reasonable practice since classers also tend to ignore them while estimating staple length manually. Lord and Underwood [47] have reported that a simple relationship can be established between effective length and staple length for American upland cottons of 19 to 32 mm (0.75 to 1.25 in.) lengths. This is given by

$$\text{American staple} = 0.91 \times \text{effective length}.$$

However, they reported that for Egyptian cottons the effective length corresponds reasonably close to the classer's estimate of the staple length.

The theoretical analysis of fiber length distribution in terms of frequency, survivor, and beard diagrams is reported by Morton and Hearle [5]. Eventually several methods were developed for the reliable estimation of fiber length [48–52], described fully in standard texts [5,6,11]. The photoelectric scanning principle as used in the Fibrograph instrument is most distinctive [52]. In Fibrograph, fiber samples are presented in the form of a pair of carefully prepared fringes. The light transmitted through these fringes is monitored by photoelectric current. The amount of light passing through the fiber sample is linearly proportional to the number of fibers in the light path. The changes in the photoelectric current are recorded graphically in the form of a Fibrogram,

as shown in Fig. 2.15. From this Fibrogram various length parameters of practical interest, such as mean length (*OM*), upper-half mean length (*OR*), and index of uniformity, given as the ratio of *OM* to *OR*, can be analyzed.

Flax

This fiber grows on the stem of an annual plant belonging to the *Linum usitatissimum* species. After the desired maturity is attained, the entire plant is pulled out with roots and subjected to the retting process for the extraction of the fibers. Retting is a fermentation process which separates the flax fibers held together in the stems by the woody matter and cellular tissues. Subsequent to the retting process, the fibers are subjected to breaking and scutching, where the woody matter is removed. The flax strand is extracted in the form of a bundle of individual fibers that stick together. Following scutching, the strands are subjected to a hacking process, where the larger strands are separated into finer bundles of fibers. The long fine fibers and short fibers, called *line* and *tow*, respectively, are combed or carded for the further alignment and parallelization of the fibers.

Commercial flax, sold in strands consisting of many individual fiber cells, is usually yellowish white, having average fiber lengths of about 6 to 64 mm (0.25 to 2.5 in.) with a mean diameter of 0.02 mm. The color of the raw fiber varies depending on the retting conditions. The flax fiber is long, transparent, cylindrical, and generally smooth but sometimes striated in appearance when viewed under the microscope, as shown in Fig. 2.16. The width of the fiber varies several times along its length, exhibiting characteristic nodes and cross-markings at many points. However, the fibers do not show convolutions like cotton fibers. The fiber cell has a narrow but clearly defined lumen or canal running through the center that disappears toward the end. The end of the fiber is tapered. The cross-sectional shape of a mature flax fiber is polygonal with well-built thick cell walls. The immature flax fiber has thinner cell walls, longer lumen, and oval cross-sectional shape.

The average breaking strength of a flax fiber is approximately 57 cN/tex, and the breaking elongation is only 1.8% for dry fibers and 2.2% for wet fibers. The wet strength of a flax fiber is roughly 20% more than the dry strength, and the moisture regain is around 12% at a relative humidity of 65%.

Originally, flax was used for sail cloth and tent canvas, sewing threads, fishing lines, table cloths, and sheets, while today linen is used for fine cloths and garments. In recent years, it has also been used in blends with cotton, silk, and polyester fibers for clothing. Owing to its high heat conductivity, the garments feel cool and comfortable in warm weather.

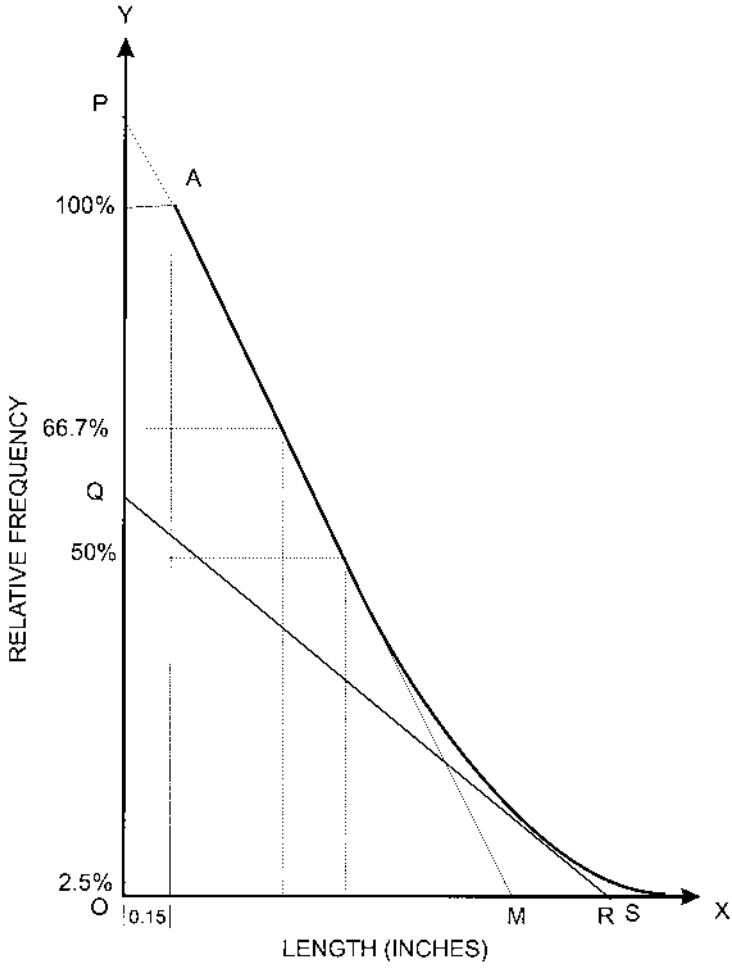


Fig. 2.15 Fibrogram. (From Refs. 5 and 11.)

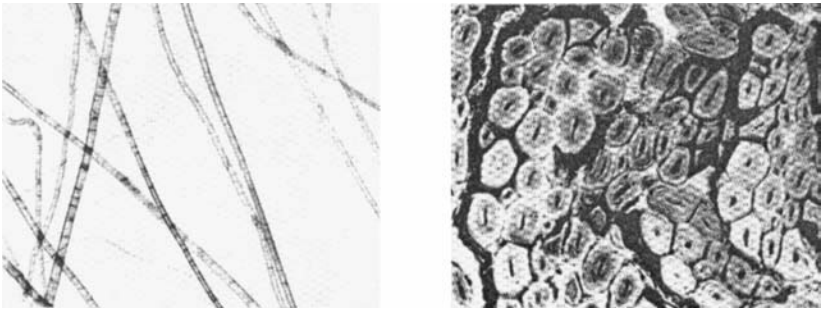


Fig. 2.16 Longitudinal and cross-sectional views of flax fibers. (From Ref. 41.)

Hemp

Hemp is an annual herbaceous plant of the species *Cannabis sativa*. It is also called industrial hemp if it has a δ-9-tetrahydrocannabinol (THC) level below 0.3%, being legalized for cultivation in many countries, such as the United States, Canada, Germany, France, Switzerland, and China. Hemp has traditionally been grown for its valuable and versatile high quality (primary bast) fibers. The production of these fibers has traditionally been a very labor intensive process. After harvesting, the hemp stalks are dew retted, or soaked with water with or without microorganisms to initiate a process of retting. Aerobic and anaerobic bacteria and fungi break down the pectins so that the fiber bundles are released from the epidermis and cortex. After the retting process, the plants are dried, and then the fibers are separated from the hurds and cleaned by breaking, scutching, and shaking processes. Recently, alternative fiber separation processes have been developed, using technologies such as ultrasound and steam explosion, which are much less labor intensive. The process of separating fibers from the hurds is often done with one piece of equipment, called a decorticator, consisting of crushing rollers and pin rotors. Following decortication or breaking and scutching, the long strands of hemp are hackled or combed. Once separated, the bast fibers are ready for spinning and weaving into textiles or for pulping into high quality pulp. Because of their high tensile strength, bast fibers are ideal for such specialized paper products as tea bags, industrial filters, currency paper, or cigarette paper [53,54].

Hemp fibers are generally slightly coarser than flax. The color of the raw fiber varies depending upon the retting method and conditions. When

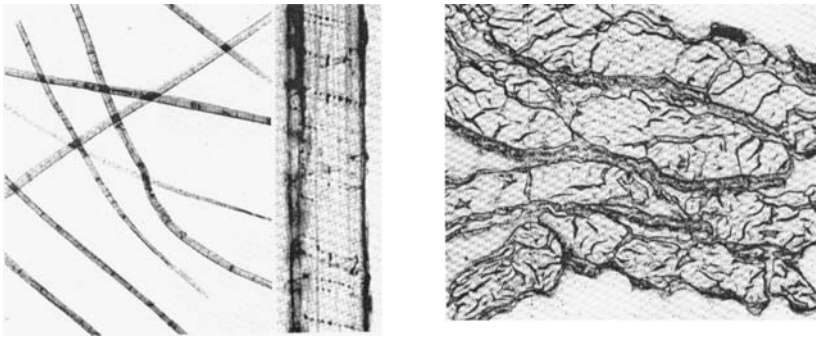


Fig. 2.17 Longitudinal and cross-sectional views of hemp fibers. (From Ref. 41.)

hemp fibers are viewed under the microscope, as shown in Fig. 2.17, cells exhibit a somewhat uneven width and also show many fissures and cross-markings. The lumen is usually indistinct and irregular. The fiber cells are more rounded than those in flax.

Commercial hemp fibers are slightly brownish with average fiber lengths of about 15 to 75 mm (0.75 to 3 in.) with a mean diameter of about 35 μm. The strength of hemp fibers, 57 cN/tex, is almost similar to that of flax fibers, with breaking elongation of about 2% for the dry fibers. Table 2.7 shows the comparative properties of hemp, flax, and cotton fibers [55].

Jute

Jute is extracted from the inner bark of herbaceous annual plants of the *Corchorus* family. This plant grows well in tropical and damp climates. Most of the

Table 2.7 Comparison of the Properties of Bast Fibers with Those of Cotton

Property	Hemp	Cotton	Flax
Fiber fineness (denier)	3–20	1–3	2–16
Moisture absorption (%)	8	8	7
Strength (cN/tex)	44–53	26–53	44–53
Extension at break (%)	2–3	3–7	~3

Source: Ref. 55.

world crop comes from India, Bangladesh, and Thailand. After harvesting, the fibers are separated from the stem by a retting process similar to that used for the extraction of flax.

Commercial jute, sold in bundles of individual fibers, usually varies in color from yellow to brown to dirty gray. It has a natural silklike luster, but has coarse and rough feel; however, best quality jute fibers are soft and smooth. The commercial grading of the quality of jute fiber is based on its color and strand length. The strand length varies from approximately 1.5 to 3.6 m (5 to 12 ft). Jute fiber is cylindrical and smooth but exhibits nodes and cross-markings along its length when viewed under the microscope, as shown in Fig. 2.18. The single cells of jute fiber are on average about 2.6 mm long and 0.12 mm in diameter. The cross-sectional shape of this cell is polygonal with five or six sides. Mature fibers have thick cell walls and a broad oval irregular lumen, unlike the regular lumen of flax. Toward the tapered ends of the cell, the lumen widens and the cell walls become correspondingly thin.

The average tenacity of jute is low and variable compared to flax. Even in an individual fiber, the strength varies greatly due to the inherent irregularity in the thickness of cell walls. The breaking elongation is about 1.7%. Jute strand is highly hygroscopic and has a moisture regain of 13.75% at a relative humidity of 65%.

Jute is used in many industrial applications, e.g., storage, transportation, and packaging. The familiar products made out of jute are hessian cloth, cords and twines, sacks, bags, covering material for cotton bales, bundle cloth, wrapping, bedding foundations, and carpet backing.

Wool

The most important and widely used natural fiber of animal origin is wool. The term wool is usually restricted to the cover of sheep only. When the sheep

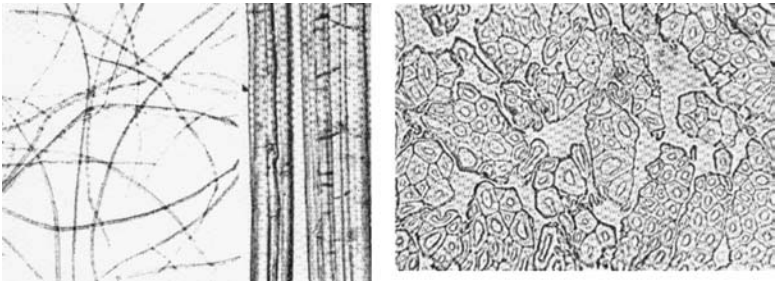
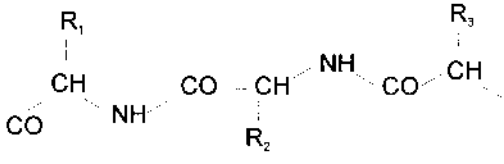


Fig. 2.18 Longitudinal and cross-sectional views of jute fibers. (From Ref. 41.)

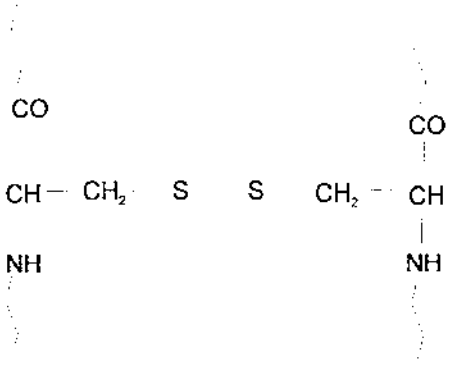
has two coats, the long coarse fibers forming the protective outer coat are called hair, and the short, fine and delicate fibers of the undercoat that keep the animal warm are called wool. Modern cross-bred sheep of different varieties are reared primarily for wool only, where the outer covering of the fleece is relatively small and often totally absent, such as in case of merino wool. The breeds that have a relatively high proportion of coarse hair are generally considered to be of poor breeding. Among many different breeds developed in different parts of the world, the merino sheep is the most important source of quality wool because the outer coating of coarse hair in this breed is virtually absent. The merino sheep produces fine, soft, and delicate wool. Australia, South Africa, and South America, are the main countries where large flocks of merino sheep are raised.

The fleece of wool—a fibrous covering of sheep—is removed in one piece, usually by electrically operated clippers. The shorn wool obtained by such a method is known as ''fleece'' or ''clipped wool''. After shearing, the wool is ''skirted'' to remove the soiled wool from the edges. The quality of wool fibers is graded on the basis of their color, length, fineness, and the presence of foreign matter. The quality of wool depends on the breed of the sheep and the environmental conditions under which the sheep were reared. An earlier practice of grading wool was to relate its fineness in terms of spinnability on the scale of the English worsted count system. For example, 60^s wool means the quality of wool is capable of being spun into a yarn of 60^s worsted count; in other words, 1 lb of wool would yield 60 hanks of 560 yards each. However, in recent years the grading of wool is increasingly being carried out on the basis of the objectively measured average fineness of the wool fibers. The length plays a secondary role in determining its quality.

Chemically, wool is a complex protein known as keratin. The keratin consists of a number of α-amino acids which are in turn linked through amino and carboxyl groups to form a polypeptide chain of the following form:



The polypeptide chains of the keratin molecules are cross-linked to the adjacent chains through cystine linkages of the covalent disulfide type:



However, the intermolecular cross-linking known as salt linkages formes between free acidic and basic side chains, e.g., between those of glutamic acid and lysine [56]. Some cross linking can also occur due to hydrogen bonding between the hydroxyl groups (OH).

The wool fiber is a circular cylinder that tapers from the root to the tip; it has a natural waviness in the form of a three-dimensional spirally twisted crimp. The gross internal structure of the wool fiber when observed under the microscope appears as four distinct regions, as shown in Fig. 2.19. These regions are

1. The epicuticle, or outer sheath
2. The scales–cell layer
3. The cortex
4. The medulla (often absent)

The outer sheath, or epicuticle, is a nonprotein thin water-repellent membrane acting as waterproof coating. However, this epicuticle has tiny microscopic pores through which water vapor permeates into the internal structure of the fiber. Thus, the water vapor from the perspiring human body is absorbed by this outer sheath into the interior of the wool fiber without a feeling of dampness. This absorbed water is eventually released slowly into the air. Beneath the epicuticle is the cuticle, scalelike cells which overlap each other like the shingles on a roof. The free end of these cuticular scales is pointed toward the tip of the fiber. This upward pointing of the free ends of these cells imparts a special frictional effect to wool fibers, particularly when they are rubbed in the direction opposite to the fiber tip, thus creating a differential frictional effect. The cortex—the core of the fiber—is enclosed within the cuticle and forms more than 90% of the total weight of the wool fiber. The cortex consists

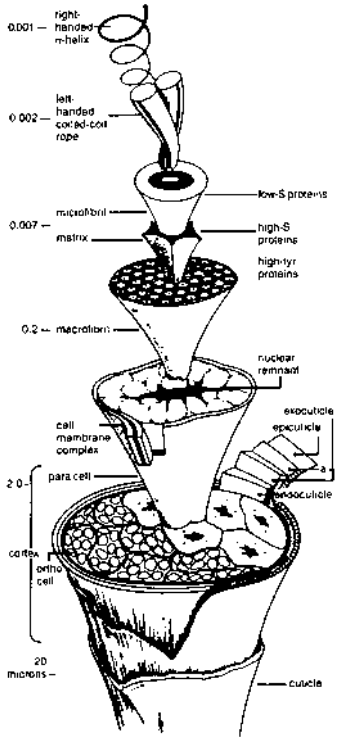


Fig. 2.19 Structure of wool fiber. (From Refs. 57 and 58.)

of millions of long spindle-shaped cortical cells thick in the center and tapering toward each end. However, recent studies of detailed examination of very thin transverse and longitudinal section reveal that the cortical cells may be regarded as space-filling polyhedra with unlimited sharing of faces and corners [57]. These cortical cells are built up of fibrous components known as fibrils. The cortex of a wool fiber is shown to have a bilateral structure; one side is called paracortex and the other orthocortex. The chemical structures of proteins in these two forms are different. The orthocortex cells are clearly differentiated into macrofibrils, which are large aggregates of the microfibrils. The paracortex cells are packed more compactly, and division into large macrofibrils is indistinct [58–60]. The dyeing affinities of para- and orthocortex are different due to their different chemical compositions; the paracortex being more stable

is less accessible to dyes than the orthocortex. This bilateral structure imparts to the fiber a crimped form that is in phase with the mutual twisting of the two components. Only coarse wool fibers have a hollow space in the center running along the length of the fiber, which is known as medulla. Fine wool fibers do not have a medulla.

The natural three-dimensional crimp of wool is unique among all natural fibers. The practical significance of this natural waviness can be understood from the fact that wool fibers when twisted hold together coherently, but the resulting yarns remain fluffy and bulky. The air entrapped in such bulky yarns helps in forming an insulating layer, thus imparting warmth to the human body. The unusual elasticity of wool fibers is attributed to this crimped configuration. The wool fiber acts as a spring when loaded under axial tension. It snaps back to wavy form when this axial tension is removed.

The length of wool fibers varies between 38 to 125 mm (1.5–5 in.) for fine wools, 65–150 mm (2.5–6 in.) for medium wools, and 125–375 mm (5–15 in.) for coarse wools. The natural luster of wool varies and largely depends on the type of wool and the surface of the fiber, which reflects light. The density of the wool fiber is 1.32 g/cm^3, which is slightly lower than that of cotton. The wool fibers have relatively lower tenacity but high extensibility, which are attributable to the chemical cross-linking of molecular chains of protein molecules. Wool fibers do not show very good recovery under very high stresses, particularly under humid conditions, but show reasonably large recovery from high strains. This high resiliency of the wool fibers and their characteristic of elastic deformations under small stresses make them highly desirable for apparel fabrics.

The moisture regain of wool fibers under standard atmospheric conditions (65% RH) is approximately 16%. The moisture sorption characteristic of wool fibers has a particular practical importance; the warmth retention properties of wool garments improve as they absorb moisture from the air. This moisture sorption property makes wool fibers partly flame retardant also. Wool decomposes completely when treated with hot concentrated sulfuric acid; however, it is, in general, resistant to other mineral acids of all strengths. Nitric acid at elevated temperatures tends to damage wool fibers due to oxidation. However, dilute sulfuric acid does not affect wool. The wool fiber is very sensitive to alkalis; it completely dissolves in caustic soda solution. The wool fibers are very easily attacked by moths (grubs), but they are fairly resistant to mildew and bacteria.

Mohair

Although wool is the most widely used natural fiber from animal origin, other animal fibers, such as mohair and cashmere, have carved out their own market

share in niche products. Mohair is considered a relatively luxury fiber compared to wool. The long, relatively finer, straight, smooth, and lustrous fiber in the single coat of the Angora goat is called mohair [61,62]. The Angora goat is a unique breed known to mankind in ancient times and is believed to have originated in the Asian Himalayan regions [62]. Good quality mohair is produced today in South Africa, Turkey, and the United States. South Africa accounts for a market share of about 60% of the world production of mohair [62].

Chemically, mohair also contains the same complex protein called keratin as that in wool, as shown in Fig. 2.20. The mohair fiber consists predominantly of orthocortex and an epidermis of many overlapping scales. Sometimes it also exhibits a medulla. The protective outer cover of cuticle cells covers the cortex. The cuticle consists of three layers, namely, epicuticle, exocuticle, and endocuticle, as shown in Fig. 2.20. Each cuticle cell is covered by a thin semipermeable membrane, the epicuticle, comprised of protein and lipid [63]. For further details, the reader is referred to excellent reviews by Hunter [63] and other researchers [64–66].

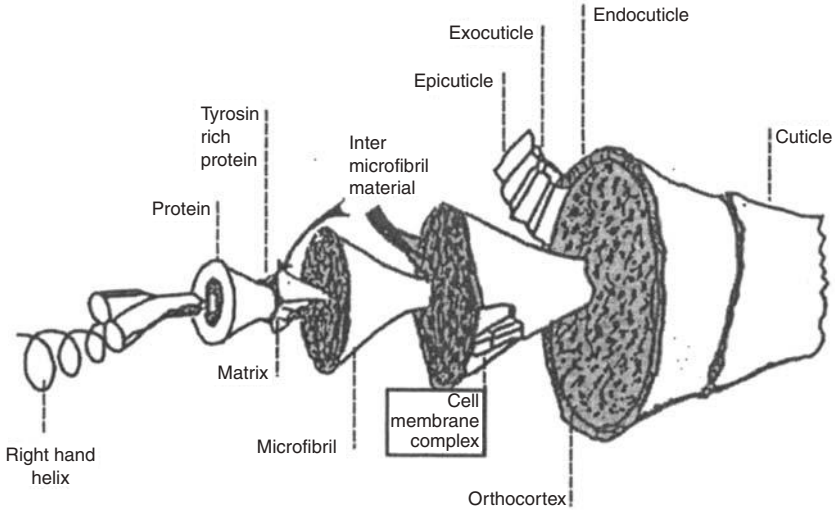


Fig. 2.20 Structure of mohair fiber. (From Refs. 62 and 63.)

Mohair appears circular in cross section, with small spots caused by entrapped air bubbles, as shown in Fig. 2.21. The longitudinal structure exhibits scales at high magnification, as shown in Fig. 2.22. Due to its thinner scale structure compared to wool, mohair exhibits better luster, smoothness, and lower friction and felting properties. The length and fineness of mohair fibers vary according to the age of the animal. An Angora kid of about six months would yield fibers from 100 to 150 mm in length with fineness of about 25 to 30 μm. Fully grown Angora goats would produce mohair fibers from 225 to 300 mm in length (12 months growth) with fineness of about 35 to 40 μm. Most physical properties of mohair are generally similar to those of wool. For a detailed account of the physical and chemical properties of the mohair fiber, readers are referred to the review by Hunter [63] and recent publication by Hunter and Hunter [62]. However, mohair has better abrasion resistance than wool, attributed to its thinner scale structure, which in turn results in better wear resistance. Therefore, mohair finds its best application in products, such as fabrics for upholstery, throws, and carpets, where durability is the most important consideration. Mohair is generally more expensive than wool, so it is also used for blending in small proportion with wool for producing cost-effective apparel fabrics with desirable characteristics.

Cashmere

The fine and long fiber obtained from the Cashmere goat is another luxury fiber of animal origin, principally produced in northern China, Mongolia,

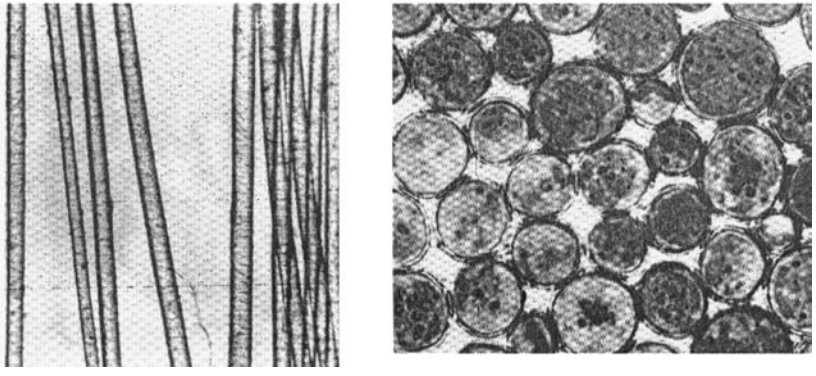


Fig. 2.21 Longitudinal and cross-sectional views of mohair fibers. (From Ref. 41.)

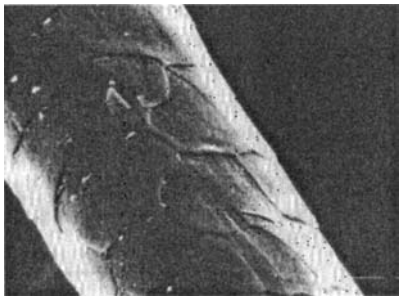


Fig. 2.22 Longitudinal view showing the scale structure of a mohair fiber. (From Ref. 62.)

Tibet, India, Australia, New Zealand, and more recently in South Africa [67]. The Cashmere goat is covered with an outer coat consisting of coarse and long hair of about 50 to 125 mm in length. The undercoat, which is also known as down, is very fine (12.5–19 μm) with an average length of 35 to 50 mm. The goat sheds the undercoat and also some outercoat of hair through the natural process of molting. During this molting period, the goat is combed, and the two types of fibers, namely, outercoat and undercoat (down), are separated. The approximate yield per animal is about 250 g. The fineness and length of the down make cashmere a valuable and luxury fiber that can be used to produce very soft, comfortable, and luxurious fabrics commanding very high premium in the market [67].

Chemically, cashmere is very similar to wool and mohair and is made up of a complex protein called keratin. The gross structural difference between cashmere and fine merino wool fibers is small and not clearly distinguishable. At a fine structure level, cashmere displays the predominance of orthocortical and mesocortical cells, whereas wool has a predominance of orthocortical and paracortical cells [68]. The dimension of the surface scales are much smaller ($\sim$ 1–4 μm) than the corresponding features on wool fiber.

Camel Hair

Camel hair of textile value is produced from the two-humped Bactrian camel mainly found in Mongolia and Northern China. The camel grows two types of fibers, outer protective hair which is coarse and long and an insulating fine undercoat of medium length. This undercoat yields soft, fine, and long

fibers of textile value used for producing blended fabrics, overcoats, dressing gowns, and knitwear. The hairs from the coarse outer coat are mainly used for ropes, tents, carpet backing, and heavier outer garments in the areas where these camels are reared. Unlike the shearing of wool, mohair, and cashmere, the harvesting of camel hair is a natural process. The camel molts when the fibers form matted tufts that hang down from the camel head, sides, neck, and legs. These fibers are harvested by pulling or by gathering the clumps [67]. Each animal yields about 2.5 to 5.0 kg of fiber per year.

The fineness of camel hair varies considerably depending upon the coat. The fiber diameters of outer coat vary from 30 to 120 μm, whereas the dehaired down fiber (undercoat) diameters range from 16 to 20 μm, and for the intermediate coat the diameters range from 20 to 29 μm. Figure 2.23 shows cross-sectional and longitudinal views of camelhairs. Fiber length of the down fiber varies from 36 to 40 mm and outer guard coat from 300 to 450 mm [67].

Alpaca, Llama, Vicuna, and Other Fibers

Other natural fibers of animal origin worth mentioning are obtained from alpaca, llama, and vicuna. These animals are mainly found in the mountains of South American countries, such as Peru, Bolivia, Ecuador, Chile, and Ar-

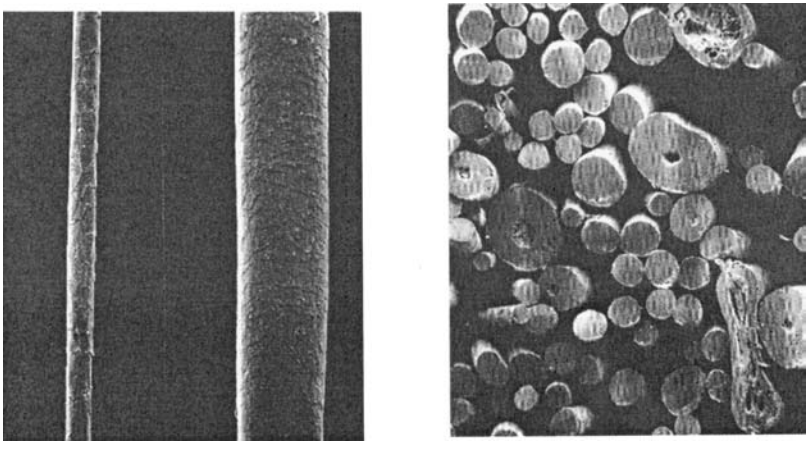


Fig. 2.23 Longitudinal and cross-sectional views of camel hair. (From Ref. 67.)

gentina. Alpaca and llama are also raised in the United States, Canada, New Zealand, and the UK in small population.

Alpaca has a complete fleece of fibers similar to the Angora goat and sheep. There is no undercoat and outercoat in alpaca. Alpaca fiber is soft, lustrous, fine, and durable. The fiber diameter varies from 20 to 36 μm, and the fiber length varies depending upon the type of alpaca. In general, after shearing, the lengths are from 25 to 30 cm for baby alpaca to 50 cm for adult animals [67]. The llama is somewhat similar to alpaca but is larger. The hair growth is normally between 70 to 100 mm per year and the animal yields about 2 to 5 kg of fleece fiber. These animals are normally shorn every alternate year. The fiber length varies from 80 to 250 mm, and fiber diameters range from 19 to 38 μm.

Vicuna is native to Peru and Bolivia and belongs to llama family. It is a much smaller animal than alpaca. The vicuna yields only about 85 to 550 g of hair with an average of about 200 g per animal. The fine hair of textile value comes from the area just behind the front legs of the animal. The diameters of vicuna fibers range from 12 to 15 μm with an average of about 13 μm, and fiber length is about 20–25 mm. The fibers are tawny brown in color and produce very fine and durable fabrics. The vicuna fibers are usually woolen spun, but they are also blended with wool for worsted spinning. The fabrics are woven for suits, jackets, overcoats, and scarves [67]. Figure 2.24 shows longitudinal and cross-sectional views of alpaca, llama and vicuna fibers.

Silk

Silk is another natural fiber of animal origin widely used for apparel purposes. It is produced by silkworms in the form of a fine continuous filament up to 1–1.5 km long. The silkworm wraps this filament around itself to form a protective covering or cocoon before changing into a chrysalis and eventually into a moth. The silkworm usually produces twin filaments positioned side by side and held together with a natural gum known as sericin. The most important silkworms of commercial importance are *Bombyx mori*, living on the leaves of the mulberry tree. Other wild varieties of silkworms are Eri, Tusa, and Muga, living on the castor plant. The main silk producing regions are China, India, the Far East, and other Mediterranean countries.

The cocoons are soaked in hot water to soften the sericin gum around them. In turn the filaments from several such softened cocoons are thrown (i.e., twisted) and reeled in the form of skeins. The natural gum, sericin, is usually transferred onto the filament during this reeling process. It acts as a sizing material and prevents the yarn from mechanical damage during weaving.

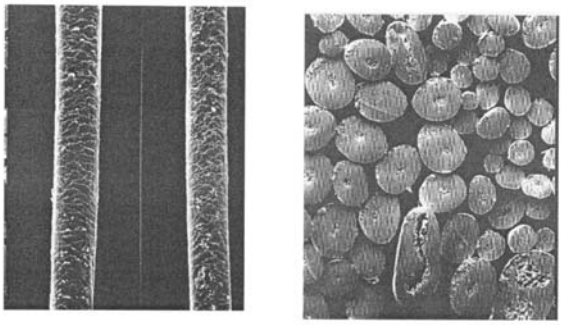


Fig. 2.24 Longitudinal and cross-sectional views of (a) alpaca, (b) llama, and (c) vicuna fibers. (From Ref. 67.)

Therefore, silk fabric woven with sericin gum on it has a rough handle and harsh feel. The process of degumming may be carried out on yarns or fabrics by boiling with soap and water. There are some silk cocoons that cannot be extracted in the form of continuous filament yarn during the process of throwsting; such cocoons are used to produce waste silk which is then used in staple form.

Under the microscope, raw silk filaments show irregular surface racks and folds that are a result of the twin fine filaments cemented together by sericin gum. The cross section of silk filaments, as shown in Fig. 2.25, is irregular and oval in shape, which imparts silk its characteristic ''scroop.'' Traditionally, silk has very fine luster and is used in luxury and expensive apparel. Silk possesses high strength, smoothness, and flexibility with good moisture characteristics. The warmth retention capacity together with excellent wearability and luxurious appearance have allowed silk to withstand tough competition posed by artificial fibers such as polyester, viscose, and nylon.

2.2.4 Manmade Fibers

The ever-growing list of manmade fibers offers a variety of opportunities for the use of fibers in applications that have not been possible before. Manmade fibers offer certain physical and chemical properties which are generally not available in the traditional natural fibers. On the other hand, there are certain

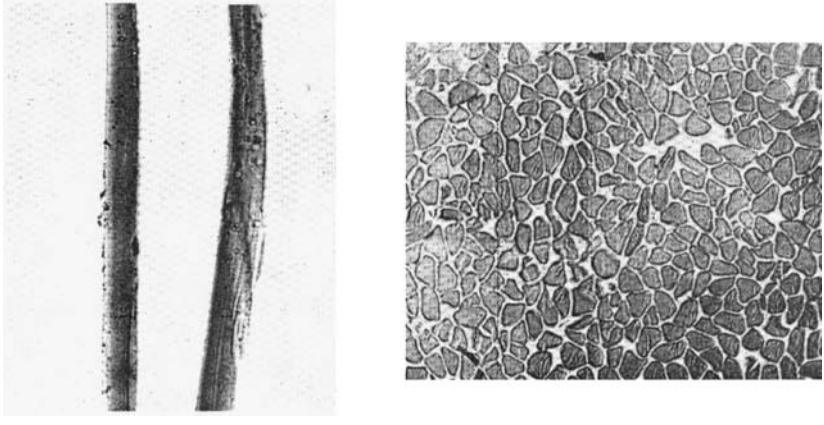


Fig. 2.25 Longitudinal and cross-sectional views of silk fibers. (From Ref. 41.)

other properties, such as thermoplasticity and unique surface characteristics, which require careful consideration when selecting sizing ingredients and slashing parameters.

Manmade fibers are usually described under two main headings:

1. Regenerated fibers
2. Synthetic fibers

Regenerated Fibers

In the production of regenerated fibers the fiber-forming polymers are derived from natural sources. These sources may be, for example, naturally available cellulose from cotton linters or wood; protein such as casein (from milk), zein (from maize), and arachin (from ground nut); and alginic acid, which is extracted from seaweed, etc. The polymer is usually dissolved in some chemical solvent, and the solution is then forced through a spinneret to form a tow of fine continuous filaments, which may in turn be chopped to produce staple fibers.

Regenerated Cellulosic Fibers

The regenerated cellulosic fibers from natural origin include viscose, cuprammonium, and acetate rayons which together account for about 7.5% of the world production of manmade fibers [4,8].

Viscose Rayon. Viscose rayon is a regenerated cellulosic fiber. The cellulose comes from cotton linters or wood pulp. The cellulose from wood, straw, cotton linters, and similar sources usually contains gummy material known as lignin. Therefore, the first step in the production of viscose rayon involves the purification treatment of wood pulp with caustic soda, which converts it into alkali cellulose. After aging, the alkali cellulose is treated with carbon disulfide to form sodium cellulose xanthate and then dissolved in a solution of caustic soda. It is then allowed to ripen for several days at a controlled temperature. During the process of ripening, the solution is filtered repeatedly. The viscosity of this solution decreases initially and then increases nearly to its original viscosity; the solution is then spun into an acidic coagulating bath. The coagulating bath contains a predetermined mixture of sulfuric acid, sodium sulfite, zinc sulfate, and glucose, which precipitates the cellulose in the form of a solidified viscose filament. The filament is then drawn and wound on packages. Depending on the ways in which the filaments are treated after they emerge from the coagulating bath, the process is termed either pot or box spinning, bobbin spinning, or continuous spinning. The pot and bobbin

spinning processes are intermittent in nature since batches of spun filament are subjected to further treatment as and when they are available. Such batch processes are inevitably expensive in terms of labor and operating costs. Moreover, the discontinuous operation is susceptible to quality variations between batches. Therefore, modern-manufacturers have adopted the continuous spinning technique for production. The spun continuous filaments can either be twisted to form continuous filament yarns or may be mechanically converted into staple fiber of the desired length for blending with other fibers to spin staple yarns.

The cross-sectional modification of viscose rayon filament is achieved by extrusion of the viscose through orifices with cross-sectional shapes other than circular, for example, hollow, flat, lobed, dog bone, and trilobal. A flat cross section of the filament has better covering power; a trilobal cross section imparts a silklike luster to filaments; and the hollow fibers improve comfort properties because of the better moisture absorption. The longitudinal modification of rayon filaments is obtained by varying the diameter of the filaments continuously (between thick and thin places) at indeterminate variable intervals, which provides a special effect in the fabric when woven. Spun-dyed viscose rayon is produced by mixing finely dispersed pigments with the viscose dope before spinning. The pigmentation thus obtained in spun-dyed filaments is fast to light and washing. For dulling the natural luster of rayon filament, titanium dioxide is added to the dope before spinning. To enhance the spinning quality of manmade fibers on staple spinning machines, it is desirable to impart waviness or crimp. In viscose rayon, crimp is imparted mechanically by passing the filament between gearlike rollers or by chemical control of the coagulation of the filament to give nonsymmetrical cross sections. High-tenacity viscose rayon is produced by stretching during the extrusion process, when the individual filaments are in pseudoplastic state. This increases the degree of alignment and orientation of cellulose molecules along the fiber axis, resulting in increased strength and decreased extensibility. Ordinary viscose rayon is sensitive to the effect of moisture. The tenacity and initial modulus of wet rayon decrease by approximately 25%, and the filaments tend to stretch even under a small tensile stress. The resultant elastic recovery from such stretching is also very poor. To overcome this deterioration in the tensile properties of viscose rayon when wet, polynosic rayons having high wet modulus are produced. The polynosics have a degree of polymerization in the range of 500 in comparison to 300 for ordinary viscose rayon.

The chemical structure of rayon is similar to that of cotton as both are cellulosic. The filaments of regular viscose rayon appear smooth, straight, and unconvoluted, as shown in Fig. 2.26. The surface, however, has striations or

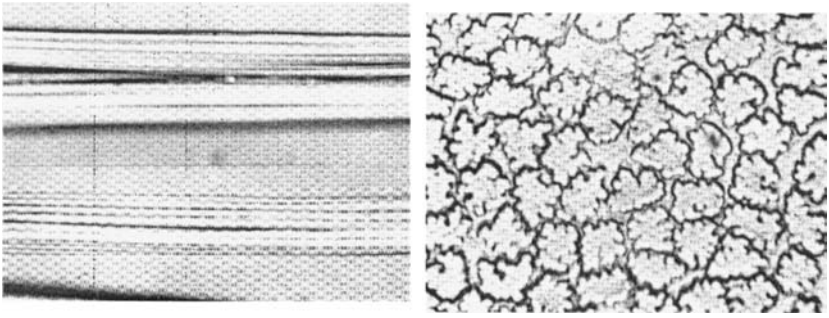


Fig. 2.26 Longitudinal and cross-sectional views of viscose rayon fibers. (From Ref. 41.)

longitudinal channels running along the length of the filaments. These channels or striations give a deeply serrated appearance to the cross section of viscose rayon, as shown in Fig. 2.26. Ordinary rayon has a dry tenacity of 17–23.0 cN/tex (2–2.6 g/den), compared to 35–46 cN/tex (4.0–5.2 g/den) for high tenacity and polynosics, respectively. Elongation to break is around 17 to 25% for dry and 23 to 32% when wet [4,5]. The moisture regain of viscose rayon is 13% under standard atmospheric conditions of 65% RH and 21°C.

The properties of viscose rayon lend themselves to blending with fibers such as cotton, wool, and other manmade fibers. A great variety of fabrics can be made from viscose rayon, which is available in a range of deniers in both continuous filament and staple forms. The most commonly used deniers are 1.5, 3, 4.5, 8, 12, 15, and 20; staple length varies from 32 to 200 mm (1.25 to 8 in.). The traditional uses of high tenacity rayons include tire cords, conveyor belt fabrics, automobile hoses, tarpaulins, and power belt applications. Polynosics, because of their high wet modulus, are desirable for use in blends with polyester fibers.

Cuprammonium Rayon. This is a regenerated cellulosic fiber produced from cellulose dissolved in a mixture of copper sulfate and ammonia, called cuprammonium liquor or ''cupro.'' This liquor is extruded from a spinneret to form filaments in the coagulating bath. The raw materials used are cotton linters and wood pulp. Purified cotton linters or wood pulp is mixed into the cuprammonium liquor at a low temperature, and it is then kneaded until it gives a clear blue solution. This solution is then deaerated and filtered through nickel gauze. This solution is stable even after long storage and does not

decompose, which is not the case when considering viscose solution. The deaerated and filtered solution is metered by a pump into a nickel spinneret and extruded into a stream of pure water to dissolve most of the ammonia and some copper. This action solidifies the cellulose into pseudoplastic filaments, which may be drawn to achieve the desired linear density. The drawn filaments are then passed around a roller running in a trough of sulfuric acid, which completes the process of coagulation of the cellulose and removes the remaining copper and ammonium sulfate from the yarn. In batch processes, such as reel or pot spinning, the filaments are wound either into skeins or cakes and subsequently washed to eliminate any traces of acid, copper, and ammonium sulfate, then softened by adding lubricants, and finally dried. In a continuous spinning process, the filaments are never handled during the intermittent process thus making regular, uniform, and good quality cupro filaments.

The cross section of cupro filaments is round, and the finest filament is usually 1.3 denier. The filaments have a silk like lustrous appearance. The dry tenacity of the filaments ranges between 15 and 20 cN/tex (1.7 and 2.3 g/den), and wet tenacity is roughly 9.7–11.9 cN/tex (1.1–1.35 g/den). Other physical properties are similar to those of ordinary viscose rayon. In comparison to viscose, cupro is more expensive because of its extra fineness, strength, attractive handle, subdued luster, and good drape characteristics. It is used to produce a variety of fine chiffons, satins, nets, etc. Fancy yarns such as slub, knot, etc., produced from cupro, are used in producing specialty effects in dresswear, sportswear, and fine drapery fabrics.

Acetate and Triacetate. Cotton linters and wood pulp are used as raw materials for producing acetate and triacetate regenerated cellulosic fibers. However, unlike in viscose and cupro rayons, the wood or cotton cellulose is chemically modified to a different substance—cellulose acetate—to make it spinnable, and after spinning the cellulose is left in its modified form as a fiber. The purified cotton linters or wood pulp is soaked in glacial acetic acid to make it more reactive so as to readily acetylate. The cellulosic fibers soaked with an excess of acetic acid and acetic anhydride are transferred to a closed reaction vessel fitted with a powerful stirrer. All the ingredients are thoroughly mixed together; however, no chemical reaction yet begins. A small quantity of sulfuric acid dissolved in roughly eight times its weight of glacial acetic acid is added to initiate the acetylation process. The acetylation reaction is highly exothermic in nature; the solution is maintained at a temperature below 20°C by cooling for the first hour and at 25 to 30°C for the next 7 to 8 h. This reaction yields primary acetate (cellulose triacetate), in which three carboxyl groups of each glucose unit are substituted by the acetate groups. The cellulose

triacetate is then partially hydrolyzed by allowing it to remain in water for up to 20 h. During this process, the completely acetylated cellulose triacetate is transformed into a secondary acetate. The secondary acetate is precipitated from an aqueous solution and then dried. The flakes of secondary acetate are ground and used in spinning acetate filaments by any of the three spinning processes, namely, dry spinning, wet spinning, or melt spinning. In addition, acetate fibers are also spun in various modified forms by manipulating the spinning process. Spun-dyed acetate fibers are produced by adding pigments to the spinning solution before extrusion. Titanium dioxide is added to diminish the natural luster. The orifices of the spinneret are modified to shapes other than circular to produce many variations in the cross-sectional shapes of the fibers. Fancy yarns, such as those with thick and thin places and slubs, are produced by varying the rate of feed of the solution to the spinneret.

Acetate may be produced in any length and fineness; it can be manufactured either in continuous, short staple or long staple (38 to 175 mm) form in a variety of deniers (1.5 to 5.0). The tenacity of acetate fibers is rather low, 9.7 to 11.5 cN/tex (1.1 to 1.3 g/den), and breaking elongation lies in the range of 23 to 30% for dry and 35 to 45% for wet fibers. However, acetate shows plastic recovery of approximately 48 to 65% from 4% extension, beyond which plastic deformation takes place. The moisture regain of acetate fiber is 6.5% compared to 13% for viscose rayon. Acetate does not absorb as much water as viscose or cuprammonium rayon because the majority of water-affinitive hyroxyl groups of cellulose molecules are replaced by acetate groups, thereby decreasing the inherent attraction of acetate for water molecules. Cellulose acetate is a thermoplastic fiber, softening at 205°C and melting at 232°C. The microscopic appearance of an acetate filament differs from those of viscose and cuprammonium rayon filaments. The cross-sectional shape appears to be made up of a number of rounded lobes, as shown in Fig. 2.27. In longitudinal direction, it shows folds and ridges.

The triacetate fiber is produced by complete acetylation of all the three available hydroxyl groups of each glucose unit of the cellulose molecule. The precipitated triacetate formed after the acetylation process is dissolved in methylene chloride. This is later spun by any of the spinning processes, namely, dry, wet, or melt. It is drawn and produced in the continuous filament form or chopped and mechanically crimped for use in the making of staple fiber yarns.

Triacetate fiber shows striations along its length and has a multilobal cross section, as shown in Fig. 2.28. The properties of triacetate fibers are similar to those of acetate fibers except for handle, moisture absorption, and thermal behavior. Unlike the soft handle of acetate, triacetate has a firm and

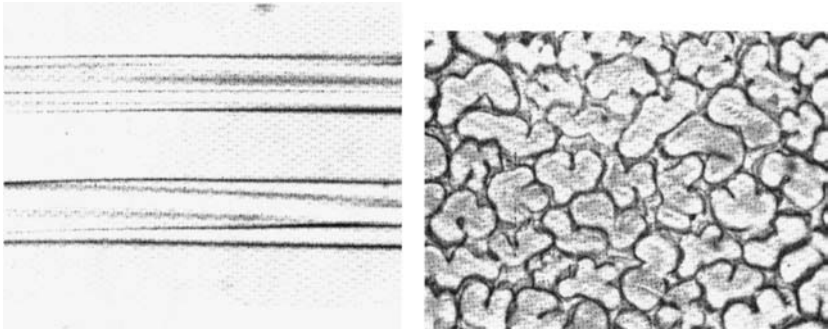


Fig. 2.27 Longitudinal and cross-sectional views of acetate fibers. (From Ref. 41.)

crisp handle. Because of the nonavailability of hydroxyl groups, triacetate has poor moisture regain (2.5%) and water absorption characteristics. This makes it difficult to size. Triacetate is thermoplastic in nature and softens when heated to 170°C. During heating, the internal stresses generated in the manufacturing process are relieved, which allows the molecular orientation to take place along the fiber axis in the crystalline regions, resulting in increased crystallinity and better packing. The thermoplasticity of triacetate well below its melting point, technically known as heat setting, provides an excellent means of stabilizing shrinkage of fabrics, thereby imparting better dimensional stability. This heat-setting characteristic of triacetate fabrics can be advantageously used by inducing deliberate thermomechanical distortions to mold fabrics into desired shapes. The fabrics can be held permanently in that shape after setting, for example, in setting pleats and creases permanently in triacetate garments such as ladies' skirts.

Because of its good shape retention properties, triacetate is predominantly used in producing knitted and woven underwear and lingerie fabrics. The low moisture take-up behavior renders the triacetate garments drip-dry and retains a wrinkle-free appearance, thus eliminating the need of ironing. The high melting point of triacetate makes it excellently suitable for blending with fibers that require high ironing temperatures such as cotton and linen; it also finds use in some industrial applications where fabrics are exposed to elevated temperatures.

Lyocell. This represents a relatively new class of regenerated fiber produced from the cellulose of wood pulp as basic raw material, which is

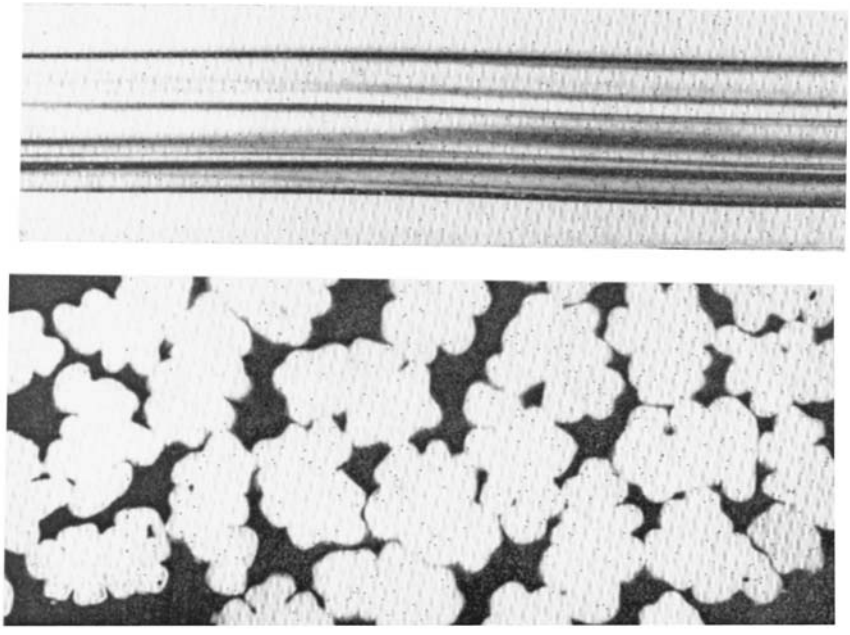


Fig. 2.28 Longitudinal and cross-sectional views of triacetate fibers. (From Ref. 41.)

from natural origin, renewable, and biodegradable. The original process was developed by Akzo Nobel and was subsequently licensed to Courtaulds during the 1970s. Akzo Nobel was not in a position to develop it further and Courtaulds then developed a stable and controlled process to produce the first lyocell fiber in the late 1980s. It was first introduced by Courtaulds Fibers (now Acordis Fibers) under the trade name Tencel® in 1992 [69]. More recently, Lenzing AG, a company in Austria, started producing Lenzing Lyocell similar to Tencel. The Federal Trade Commission in the United States classified lyocell as a generic name as cellulose fiber in a subcategory under rayon.

The wood pulp is obtained from trees specially grown on managed farms for producing lyocell. The pulp is dissolved in nontoxic organic solvent (chemically known as N-methyl morpholine oxide) and then spun into fine fiber. Then it is washed to eliminate the solvents. The solvent used is almost completely recovered from the manufacturing process. This makes this fiber com-

pletely environmentally friendly unlike other synthetic fibers that contaminate the atmosphere, earth, and water due to emissions. Because it is produced from cellulose, it is biodegradable; though it will not disintegrate completely if disposed of in a landfill. The products made from lyocell can be recycled, incinerated, or digested in sewage. The degradation of the fiber takes place in about 8 to 10 days.

Besides the environmental safety of lyocell, its success is attributed to its outstanding physical and chemical properties. It has a much higher dry and wet tensile strength than either cotton or rayon. Its dry strength, 35 cN/tex, is somewhat comparable to that of polyester. Its high wet strength, 29 cN/tex, provides ease in textile and garment manufacturing processes, and it thereby exhibits a high degree of dimensional stability. In its wet state, lyocell retains almost 85% of its dry strength. It is the only manmade fiber of cellulose origin which is stronger than cotton when wet. Table 2.8 shows the comparison of tensile properties of lyocell with viscose, cotton, and polyester [69].

One of the most important physical properties of Tencel is its potential to fibrillate. Fibrillation is a process in which the wet fiber, through abrasive action, develops microfibrils (tiny fibers) on its surface. By manipulating or controlling fibrillation, a variety of different fabric finishes may be achieved. The surface fibrils of Tencel can be manipulated to produce a luxurious, soft touch fabric with surface effects such as peachskin or mill wash. Figure 2.29 shows photographs of fibrillated and nonfibrillated Tencel fibers. The other important properties of lyocell fibers include inherent softness, drape, wrinkle resistance, and fluidity, which are imparted to fabrics irrespective of surface effects. The dyeability of lyocell fiber is very good and versatile, which makes fabric dyeable to vibrant colors. This aesthetic appeal due to good dyeing

Table 2.8 Comparison of Tensile Properties of Tencel Fiber with Viscose, Cotton, and Polyester

Property	Tencel	Viscose	Cotton	Polyester
Linear density (decitex)	1.6	1.6		
Dry tenacity (cN/tex)	42–44	23–27	21–25	42–53
Dry elongation at break (%)	14–16	20–25	7–9	25–30
Wet tenacity (cN/tex)	37–40	10–16	27–31	42–53
Wet elongation at break (%)	16–18	25–30	12–14	25–30

Source: Ref. 69.

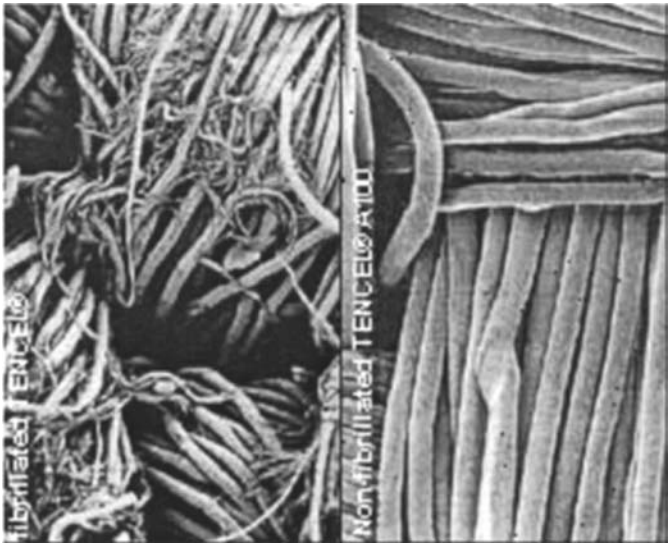


Fig. 2.29 Fibrillated and nonfibrillated Tencel® fibers. (From www.tencel.com.)

characteristics can be enhanced further by surface effects and different textures to simulate silk, suede, and leather touch.

Most lyocell production today is used for developing different products for women's wear. Its uses range from casual denims to tailored suits. A small percentage of lyocell is found in casual men's wear such as golf shirts. Other uses of lyocell products include industrial textiles, special types of papers, and nonwovens. Nonwoven applications are in artificial leathers, filters, hygiene products, and medical wipes. Industrial applications include protective suits in the work wear industry, coated fabrics, military fabrics, oil filters, and ropes. Some cigarette manufacturers are also using lyocell to make ultra low tar cigarettes. Lyocell can also be found in upholstery fabrics and window treatments.

Although 100% lyocell fabrics have appealing characteristics, blending with other fibers enhances yarn quality and fabric appeal. It can be easily blended with fibers such as wool, cotton, silk, flax, and various other manmade fibers. Cotton blended with lyocell becomes stronger, wool/lyocell blends are more absorbent, and rayon/lyocell blends have better stability [69].

The protein fibers of natural origin, such as wool, silk, and other animal fibers, are composed of long chain protein molecules. These protein molecules are formed by linking together small amino acid molecules in different proportions and in different sequences. Though proteins are composed of long chain molecules (a primary requirement for a fiber-forming substance), the molecules must be linked and aligned with each other in such a way that they help to form a fiber. Some protein molecules have a tendency to coil into a compact ball where chemical cross-linkages may occur to keep the chains coiled. These are called globular proteins, which may be unfolded into a straightened form by removing cross-linkages. Such straightened form can be dissolved in a number of solvents that allows it to be extruded through the fine holes of a spinneret. A number of such proteins are commonly available, such as casein from skimmed milk, zein from maize starch, arachin from ground nut protein and soybean protein, etc., which satisfy these basic requirements for fiber formation.

Casein. Casein is obtained from the coagulum of the skimmed milk treated with an acid at 40°C. Casein is then dissolved in caustic soda and allowed to age until a suitable viscosity is developed; then it is filtered and deaerated. The spinning solution is wet spun by extrusion through spinnerets into a coagulating bath containing sulfuric acid, formaldehyde, glucose, and water. The casein fibers collected as tow are soft, weak, and fragile. On wetting casein filament softens and swells due to the easy penetration of water molecules. Such untreated casein is therefore not suitable for any practical textile use. The fibers are hardened with formaldehyde, which helps them to withstand wetting. The formaldehyde reacts with the free amino groups of casein to form cross-linkages, which tie casein molecules together, thus preventing them from being forced apart by water molecules.

Casein fibers have smooth surface and are bean shaped to nearly round in cross section. They have excellent warmth and a soft handle, making them suitable for mixing with wool. The tenacity of casein fibers is 9.7 cN/tex (1.1 g/den) when dry; however, on wetting the tenacity drops to about 2.6 to 5.3 cN/tex (0.3 to 0.6 g/den). The elongation at break is 60 to 70% both in the wet and dry conditions. Wet casein fibers generally soften on heating. The fibers become yellowish and brittle when heated above 100°C for a prolonged period. Casein blends very well with cotton, rayon, and wool because of its warmth, resilience, and soft handle. Casein/wool blends are used for knitted jersey fabrics where a soft full handle is required. It is also used in felt hats, pressed felts for floor coverings, carpets, padding, insulating fillings, etc.

Alachin. Alachin is a protein obtained from groundnuts. The solution of groundnut protein in dilute caustic soda is allowed to mature for 24 h under

controlled conditions, until a suitable viscosity is achieved. This solution is filtered and then extruded from the orifices of the spinneret into an acid coagulation bath containing a solution of sulfuric acid, sodium sulfate, and other auxiliary chemicals. The temperature of the coagulating bath is maintained between 12 and 40°C. The groundnut protein fibers have a soft woollike handle and are primarily used advantageously in blends with wools because of their low cost. However, it is also used in blends with cotton and rayon for the production of fabrics for shirting, pajamas, dress materials, tropical clothing, sport shirts, carpets, etc.

Zein. Zein fiber is made of the protein called zein obtained from corn meal. The zein is dissolved in sodium hydroxide solution, which is then filtered and deaerated. The solution is allowed to mature for several hours until the desirable viscosity is attained. During the process of maturation, the coiled molecules of zein protein are able to unfold and straighten themselves out. The spinning solution is then pumped and extruded into a bath containing formaldehyde for coagulation. The zein filaments are subsequently hardened in formaldehyde for creating further cross-linkages between zein molecules. Zein fibers have as warm a feel as wool but are softer and resilient, having also a luxurious feel. Zein fibers have been used mostly in blends with cotton, rayon, nylon, and wool. Zein, soybean, and collagen protein fibers are no longer commercially produced and consequently are of no practical importance to the textile industry.

Miscellaneous Regenerated Fibers

Alginate Fiber. Alginic acid is a polymeric substance available from brown seaweeds. Alginic acid is abundantly available in natural seaweeds, in virtually unlimited quantities across the world's seashores. The molecules of alginic acid and its salts have long chain molecules suitable for fiber formation. The alginic acid is dissolved in sodium carbonate and caustic soda to form sodium alginate and allowed to stand until an undissolved sediment is formed, which may be removed. This sodium alginate solution is bleached and sterilized by adding hypochloric acid and then filtered. The solution is wet spun into a coagulating bath containing calcium chloride, hydrochloric acid, and a small amount of surface active agent. The sodium alginate emerging from the spinning jet is precipitated in the form of calcium alginate filament. These filaments are drawn, washed, lubricated, dried, and wound.

Alginate fibers are round to oval in cross section with a serrated outline. The tenacity of dry alginate fibers varies from 14.1 to 17.7 cN/tex (1.6 to 2.0 g/den) and elongation to break from 2 to 6%. However, the wet tenacity is very low (4.4 cN/tex). Alginate fibers are nonflammable but decompose to ash when

held in a flame. Alginate fibers are insoluble in water but readily dissolve even in a mild alkali such as soap water. This is a serious drawback, limiting its practical use for textile applications. However, alginate fibers are used in knitting hosiery such as socks to form the bridge between two units, thus enabling continuous production. The socks are later separated by cutting and dissolving the courses of alginate yarns in an alkaline solution. This enables the production of defect-free welts of socks of all types. In medical use, sodium/calcium alginate is used as styptic elastic dressings, which is nontoxic and absorbable in the bloodstream. It is also used in dental surgery for plugging cavities.

Natural Rubber Fibers. Rubber is a natural polymer obtained by the coagulation of the latex produced by the rubber tree. The raw rubber is a tough, elastic material which softens on heating and becomes plastic. Due to this thermoplastic property, rubber can be molded and shaped either by extrusion or by compression molding. Sulfur is added to the thermoplastic rubber, which is later vulcanized or cured. A cured or vulcanized rubber acquires unusual elasticity. Even before the process of vulcanizing was invented, the rubber filaments (threads) were made by cutting strips from raw rubber. To produce extruded rubber filaments, the rubber latex is mixed with vulcanizing agents, accelerators, pigments, and antioxidants. It is then extruded through glass spinneret into a coagulating bath containing acetic acid. The filaments are washed, dried, and heated to vulcanize the rubber. The rubber filaments are either used in this form or in the core of core-spun stretch yarns. The sheath of such a core-spun yarn is made either from cotton, rayon, wool, or any other synthetic fibers. The tenacity of rubber filaments is quite low (4.0 cN/tex), while their elongation is very high (200–400%). Under normal conditions it has 100% instantaneous recovery. Its moisture regain is negligible, and it has a very high electrical resistance. Rubber deteriorates on prolonged exposure to sunlight. The rubber filaments and strips are extensively used as elastics in sportswear, underwear, and hosiery to provide support and improve the fit of garments.

Carbon Fiber. Carbon fiber is defined as a fiber containing at least 90% carbon, obtained by the controlled pyrolysis of appropriate fibers. The term ''graphite fiber'' is applied to fibers that have more than 99% carbon. Large varieties of fibers called precursors are used to produce carbon fibers of specific characteristics. The most commonly used precursors are polyacrylonitrile (PAN), cellulosic fibers (viscose rayon, cotton), petroleum or coal tar pitch, and some phenolic fibers. The application of heat to the precursor removes the oxygen, nitrogen, and hydrogen to form carbon fibers. The production techniques used vary depending upon the precursor, but in general it involves the steps of oxidation and carbonization.

The properties of carbon fibers depend upon the type and properties of the precursor, the processing conditions and the degree of heat treatment. In general, the higher the tensile strength of the precursor, the higher is the tenacity of the carbon fiber. Tensile strength and modulus are significantly improved due to carbonization. The tensile strength of carbon fiber is almost three times that of steel, with density of only 1.75 g/cm^3 (steel: 7.87 g/cm^3). This makes carbon fibers suitable for aerospace applications, where lighter materials in aircraft construction lead to fuel savings.

Carbon fibers are used both in woven and nonwoven fabrics. The weaving of carbon fiber yarns requires sizing. Carbon fibers are primarily used in composites, where tow or more components are used. In fiber-reinforced composites, normally it is fiber and resin. The applications include engineering components such as bearings, gears, cams, fan blades, and automobile bodies. Other applications include decoration in automotive, marine, and general aviation interiors; entertainment and musical instruments; conductivity in electronics technology; etc.

Glass Fiber

This is an inorganic fiber of mineral origin in which the fiber-forming substance is glass. Glass is composed of mainly silica sand (silicon dioxide) and other ingredients such as aluminum, calcium and magnesium oxides, and borates. The exact composition is normally dependent upon the desired end-use properties such as heat and chemical resistance. The glass fiber manufacturing is the high temperature conversion (above 1600°C) of different ingredients into a homogeneous melt. This molten glass is then converted into glass fiber of desired linear density.

Mechanical properties of glass fiber vary depending upon the thermal history. Glass fiber has high tensile strength (stronger than steel of the same diameter) and modulus but low elongation when compared to most available fibers. Other important properties of glass fiber are excellent ignition resistance, good chemical resistance, noncorrosiveness, good mildew resistance, and good electrical insulation. Glass fibers do not absorb water and so do not shrink. Major disadvantages of glass fibers are their low abrasion resistance and brittleness, making them difficult to process in textile operations [70].

When used on its own in the form of single, plied, or cabled yarn, glass fiber can be woven, braided, or converted into sleeves. Glass fibers have found many applications as reinforcement in thermoplastic composites. The glass reinforcements are made in various forms in order to make them suitable for a variety of processes and to provide desired thermomechanical and electrical properties.

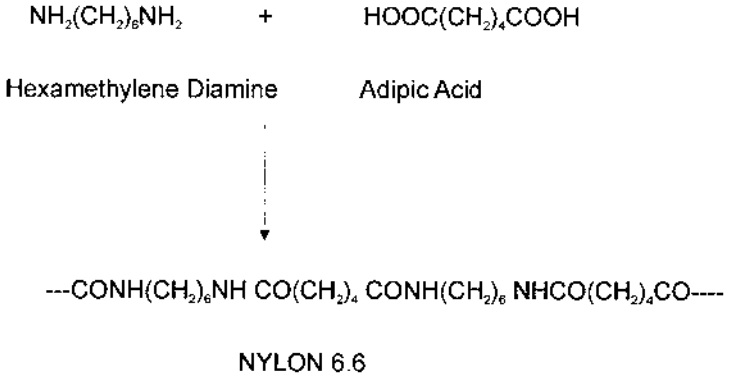
Notable textile applications of glass fibers are in printed circuit board, electrical insulation (tapes, fabrics, cable reinforcement, and braided tubes), air filtration, anticorrosion reinforcement, adhesive tapes, sports and leisure goods, roofing membrane reinforcement, coated fabrics, wall covering, decorative fabrics, clutch discs, brake linings, and other aircraft and marine uses.

Synthetic Fibers

The synthetic fibers are made by synthesis from monomers. The monomers have reactive groups at either end of the molecule so that two such molecules could be combined together to give a molecule which is twice as long with a reactive functional group at either end, known as a dimer. Then two such molecules would be combined with each other to form a molecule which is four times the length of a monomer. Such a repeated and concurrent doubling process of molecules (known as polymerization) could result in very long chain molecules (known as polymers), a prerequisite for producing fibers.

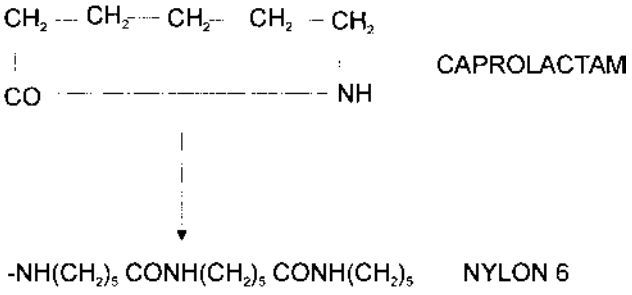
Polyamide Fibers. The generic name of any long-chain synthetic polyamide fiber is nylon. As the name implies, it is produced by the recurring polymerization of amide groups in the main polymer chains. These synthetic polyamide fibers are most widely used and form one of the most important of all classes of textile fibers. Synthetic polyamides are formed by condensation polymerization of small reactive molecules (monomers) in which the linkages of molecules occur through the formation of amide groups. Among a variety of synthetic polyamides produced by the condensation reactions only a few have received commercial attention in the textile industry. Two of the most noted polyamide structures of commercial value that account for the bulk of world production are nylon 6.6 and nylon 6.

Nylon 6.6 is produced by condensation reaction between hexamethylene diamine and adipic acid as follows:



It is referred to as nylon 6.6 because each of the components contains 6 carbon atoms.

The second type of polyamide, known as nylon 6, is produced by the self-condensation polymerization of an amino acid or a derivative such as caprolactam (product of ω-caproic acid):



Nylon 6 and nylon 6.6 together constitute the bulk of the worldwide production of polyamide fibers. Other types of nylons that are commercially produced include nylon 4, nylon 7, and nylon 11. The chemical structures of both nylon 6 and nylon 6.6 are reasonably identical, differing only in the arrangement of the atoms in the amide groups.

The molecular weight and the molecular weight distribution of nylon 6 and nylon 6.6 are different due to the differences in the polymerization techniques used in their manufacture. Although the general characteristics of nylon 6 and nylon 6.6 are similar, they differ in certain physical properties as follows:

1. The melting point of nylon 6.6 is higher (about 250°C) than that of nylon 6 (215°C). Therefore, nylon 6.6 has a better resistance to high temperature and can withstand higher temperatures without a loss in tensile strength.
2. Nylon 6 has a better elastic recovery and resistance to fatigue.
3. Both nylon 6 and nylon 6.6 suffer degradation and turn yellowish under ultraviolet light to varying degrees when exposed to sunlight for extended periods. Nevertheless, additives are used to stabilize yarns against degradation by ultraviolet radiation.
4. When dyed with acid dyes in the same dye bath, nylon 6 will pick up deeper shades than nylon 6.6, although the fastness is generally better for nylon 6.6.
5. Nylon 6 fibers blend more easily with other fibers than nylon 6.6. The softer handle of nylon 6 is advantageous in some applications, such as in the manufacture of tricot fabrics and in fabrics produced from false-twisted textured yarns.

Both nylon 6.6 and nylon 6 are produced to different fineness and either as staple fiber or as continuous multi- or monofilaments, as desired. The cross-sectional shape of nylon fiber is rodlike, round, and with a smooth surface, with no longitudinal striations, as shown in Fig. 2.30. Some special types of nylon fibers are produced with trilobal or multilobal cross sections (as shown in Fig. 2.31) for certain end uses.

Nylon fibers have tenacities varying from 40 to 50 cN/tex for low tenacity fibers to as high as 79.5 cN/tex for high tenacity fibers. The elongation at break of high tenacity nylon is about 19 to 24% as compared to 30 to 37% for regular filament and staple. The elastic recovery of nylon fiber is quite high, almost

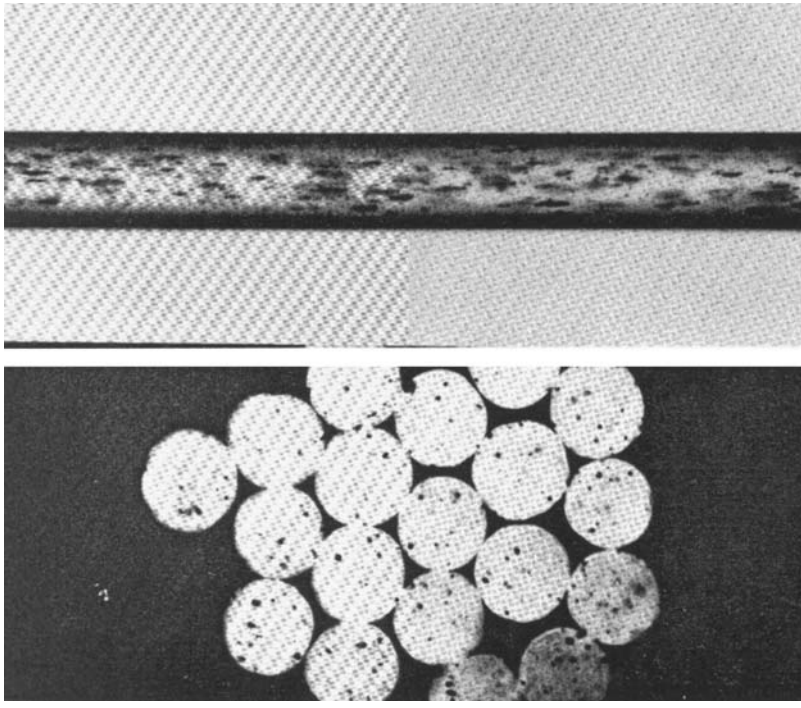


Fig. 2.30 Longitudinal and cross-sectional views of nylon fibers. (From Refs. 7 and 41.)

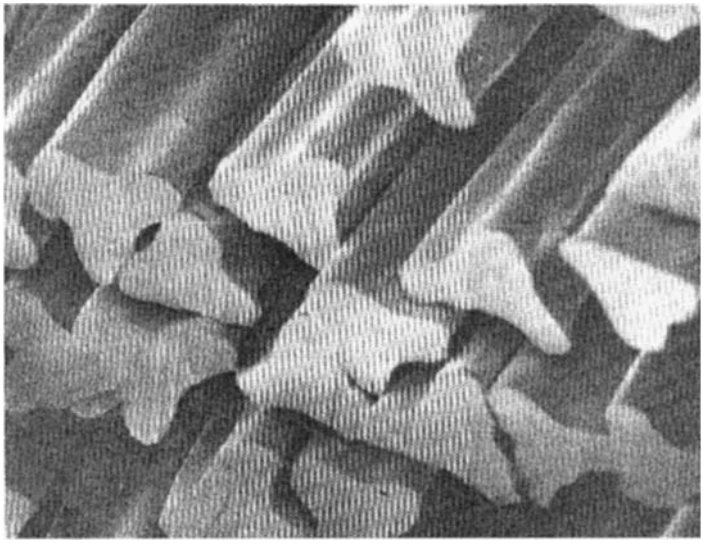


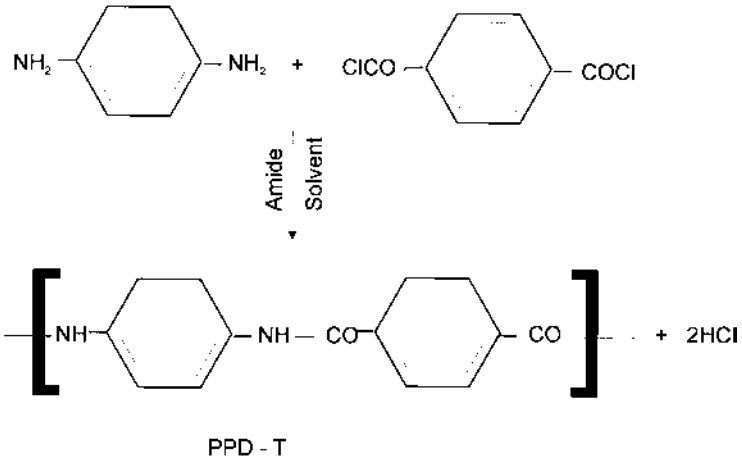
Fig. 2.31 Trilobal nylon fibers. (From Ref. 42.)

100% at 8% extension for regular filaments. The initial modulus of regular nylon filaments varies between 350 to 530 cN/tex. Nylon has a moisture regain of only 4 to 4.5%, which is quite low in comparison with most natural fibers. Nylon can withstand temperatures of up to 150°C without appreciable loss in strength. Due to the thermoplasticity of nylon fibers, it can be readily heat set at 205°C for attaining desired dimensional stability and crease resistance in fabrics. The resistance of nylon to some chemicals such as alcohols, aldehydes, alkalis, ethers, dry cleaning solvents, soaps, detergents, etc., is quite good. However, concentrated hydrochloric acid and sulfuric acid (above 5.0%) degrade the fiber and cause a loss in tensile strength. Oxalic acid, even at a 3.0% concentration, causes severe deterioration at elevated temperatures of about 100°C. The burning resistance (flammability) of nylon fiber is considered very satisfactory for all textile applications because when ignited it melts and falls away, and the flame extinguishes itself and inhibits further flame propagation. Nylon has a very good dye affinity and may be dyed with a wide range of dyestuffs.

Nylon fibers and filaments are used in a variety of textile applications, such as woven and knitted apparel, furnishings, and household textiles because

of their excellent mechanical properties and wear resistance. They are also extensively used in carpets and industrial applications such as tire cords, hoses, parachutes, conveyor and transmission belts, and filter fabrics.

Aromatic Polyamides. The aromatic polyamides, also known as aramids, are characterized by a long chain of synthetic polyamide containing at least 85% of amide (—CONH—) linkages attached directly to aromatic rings. The most important commercial fibers belonging to this class are Twaron®, Kevlar®, and Nomex®. Kevlar, chemically known as Poly(*p*-phenylene terephthalamide) (PPD-T), is prepared by the polycondensation of *p*-phenylene diamine (PPD) and terephthaloyl chloride (TCl) in a dialkyl amide solvent at a low temperature [71]:



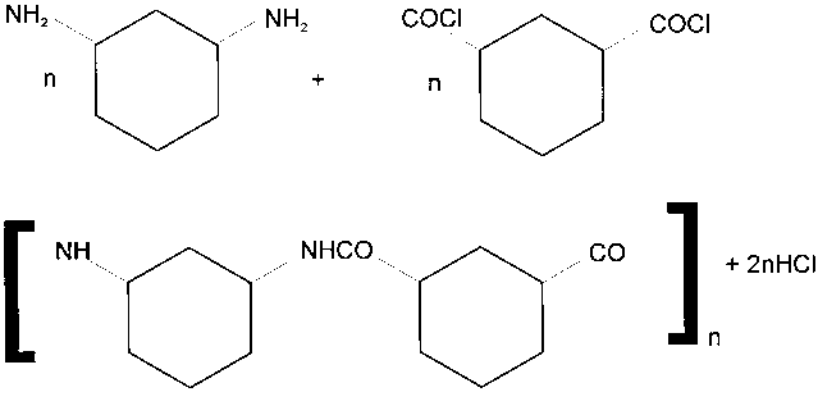
PPD - T

Other varieties of Kevlar filaments are Kevlar 29, Kevlar 49, Kevlar 68, and Kevlar 149. Kevlar 29 and Kevlar have almost similar tensile properties, while Kevlar 49, Kevlar 68, and Kevlar 149 filaments have higher initial tensile modulus and a greater degree of crystalline orientation [71]. Most Kevlar fibers have a bright yellow color excepting Kevlar 149, which has a deep gold color. Most Kevlar fibers are available in 1.5 denier per filament and in round cross section. The breaking tenacity of Kevlar is approximately 194 cN/tex (22 g/den), which is almost five times that of steel and slightly more than twice that of nylon, polyester, and fiberglass [71]. The initial modulus of Kevlar is 42 N/tex (475 g/den), which is roughly twice that of steel wire. The breaking elongation of Kevlar is only 4%.

Kevlar fiber is used in fabric form for producing bullet-proof vests, and the Kevlar reinforced composite materials for other hard armor applications

[71]. The ballistic resistance of Kevlar fiber–based material is found to be much higher than that of nylon-based fabric [72]. Other areas of application of Kevlar fibers are protective clothing, helmets, tire and drive belt reinforcements, structural supports for aircraft and boats, parachute fabrics, conveyor belts and high pressure hoses, automotive hoses, ropes and cables, automotive clutches, disk brakes, and brake shoes.

Nomex is another aromatic polyamide, chemically known as poly(*m*-phenylene isophthalamide). It is produced by the condensation polymerization of *m*-phenylene diamine with the diacid chloride [7]:



The most noteworthy characteristic of this fiber is its high thermal resistance—the melting point is 371°C and the softening temperature above 300°C. Nomex also shows good resistance to x-rays. The tenacity of Nomex is 47 cN/tex (5.3 g/den) and breaking elongation is 22% at 65% RH. However, the wet fiber has a tensile strength of 36 cN/tex (4.1 g/den) and a 16% elongation at break. Nomex has good chemical resistance and dimensional stability.

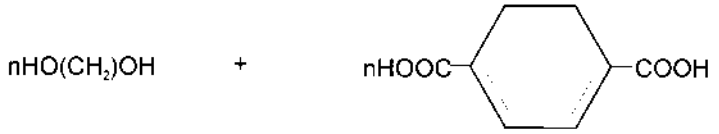
Due to its high thermal resistance, the foremost applications of Nomex fibers are in spacesuits and specialized military apparels, infant wear, racing drivers' overall, and high temperature gas and chemical filtration. It is also used as a protective screen against high energy nuclear radiation.

Polyester Fibers. Polyesters are formed by the condensation polymerization of small molecules linked together by an ester group formed by reacting an acid with an alcohol. Among several different polyester types, the two most widely used are

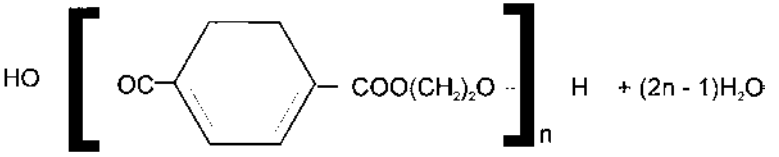
Polyethylene terephthalate fibers (PET polyester, e.g., Dacron®)

Poly-1,4-cyclohexylene–dimethylene terephthalate fibers (PCDT polyester, e.g., Kodel®).

Poly(ethylene terephthalate) fiber is formed by the condensation polymerization of terephthalic acid or its derivative such as dimethyl terephthalate with ethylene glycol:

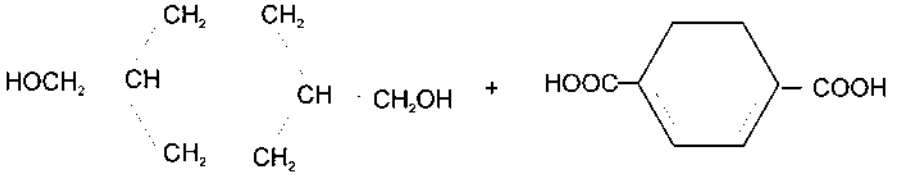


Ethylene Glycol Terephthalic Acid

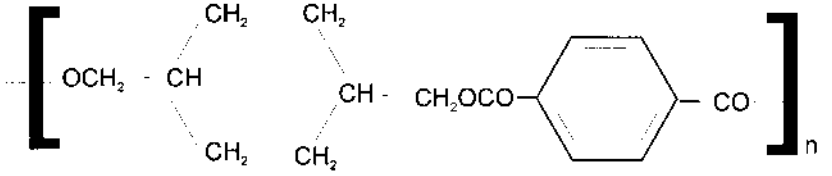


Polyethylene Terephthalate (PET)

The PCDT polyester fibers are spun from the polymer obtained from the condensation reaction of terephthalic acid with 1,4-cyclohexanedimethanol:



1-4 Cyclohexanedimethanol Terephthalic Acid



The PCDT polyester is thus fundamentally different in chemical constitution from that of PET polyester fibers most widely produced commercially.

Polyester fibers are produced in the form of continuous filament, staple fiber, and tow of a variety of different linear densities and cross-sectional shapes. Polyester fibers have a smooth and rodlike cylindrical surface, having a generally circular cross section, as shown in Fig. 2.32. However, some other types are produced with a special trilobal or hollow cross section, as shown in Fig. 2.33. Polyester is also produced with bright, semidull, or dull luster. It has excellent tensile strength, elastic recovery from stretch, compression, bending, and shear; low moisture content; and high abrasion resistance. It has a high initial resistance to tensile deformation in the early region of extension (0 to 5%) to which fibers are generally subjected in real use. Polyester is a thermoplastic fiber that softens when heated and eventually melts at elevated temperatures; however, the melting point is high enough for all normal textile uses. It fuses and forms a hard bead when ignited. In view of all practical purposes, polyester is an inert fiber, resistant to the majority of low concentration mineral acids, alkalis, and common organic solvents. Being hydrophobic in nature, polyester fiber does not absorb moisture/perspiration readily, making it somewhat uncomfortable to wear in a warm climate. The hydrophobicity of polyester makes it difficult to dye. It is commonly dyed with water-insoluble disperse dyestuff at a high temperature and pressure.

The most important and useful property, and of great practical interest of polyester fibers, is their ability to be heat set at elevated temperatures (200 to 220°C). This helps to impart dimensional stability to fabrics, which may be affected in subsequent heat treatments or finishing processes. This has led to the development of ''permanent press'' and ''easy care'' treatments of garments, in which the heat setting of the polyester fiber takes place in the garment itself, which is set in a desired shape. Such a thermal characteristic of polyester materials enables the texturizing of continuous filament materials. Texturizing is a process which induces a thermomechanical deformation in polyester filaments to increase their bulk and stretch characteristics. Such bulky stretchable texturized filaments impart better bulk and stretch to woven and knitted fabrics..

Polyester fibers are now used in virtually every type of textile and apparel applications, including carpets, upholstery, and industrial uses. A large proportion of polyester fibers are made in the staple form for use in blends with other staple fibers such as cotton, wool, viscose rayon, linen, etc. Other applications of polyester fiber include tire cords, ropes and twines, nets, sail cloth, filling in pillows and quilts, sewing threads, conveyor belts, and fire hoses.

Polybutylene Terephthalate (*PBT*). The modification of polyester is an important area of research aimed at developing new fibers with new characteristics and performances. PBT is also a class of polyester obtained by the polymer-

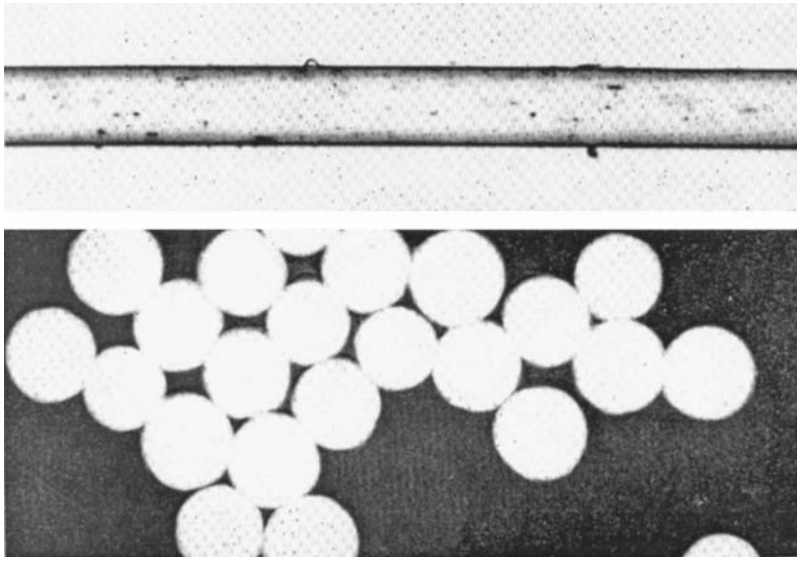
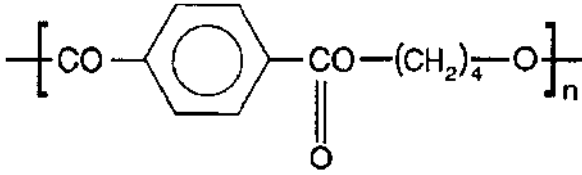


Fig. 2.32 Longitudinal and cross-sectional views of polyester fibers. (From Ref. 7.)

ization of 1-4-butylene glycol with DMT or PTA. The resultant chemical structure of PBT is as shown:



Polybutylene Terephthalate

Like other thermoplastic materials, PBT is available in resin form. The PBT resin is a basic thermoplastic compound, which can be converted into fiber, plastic, film, and coatings. PBT is widely used in the plastic form due to its high strength, is easy to mould, and has high chemical resistance and low warpage.

Polybutylene terephthalate is available in continuous filament form with different deniers and numbers of filaments. PBT can be textured due to its ther-

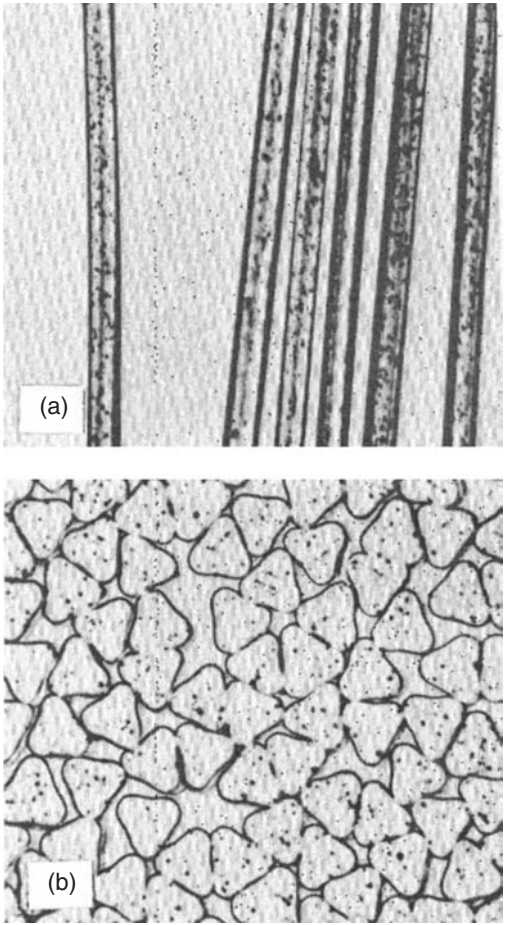
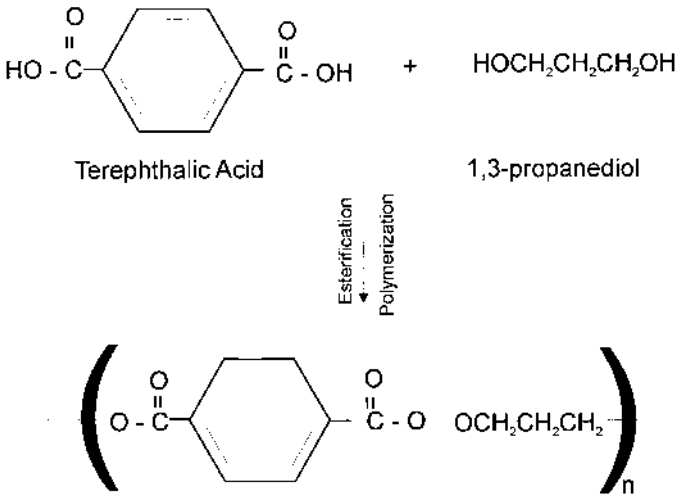


Fig. 2.33 Longitudinal and cross-sectional views of trilobal polyester. (From Ref. 6.)

moplasticity. PBT fiber has high stretch and recovery with low ductility, good tensile strength, and resistance to chlorine, chemicals, and UV light. PBT fiber is soft, supple, lustrous, and pleasant to the touch. Due to low humidity take-up levels (~0.4%), PBT dries up very quickly. PBT fibers process well both in weaving as well as knitting. Therefore, PBT fibers are used in sportswear, gymnastic clothing, underwear, and swimsuits where good recovery and shape retention are necessary.

Polytrimethylene Terephthalate (*PTT*). It is a class of polyester made by polycondensation of 1,3–propanediol (PDO) with terephthalic acid, as shown [73]:



Polytrimethylene Terephthalate (PTT)

Although this polymer was synthesized in 1941 by Whinfield and Dickson [74], it remained unnoticed because of the nonavailability of PDO as raw material. Recent commercially viable synthesis of PDO introduced by Shell Chemicals and Degussa has facilitated the production of PTT, which is a good fiber-forming polymer.

Polytrimethylene terephthalate fibers have higher elastic recovery than PET and nylon 6.6. Table 2.9 shows the comparison of some physical properties of PTT to polyester and nylon 6.6 [75]. Unique softness attributed to a low Young's modulus and excellent elastic recovery under low load of PTT fiber creates a high wearing comfort and a rich drape. The unique tensile behavior

Table 2.9 Comparison of the Physical Properties of PTT, PET, Nylon 6.6, PEN, and Fibers

Property	PTT	PET	Polyamide (nylon) 6.6	PEN
Tensile strength (cN/tex)	33.5–37.1	37.1–44.1	41.5–45.0	80–90
Elongation (%)	36–42	30–38	32–44	5–8
Initial modulus (cN/tex)	230	970	310	2000–2300
Elastic recovery at 20% elongation	88	29	62	—
Density (g/cm^3)	1.34	1.38	1.14	1.36
Moisture regain (%)	0.4	0.4	4.5	0.2–0.4
Shrinkage at boiling (%)	14	7	13	3–5
Melting Point (°C)	230	254	253	270–275

Source: Refs. 75 and 76.

and elastic recovery of PTT fiber are attributed to its zigzag-shaped molecular chains in the fiber structure.

The development of PTT fiber is considered a potentially significant contribution toward new materials for textile end uses. The PTT fiber can be blended with other fibers such as natural and viscose fibers due to its compatibility and ease of processing in a typical textile operation. PTT has found a broad range of applications, including textiles, carpets, nonwovens, thermoplastics, and films. The future commercial exploitation of PTT will much depend upon the economics of its production, product development, and availability.

Polyethylene Naphthalate (*PEN*). This is a class of polyester fiber made from either the polyethylene naphthalate homopolymer or the polybutylene naphthalate (PBN) homopolymer in a melt-spinning process similar to that used for PET and PBT fiber manufacturing [76]. PEN-based fibers have improved tensile modulus; higher heat resistance; improved resistance to hydrolysis, chemicals, and rotting; and better dimensional stability when compared to PET fibers. Besides, PEN fibers have extremely high moisture resistance and wet strength. Table 2.9 compares the properties of PEN fibers with other fibers.

Due to superior properties of PEN fibers, they are used in differentiating products such as tire reinforcement, geotextiles, high performance sailcloth, automotive seatbelts, hoses and drive belts, rope and cordage, composite reinforcement, and tents and tarpaulins.

Polyvinyl Derivatives. The compound containing the vinyl group (—CH_2═CH—) having a double bond are polymerized to form a long-chain molecule by the process known as addition polymerization. The resultant polymers are called polyvinyl compounds. Addition polymerization is a process in which a polymer is formed by the addition of one monomer to another without the elimination of water or other molecules. Polyvinyl compounds have been used in the making of a number of synthetic fibers. Out of the many different classes of fibers spun from polyvinyl derivatives some of the most important fibers are discussed below.

Polyacrylonitrile Fibers. The most important fibers in this class include those spun from polymers or copolymers of acrylonitrile. This may be further subdivided into two major groups, viz. (1) acrylic fibers and (2) modacrylic fibers.

Acrylic Fibers. Acrylic fibers are spun from polymers containing at least 85% by weight of acrylonitrile units (—CH_2—CH(CN)—). Earlier polyacrylonitrile fibers were spun by homopolymerization of 100% by weight of acrylonitrile units. However, all modern types of acrylic fibers are spun from at least 85% by weight of acrylonitrile copolymer. The other 15% of the comonomer unit may include any of the most commonly used monomer such as vinyl chloride, vinyl acetate, methyl acrylate, and 2-vinyl pyridine.

Acrylic fibers have kidney bean cross-sectional shape, which affects the bending stiffness and consequently the fabric properties. Wet-spun acrylic fibers are generally round or bean shaped in cross section, as shown in Fig. 2.34. Dry-spun acrylic fibers have flat or dog bone shaped cross section, as shown in Fig. 2.34. Acrylic fibers are produced mainly as continuous multifilament yarns intended for conversion into staple fibers. These staple fibers are produced in a variety of deniers and lengths for processing on cotton, woollen, and worsted spinning systems.

The properties of acrylic fibers differ widely depending upon a particular type of acrylonitrile copolymer used, wet or dry spinning conditions, and drawing to which it is subjected. Acrylic fibers have medium tenacity (25 to 35 cN/tex), relatively high elongation to break (30–40%), and excellent elastic recovery from small deformations, for example, 90 to 95% at 1% extension. At higher extensions (above 10%), the recovery is only 50 to 60%. The moisture regain of acrylic fibers varies between 1 to 3%. Acrylic fiber sticks to metal surfaces at 215–255°C when pressed against them. At high temperatures the fibers decompose, as acrylic fibers do not have a typical melting point. Acrylic, being a thermoplastic material, can be heat set for dimensional stability. Acrylic fibers have a good resistance to all normally used chemicals in textile processing, which include dilute acids and alkalis, bleaching agents, and dry cleaning solvents.

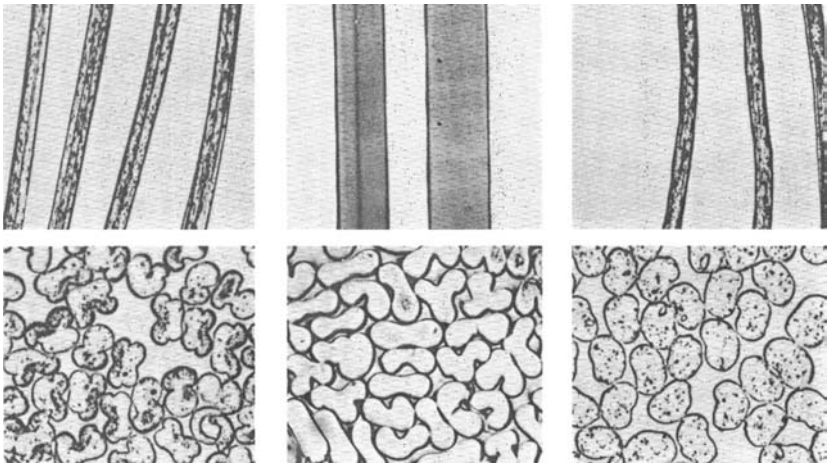


Fig. 2.34 Longitudinal and cross-sectional views of acrylic fibers. (From Ref. 6.)

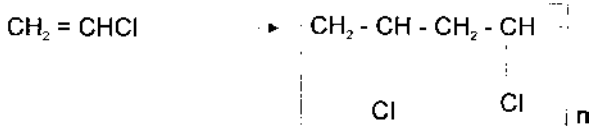
Acrylic fibers are used extensively in furnishing fabrics, woven and knitted apparel, nonwoven felts and blankets, flocked fabrics, awning fabrics, and filtration fabrics.

Modacrylic Fibers. These fibers are spun from many different copolymers of acrylonitrile. The polymer contains less than 85% by weight of acrylonitrile units (—CH_2—CH(CN)—). However, like acrylic fibers, details of the chemical structure of individual modacrylic fibers are seldom made available by different manufacturers. Verel® is a modified acrylic fiber containing between 35 and 85% acrylonitrile, first introduced by Eastman Chemical Products Inc. This fiber is manufactured in staple form, but in various deniers ranging from 3 to 40 in bright or dull luster. The modacrylic fibers are spun in 100% form or in blends with wool, cotton, viscose, nylon, and polyester.

The most outstanding characteristic of modacrylic fibers is their good dyeability. These fibers generally have higher moisture regain (3.5 to 4.0%) in comparison with other acrylic fibers, their tenacity ranges between 15 and 21 cN/tex, and breaking extension of 30 to 35% under standard atmospheric conditions. Despite higher moisture regain of modacrylic fiber, its mechanical properties are only slightly affected. This fiber has very good flame retardancy as it self-extinguishes but does not get ignited easily.

The 25:75 blend of modacrylic and cotton is most commonly used for producing knitted goods, sports shirts, underwear, and children's garments. The softness of modacrylic fiber, whiteness, flame retardancy, and excellent shrinkage behavior are useful features, particularly in producing pile fabrics used for liner fabrics; floor coverings; trimmings for collars, cuffs, boots, and shoes; etc. Modacrylic fiber is also used in carpets because of its high resistance to abrasion and soiling, good covering power, and better dyeability. Industrial applications of modacrylic fiber include filter cloths, protective clothing, and fire-resistant upholstery fabrics. Modacrylics are also used for wigs.

Polyvinyl Chloride Fibers. These fibers are spun from polymers or copolymers of vinyl chloride:



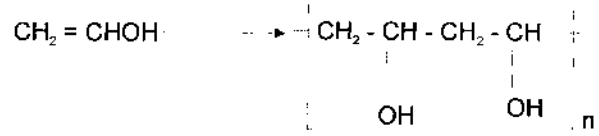
Polyvinyl chloride fibers may be further classified as follows:

1. Polyvinyl chloride fibers (100% PVC)
2. Vinyl chloride copolymer fibers
3. Chemically modified PVC fibers

These fibers are produced in a wide range of deniers both in staple and continuous filament forms. These fibers are smooth and rodlike and have nearly circular cross sections. The tensile strength of PVC fibers is around 24 to 27 cN/tex at an elongation at break of 12 to 20% irrespective of wet or dry conditions. The moisture regain of PVC fiber is virtually zero, and the fiber does not swell when wet. Therefore, the hydrophobic characteristics and excellent flame retardancy of PVC fibers are exploited commercially for making waterproof protective clothing by coating with PVC. However, PVC fiber has very poor thermal properties—it shrinks and softens on heating above 70°C—which restricts its application to high temperature applications. However, PVC fibers do not burn and have excellent resistance to acids, alkalis, and a wide range of chemicals and solvents. These fibers are very widely used in industrial applications such as filter fabrics, protective clothing, tarpaulins, awnings, gliders, and boats. PVC fibers are also used in furnishings and upholstery fabrics specifically for car seat coverings and hoods. PVC fiber is used for outerwear apparels to make water-resistant fabrics such as rainwear and sports

jackets. However, the thermal sensitivity of PVC fiber restricts their use on a wide scale for apparel end uses except in protective clothing.

Polyvinyl Alcohol (*PVA*) *Fibers.* These fibers are spun from polymers or copolymers of vinyl alcohol:

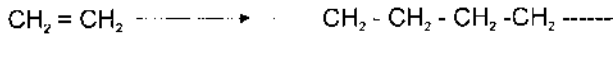


Vinyl Alcohol Polyvinyl Alcohol (PVA)

Polyvinyl fibers produced without being subjected to heat and aldehyde treatments after spinning have a tendency to dissolve in hot water. PVA fibers are, therefore, insolubilized after treatment with heat and formaldehyde. It is manufactured in continuous filament, staple, and tow forms. Staple fibers are produced in various deniers and lengths to make them suitable to process on cotton, woollen, and worsted spinning systems. PVA fibers have a smooth surface, are white with a silklike luster, and generally have a U-shaped cross section with a flattened tubelike appearance. They have excellent tensile strength (30 to 50 cN/tex) and a breaking elongation of approximately 15 to 25%. Also they have excellent impact and abrasion resistance, making them extremely durable. However, PVA fibers, because of the low elastic recovery, exhibit lower dimensional stability and wrinkle resistance. They have very high resistance to acids, alkalis, and many other chemicals used in the textile industry. In blends with cotton or rayon these fibers are used in various apparel applications including sportswear, interlining, socks, gloves, intimate garments, and dresses. The high durability, strength, and chemical resistance have enabled their use in many important industrial applications such as fishing nets, ropes, hoses, tarpaulins, tire cords, filter cloths, and sacks. The water-soluble fibers are used advantageously in surgical threads and scaffolding fiber and also to produce fancy and novel effects in yarns spun from blends containing PVA fibers so as to dissolve the PVA fibers subsequently.

Polyolefin Fibers. These fibers are spun from polymers or copolymers of olefin hydrocarbons, such as ethylene and propylene. The two most commonly used fibers in this category are polyethylene and polypropylene.

Polyethylene. When gaseous ethylene or its copolymers are polymerized a solid substance is formed which can be extruded to produce fine fibers:



Ethylene Polyethylene

Polyethylene fibers are commonly produced in the following forms:

1. Low density polyethylene (LDPE)
2. High density polyethylene (HDPE)
3. Gel-spun ultra high molecular weight (Spectra®)

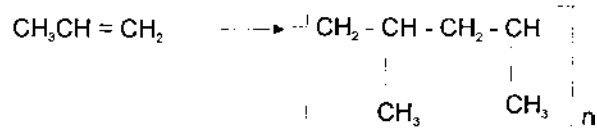
All three polymers can be spun into monofilaments in various diameters and also in spun-dyed form by incorporating pigments in the molten polymer. They are generally round in cross section, but can also be melt extruded in flat, oval, and other cross-sectional shapes to meet special end-use requirements. The mechanical and physical properties of polyethylene fiber are dependent on the conditions under which it is polymerized, spun, and stretched, because they affect the degree of branching of polymer chains. An increase in molecular weight and a reduction in the degree of branching tend to result in a higher tensile strength, stiffness, and softening temperature. The branching of molecules of low density polyethylene does not permit the high degree of crystallinity and molecular orientation, which would otherwise be possible in the case of polyethylene monofilament containing fewer or no branched polymers. For example, the tensile strength of polyethylene containing a high amount of branched molecular chains is around 8.8 to 13.2 cN/tex, whereas the linear polyethylene monofilaments are almost three to four times stronger, with a tenacity of 70 cN/tex. However, the tensile properties of various grades of polyethylene differ widely.

Low density polyethylene has poor tensile strength and a lower melting point, so it is used in certain industrial applications including ropes, cordage, filtration fabrics, and protective clothing. High density polyethylene fibers generally have higher crystallinity, tensile strength, stiffness, and softening point in comparison to low density polyethylene. Despite this, high density polyethylene cannot be used effectively in general textile/apparel applications due to its low softening point, difficulty of dyeing, poor resiliency, and crease resistance.

A recent development in this class of fibers is ultra high molecular weight polyethylene, commercially known as Spectra®. This fiber is characterized by ultra high strength and ultra low weight and is produced in a continuous filament form. On an equal weight basis, Spectra is 10 times stronger than steel. The tenacity of Spectra 900 and Spectra 1000 are 265 and 309 cN/tex, respectively, which is also slightly higher than that of Kevlar 29 (194 cN/tex). Elongation of Spectra 900 is 3.5%, and that of Spectra 1000 is 2.7%. The melting point of both Spectra 900 and Spectra 1000 is 147°C. The moisture regain of Spectra is only

1.0%. Spectra has excellent resistance to corrosive chemicals and solvents, a low dielectric constant, and excellent cut resistance. Spectra is most suited for ballistic applications, including armored panels, helmets, protective shields, and radomes. Due to its light weight and high strength it can be advantageously used in aircraft armor, vehicle armor, and naval armor. In composite forms, Spectra can also be used for boat hulls, sports equipment, structural supports, and pressure vessels. The high cut resistance of Spectra is useful in such applications as gloves for surgeons, tailors, and butchers.

Polypropylene. These fibers are spun from the polymers or copolymers of polypropylene:



Propylene Polypropylene

The polypropylene molecule consists of a long chain of carbon atoms with the bulky methyl groups attached to the sides of the chain to form a three-dimensional structure. The polypropylene structure takes a variety of forms differing in their spatial arrangements. Depending upon the stearic arrangements of the side groups, the polypropylene molecule can be classified into three groups, namely, (1) isotactic, (2) syndiotactic, and (3) atactic polypropylene. This stearic arrangement of polypropylene molecule has an important influence on the ability of the polymer to form fibers. The isotactic structure of the polypropylene molecule is characterized by the regular repetition of units of the same configuration and the location of side groups on the same side of the molecular back plane. In the syndiotactic structure, the methyl groups alternate on each side of the plane in a regular sequence; whereas in atactic polypropylene the methyl groups are randomly distributed on both sides of the backbone plane along the polymer chain. The regular stearic arrangement of isotactic and syndiotactic polypropylene fibers enables the molecules to form a compact structure due to coherent packing in an ordered manner. This increases the degree of crystallinity and allows close packing of the molecular chain, resulting in better tensile strength of the fiber. On the other hand, due to the irregularity of the stearic structure of atactic polypropylene, the fiber is predominantly amorphous.

Polypropylene fibers can be produced in a number of different forms and physical properties by varying the conditions of polymerization, spinning, and processing. Polypropylene fibers are produced in the form of multifilament, monofilament, staple, and tow. The fibers are also produced in a wide range of pig-

mented and spun-dyed forms. In recent years, some dyeable forms of polypropylenes have also been produced commercially. But such fibers usually have poorer mechanical properties. Polypropylene fibers are produced in a variety of different tenacities to suit specific end-use requirements. For general purpose textile uses, fibers with a medium tenacity of 26 to 44 cN/tex are used. For certain special applications, they are produced with a higher tenacity of up to 115 cN/tex. The density of amorphous polypropylene is 0.85 g/cm^3, and that of highly crystalline polypropylene varies from 0.92 to 0.94 g/cm^3. Thus polypropylene fibers are lighter than water and have a covering power greater than that of any other textile fiber. Polypropylene does not absorb any water, and its moisture reagin is negligibly low. The softening point of polypropylene fibers is in the region of 150°C, and the fibers melt between 160 to 170°C. Polypropylene fibers burn when exposed to flame but extinguish when removed from the flame. Polypropylene has the lowest thermal conductivity and therefore exhibits the ''warmest'' feel. It has excellent resistance to alkalis, acids, and general purpose organic solvents and laundry agents. However, polypropylene fibers are prone to UV degradation. Consequently, UV stabilizers and flame retardant additives are blended with the polypropylene chips before melt spinning. Polypropylene fibers have excellent processing behavior because their fiber-to-fiber friction is high, and they have good crimp retention behavior. Polypropylene fibers have high abrasion and bending resistance, which are particularly important for their applications in carpets and floor coverings. Polypropylene fibers are extensively used in blankets, upholstery, carpets, ropes, fishing nets, and fishing lines. In apparel applications, 100% pure polypropylene fiber is used in the knitwear field for sportswear, socks, stockings, and hosiery and in blends with other cellulosic fibers, such as rayon.

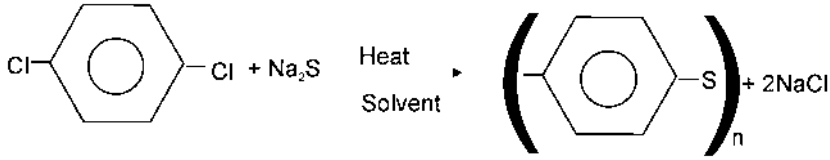
Polyurethane Fibers. These are elastomeric fibers and have elasticity similar to natural rubber. Commercial fibers are known by the names of Spandex® and Lycra®. The rubberlike elasticity is one in which the fibers, when stretched to several times their original length and released, instantaneously recover their original length almost completely. Spandex fibers are long-chain synthetic polymers composed of at least 85% of a segmented polyurethane. The fiber consists of a soft and a hard segment. The elasticity of the Spandex material is derived from its long, folded polymer molecules linked together at intervals by chemical bonds. When the filament is pulled, the long molecules unfold and the yarn stretches. The amount of deformation is restricted by the links between the molecules; when the tension is released, the long molecules tend to revert back to the folded state, and thereby the filament snaps back to its original state. To obtain such soft, rubberlike regions in the polymer chains, two classes of compounds such as polyester and polyethers are used. The polymer is formed by linking preformed segments of polyester or polyethers via the urethane group,

resulting in linear molecules, or they may be branched together with cross-linking to form a three-dimensional structure.

The segmented polyurethanes, such as Spandex, are spun into either monofilament with round cross section or partly fused multifilament yarns. Some monofilament yarns are formed by cutting thin ribbons from an extruded sheet. Because of their segmented structure, Spandex fibers may be made stronger than natural rubber filaments. The breaking tenacity of Spandex is about 5 to 9.5 cN/tex, compared to 2.2 cN/tex for natural rubber. The breaking elongation of Spandex filament ranges between 450 to 700% depending upon the denier and the type of Spandex fiber. They have excellent elastic recovery behavior, very low moisture regain (1 to 1.3%) and good resistance to acids, alkalis, and most commonly used organic solvents and laundry agents. Spandex is a thermoplastic fiber with a softening point of about 150°C and melting point in the range of 230 to 290°C.

The bare Spandex filaments are used in stretch fabrics, foundation garments, swimwear, and hosiery. Spandex base covered yarns are made by winding yarn of another fiber around the Spandex filament in a spiral arrangement. Such yarns are used primarily for foundation garments. The core-spun yarn is one in which the nonelastic fiber sheath made of cotton, wool, acrylic, polyester, etc., is spun around an elastomeric core, such as Spandex. The core-spun yarn is used in producing a wide range of woven fabrics such as lawn, heavy ducks, stretch denim, and stretch dress materials. The core-spun spandex yarns are also used in knitted fabrics to enhance recovery from stretching and thereby improve the dimensional stability of knitted garments.

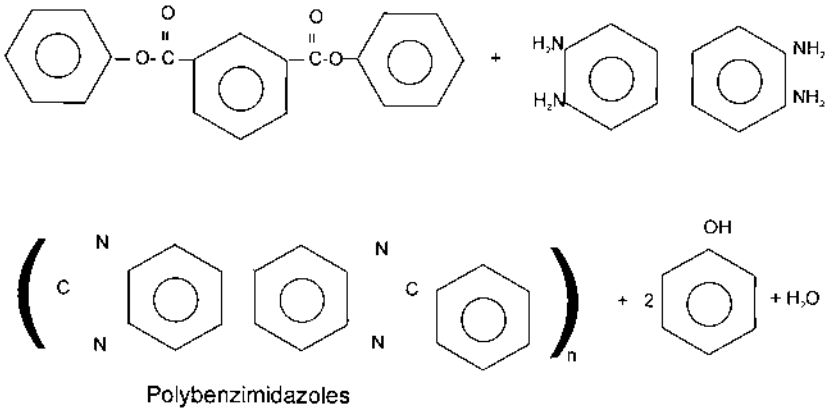
Polyphenylene Sulfide (*PPS*). These fibers fall under a new generic name, Sulfar, in which the fiber-forming substance is a long chain synthetic polysulfide with at least 85% of the sulfide linkages directly attached to two aromatic rings. The most important commercial fiber in this class is Ryton®, made by polymerizing para-dichlorobenzene in the presence of sodium sulfide as follows:



The most outstanding property of polyphenylene sulfide fiber is its high heat and chemical resistance, self-extinguishing flame retardancy, electrical insulating

property, and excellent resistance to acids, alkalis organic solvents, and oxidizing agents, besides good mechanical and physical properties. This unique combination of various properties is advantageously used in woven or nonwoven form for applications subjected to elevated temperatures, for example, filter bags for filtration of flue gases from coal-fired boilers. Other important applications include papermakers' felts, protective clothing, composites, and electrical insulation materials.

Polybenzimidazoles (*PBI*). These fibers contain linear polymers with repetitive units containing equal parts of benzimidazole [77]. A polymer of high temperature stability, nonflammability, and high chemical resistance, PBI can be made into a fiber which exhibits exclusively excellent textile and tactile performance properties not found in many other synthetic fibers. The polymer is prepared by condensation of 3,3′,4,4′-tetra-aminobiphenyl (TAB) and diphenyl isophthalate (DPIP):



Polybenzimidazoles

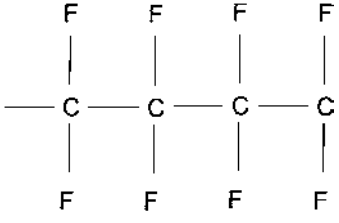
Polybenzimidazole is spun by the dry spinning process. A polymer solution or spinning dope is extruded through small holes, and the solvent is evaporated away from the fiber on its route to the winder. The spun fibers are then subjected to washing, drawing, and acid treatment before final take-up.

Polybenzimidazole fiber is produced both in filament and in staple fiber form with a round cross section. The stabilized variant of PBI sold as a staple fiber has a tenacity of about 2.3 cN/tex, with 30% breaking elongation and an initial modulus of 39.6 cN/tex. The density of the fiber is 1.43 g/cm^3, and moisture regain is 15% at standard atmospheric conditions. PBI is intrinsically nonflammable in air [78,79]. However, the mechanical behavior of fibers at elevated temperatures is adversely affected. The tenacity of stabilized PBI drops by almost 75% when the fibers are heated from 100 to 450°C, whereas the elongation

of the fibers remains practically constant up to 350 to 370°C and then drops rapidly from 30 to 5% at 450°C [77]. PBI fibers exhibit outstanding chemical stability even in severe environments, and the fiber strength is unaffected by exposure to organic liquids at 86°C for 168 h [78,79]. The high moisture regain (15%) of PBI fibers together with their soft handle contribute to wear comfort, which is as good as that of cotton and rayon.

The nonflammability properties and wearing comfort of PBI fibers are advantageously used for protective clothing for firefighters, protective hoods and helmet liners for firefighters and racing car drivers, garments for welders, and protective gloves in foundries. The special applications of 100% PBI or 40% PBI/60% high modulus aramid blended fabrics include uniforms for racing car drivers, aircraft pilots, military flight suits, and astronauts' suit as well as aircraft seats.

Polytetrafluoroethylene (*PTFE*). DuPont pioneered the development of PTFE, commercially marketed under the brand name Teflon®, as a nonstick coating for cooking utensils. It was observed that tetrafluoroethylene ($CF_2{=}CF_2$) gas when polymerized forms a waxy, insoluble and nonmelting powder with many useful attributes. It is a polymeric compound based on fluorine, which is highly volatile and reactive element in its natural gaseous state. Tetrafluoroethylene is polymerized to PTFE under heat and pressure with the aid of a catalyst. It is not possible to extrude PTFE into fiber as it cannot be melted or dissolved in other media. Teflon fiber is produced from a spinnable composition containing a blend of finely divided particles of Teflon resin with a matrix containing binder. Teflon (polytetrafluoroethylene) is made up of chains of carbon atoms fully saturated by fluorine atoms. The chemical structure of Teflon fiber is:



Polytetrafluoroethylene

Teflon is produced in different forms, such as resin, dispersions, sheets, and fibers. Teflon fiber with circular cross section is available in multifilament yarns, staple, and flock, with different deniers, number of filaments, and staple lengths suitable for downstream processing into woven, knitted, and braided structures.

The color of Teflon fiber can be natural dark brown or in bleached white form, as required.

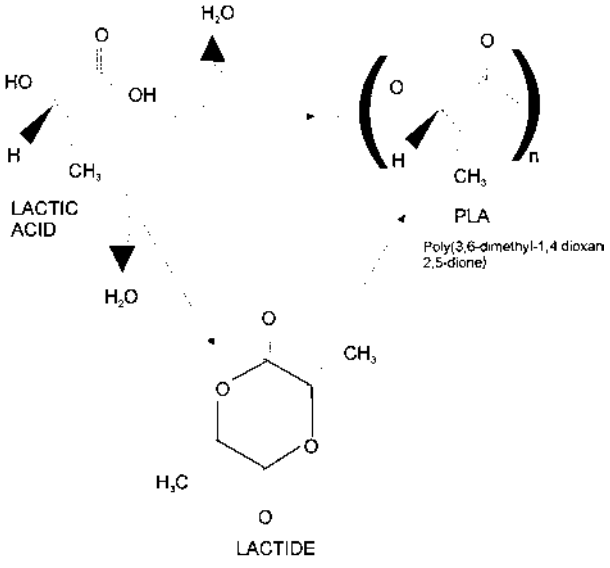
As fiber, Teflon contains long polymeric chains with high tensile and compressive strength. Teflon has a density of 2.2 g/cm^3, and it displays an excellent combination of physical, chemical, and thermal properties. Teflon can withstand temperatures up to 260°C continuously for an extended time with a short-term peak temperature of 290°C. At very low temperatures of about −268°C, Teflon fibers become less ductile but still remain serviceable in certain applications. Teflon fiber is extremely resistant to direct sunlight; an exposure to direct sunlight and weather for a period of three years has shown negligible reduction in breaking strength (2%). The coefficients of static and dynamic friction of Teflon are the lowest among all known fibers. Therefore, it finds increased applications where maintenance-free, nonstick, and easy-slipping attributes are desirable. Teflon fiber exhibits an elongation at break of 19%, with a moderate tensile strength of about 13 cN/tex. The tensile strength is not affected much by moisture content. The thermal shrinkage of up to 25% at 300°C is useful for thermal setting during the texturing operation. The low electrical conductivity of Teflon makes it useful as an electrical insulation material, particularly at high temperatures ranging between 175–290°C. The chemical resistance of Teflon fibers to all known acids, alkalis, halogens, and oxidizing agents is far higher than any known organic fiber [80].

Teflon fiber is used in many high-tech applications where its low friction coefficient and high heat and chemical resistances are required. Bearings, bushes, and other engineering parts; conveyor belts in food industries where hygienic nonstick conditions are necessary; high performance sewing threads; and hot-gas filtration bags are some of the end-use applications of Teflon fibers.

Polylactic Acid (PLA). A synthetic fiber manufactured from polylactic acid or poly lactate derived from naturally occurring sugars, such as those found in corn or sugar, is called PLA fiber [81]. Polylactic acid was discovered by Carothers (DuPont) in 1932. He produced a low molecular weight product by heating lactic acid in vacuum. He could not increase the molecular weight of the product, so they had to abandon their work. Subsequently in further work by DuPont, polylactic acid fiber was used in the medical field for sutures, implants, and controlled drug release applications. However, its use was limited due to the high cost of manufacture [82]. Recent development in the fermentation of dextrose obtained from corn has dramatically reduced the cost to manufacture lactic acid monomer—a raw material for PLA polymer [82]. This has opened up the possibility of making a biodegradable polymer from naturally renewable resources such as corn and beat, as opposed to petroleum-based polymers which

do not decompose when discarded. They have to be burned, causing further environmental pollution due to emission of carbon dioxide and dioxins in the air.

Polylactic acid is polymerized from lactic acid in two ways as shown:



In the first route, removal of the water molecule by condensation under high vacuum and temperature takes place. As a result, PLA is formed directly, producing a low to medium molecular weight polymer. In the second method, also known as the NatureWorks™ Process (Cargill Dow LLC), as shown above, the water molecule is removed under much milder conditions without using any solvent to produce a cyclic intermediate dimer, known as lactide. Further polymerization of the dimer occurs under heat, again without using any solvent. By controlling the purity of the dimer, a wide range of polymers with different molecular weights can be manufactured [82,83]. Unlike other synthetic fiber materials of a vegetable origin (e.g., cellulosics), PLA is well suited for melt spinning into fibers. Compared to the solvent-spinning process required for synthetic cellulosic fibers, melt spinning allows PLA fibers to be produced with both lower financial cost and lower environmental cost and allows the production of fibers with a wider range of properties [84]. PLA can be converted into a wide range of products such as fiber, film, bottle and paper coating, foam, resin for injection molding, etc.

Polylactic acid is readily converted into a variety of fiber forms, using conventional melt-spinning processes. Monocomponent or bicomponent, con-

Table 2.10 Key Performance Features of PLA Fiber

1. More hydrophilic than PET
2. Excellent hand, drape, and feel
3. Good resilience
4. Excellent crimp and crimp retention
5. Controllable shrinkage
6. Tenacity up to 62 cN/tex
7. Unaffected by UV light
8. Lower density than PET
9. Dyeable with dispersion dyes
10. Outstanding processibility
11. Controllable thermal bonding temperatures
12. Grades offer a range of crystalline melting temperatures from 120–170°C
13. Low flammability and smoke generation

Source: Ref. 82.

tinuous (flat and textured) and staple fibers of various types are easily produced. Primary applications of PLA are in fibers for woven, knitted, and nonwoven textiles [85]. Table 2.10 shows the key performance features of PLA fibers. PLA fibers have higher moisture regain and wicking properties than PET, which make them more comfortable to wear either in 100% PLA form or in blends with wool and cotton. The relatively high natural hydrophilicity, attributed to polar oxygen linkages in the molecular arrangement, improves the wettability and moisture vapor transmission rate of fabrics containing PLA fibers. This attribute also improves the breathability of garments. However, PLA fibers are not as wettable as cotton, but are better in comparison to PET or nylon. The lower modulus of PLA fibers leads to a better drape and handle of the fabrics. The PLA fiber has good self-extinguishing properties. The elastic recovery and crimp retention properties are better than that of PET, which leads to a better shape retention and crease resistance of the garments made from PLA. Table 2.11 compares key properties between PET and PLA fibers for apparel applications.

2.3 STAPLE YARN SPINNING SYSTEMS

Spinning is the final stage in the series of processing operations used for producing a staple yarn. In this process, two operations are performed consecutively, namely [86,87],

Table 2.11 Comparison of the Key Properties of PET and PLA Fibers for Apparel

Property	PET	PLA
Moisture management	Good wicking Contact angle = 0.135 0.2–0.4% moisture regain	Better wicking Contact angle = 0.254 0.4–0.6% moisture regain
Flammability	Burns 6 min after flame removal	Burns 2 min after flame removal
Resilience	51% recovery at 10% strain	64% recovery at 10% strain
Renewable resource	Petroleum based	Dextrose based (corn)
Drape/hand	Poor	Good
Luster	Medium to low	Very high to low
Crease resistance	Good	Excellent
Density (g/cm^3)	1.34	1.25

Source: Refs. 77 and 81–85.

1. Drafting (or attenuation) of an input fiber strand, usually a sliver containing anywhere from 20,000 to 40,000 fibers in the cross section, to a desired linear density of a yarn comprising approximately 100 fibers in the cross section
2. Providing cohesion to the fibers achieved by either twisting, entangling, wrapping, or bonding the fibers

The process of attenuation, more commonly known as drafting, is aimed at aligning individual fibers along the yarn axis, and the objective of the twisting process is to bind the parallel fibers to impart cohesion between fibers so as to resist slippage from the yarn matrix under axial tension. Such a twisted yarn is finally wound on to some suitable package. Thus the main functions of any spinning system may be signified by three processes:

Drafting
Twisting
Winding.

The manner of the execution of the three functions is unique for different spinning systems. The principles and the basic processes used in staple yarn spinning systems are discussed in the following sections.

2.3.1 Drafting and Fiber Transport

Drafting can be carried out either mechanically, pneumatically, or by a combination of these two actions. In ring and air-jet spinning, drafting is carried out me-

chanically by using a drafting system consisting of three pairs of rollers, as shown in Fig. 2.35. The fibers are firmly gripped in the nip of the bottom and the weighted top rollers. To reduce the number of fibers in the strand cross section, it is necessary for the fibers to slide past each other by overcoming the interfiber cohesion that occurs due to interfiber frictional forces. This requires a magnitude of drafting force greater than that of interfiber frictional force. The process of drafting is accomplished by driving the successive pairs of rollers at a higher surface speed than the previous pairs; the ratio of these surface speeds giving the nominal draft. The front pair of rollers is normally running at the highest possible speed. In a system of three pairs of rollers, there are two drafting zones. The first or back zone is designated the ''break draft,'' while the second or front zone is called the ''main draft''. The magnitude of break draft is usually small, varying between 1.1 and 1.5; therefore the front draft (i.e., main draft) is responsible for the major part of the total attenuation desired. The total draft is defined as the ratio of the surface speed of the front rolls to the surface speed of the back rolls and is a product of the break draft and the main draft:

$$\begin{aligned}\text{total draft} &= \text{break draft} \times \text{main draft} \\ &= \left(\frac{V_{\text{middle}}}{V_{\text{back}}}\right) \times \left(\frac{V_{\text{front}}}{V_{\text{middle}}}\right) \\ &= \frac{V_{\text{front}}}{V_{\text{back}}}\end{aligned}$$

where V is the surface speed of the respective roller pairs.

Although it is desirable that during the process of drafting the strand attenuation remains uniform, the condition is seldom achieved in practice because

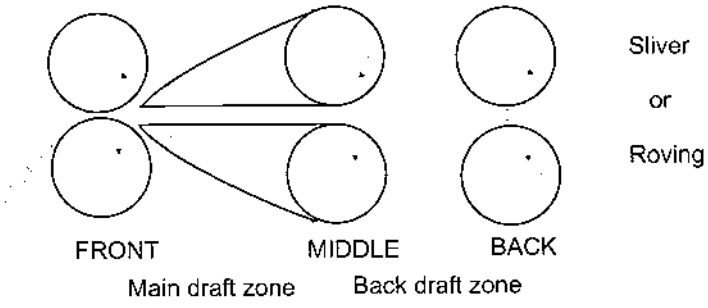


Fig. 2.35 Schematic diagram of drafting system.

the fibers between two pairs of rollers move forward in only a partially controlled manner, giving rise to irregularity. During the process of drafting, fibers are transported between the rollers by the drafting forces. The considerable length variation between fibers poses a formidable problem for the effective and controlled transportation of fibers between rollers. Fibers having a length greater than the nip to nip distance between the two pairs of rollers are transported in a much more controlled and guided manner since any end of the fiber may be gripped by either of the nips. If such longer fibers are gripped at both ends by the nips, with one pair of rollers moving at a higher speed, the fibers are likely to be stretched if the exerted drafting force exceeds the elastic limit of such fibers; otherwise the fibers will be pulled out from the back nip due to differential tensions. Such fibers once pulled out of one nip will drag other fibers in their vicinity and form a clump. The fibers shorter than the nip to nip distance move uncontrolledly and are commonly termed ''floating'' fibers. Such floating fibers, moving at different speeds, are responsible for causing unevenness.

In open-end rotor spinning the input sliver is drafted and transported by a combination of mechanical and pneumatic actions. Since the principle of rotor spinning demands the attenuation of input sliver to almost individual fibers, it is impossible to use the conventional roller drafting mechanism. The speed of the front roller will be abnormally high to manage the delivery of fibers both mechanically and economically. Therefore, an opening (combing) roller rotating at a speed of approximately 5000 to 7000 rpm is used to ensure individualization of fibers. The fibers are then transported pneumatically through the feed tube to the rotor for twisting. The principles of drafting and transportation in friction spinning are similar to those of open-end rotor spinning.

2.3.2 Twisting

The type of spinning system determines the twisting process, which varies as the underlying principles of various systems used are inherently different. In ring spinning, the ring and traveler form a twisting unit. In its passage from the nip of the front rolls to winding on the spinning bobbin, the yarn is threaded through a traveler. Therefore, for every rotation of the bobbin mounted on the spinning spindle, the traveler also rotates and one twist is inserted. The traveler is negatively driven by the dragging force of the yarn while the differential in the rotational speed of the spindle and the traveler helps accomplish winding of the yarn on the bobbin. Though this twisting method is simple and well proven for twist insertion, the productivity of ring spinning is limited due to the following two reasons:

1. For higher productivity, an increase in spindle speed is limited by the speed of the traveler, which cannot rotate faster than 35 to 40 m/s on a nonlubricated ring. At higher speeds, burning of the traveler may occur more frequently due to the heat generated by the friction between the ring and the traveler. The obvious answer to this problem may be to use a rotating ring; however, it does not reduce the cost of yarn manufacturing.
2. With an increase in spindle speed the power consumption increases as the energy consumed to rotate the yarn package will be higher.

The limitations of increasing the speed of twisting in ring spinning have been overcome in other spinning methods, e.g., in open-end rotor and friction spinning. The twist insertion and yarn winding operations are separated to avoid the necessity of rotating the yarn package at higher speeds. In open-end spinning, the twist insertion element is a rotor of relatively low mass. The attenuated fiber mass is transported to the rotor wall, via the feed tube, forming the characteristic open end. Each rotation of the rotor inserts one twist to this open end of the yarn, which has led to the possibility of increasing the speed of twist insertion and thereby spinning. Rotor speeds in excess of 150,000 rpm are used today.

The other methods of twist insertion include wrapping a yarn or a filament(s) around a strand of attenuated fibers as in wrap spinning, wrapping the outer surface fibers over a core of fibers as in air-jet spinning, and rotating the yarn tail on a frictional surface as in friction spinning. In the newer spinning systems, although the limitation of twisting speed is eliminated by adopting innovative methods, the problems of high-speed fiber drafting and the rate of transportation of fibers still remain.

One significant development still in progress is electrostatic spinning, in which the fibers are electrostatically charged and accelerated between the drafting unit (which is usually a cathode) and twisting unit (usually an anode), where they are twisted. This method, reported by workers from the USDA and China, is still undergoing development; however, its commercial exploitation is yet to be realized.

Self-twist spinning is a process in which the rotating drafting rollers are given transverse movement to insert twist both in the S and Z directions alternately, as shown in Fig. 2.36. If two strands are fed to the drafting unit, then they will twist and untwist alternately among themselves to give a coherent yarn structure [87]. This form of twisting, and the yarns produced, are unsuitable for many applications, and its use is largely limited to long staple spinning, e.g., worsted spinning, and particularly for producing high bulk

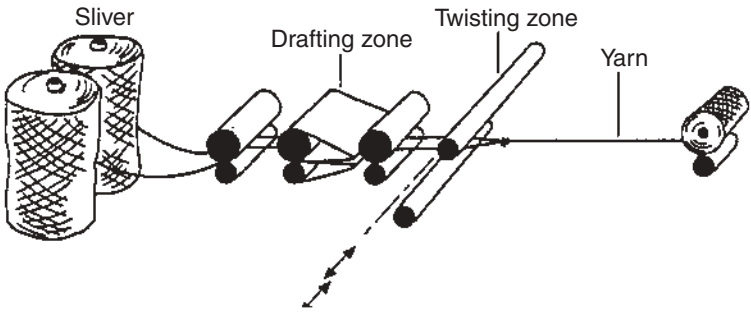


Fig. 2.36 Yarn formation in self-twisting spinning. (From Ref. 81.)

acrylic yarns for knitting. The latter do not require any up-twisting, making the production both high speed and economical.

2.3.3 Ring Spinning

Ring spinning came into existence with the invention of the ring frame by John Thorpe in 1828 and the traveler by Jenks in 1830 [88]. Despite many modifications that have taken place since then, the basic concept has essentially remained the same. Although the newer spinning systems offer a strong competition for traditional ring spinning, the versatility of the ring spinning system, particularly in terms of producing high quality fine yarns and its ability to spin any type of fiber, provides major advantages. In addition, ring spinning has also seen a resurgence due to automation in material handling and continuous operations of spinning and winding—a limitation in the traditional system.

The basic operations of drafting, twisting, and winding take place successively, as shown in Fig. 2.37. The roving from the bobbin mounted on a creel at the top is taken through the traversing eye guide before being fed to the drafting zone for attenuation. The drafting unit usually consists of two zones in a 3 over 3 rollers arrangement, as shown in Fig. 2.35. The movement of short fibers is controlled in the main drafting zone with the help of an apron, which supports their movement and minimizes the irregularity caused by the floating fibers. The drafting rollers are inclined at 45 to 60 degrees to the horizontal to enable the twist propagation from the traveler to the nip of the front rollers.

The fiber strand emerging from the nip of the front roller is threaded from the lappet, or pigtail, through the traveler, which sits on the ring and

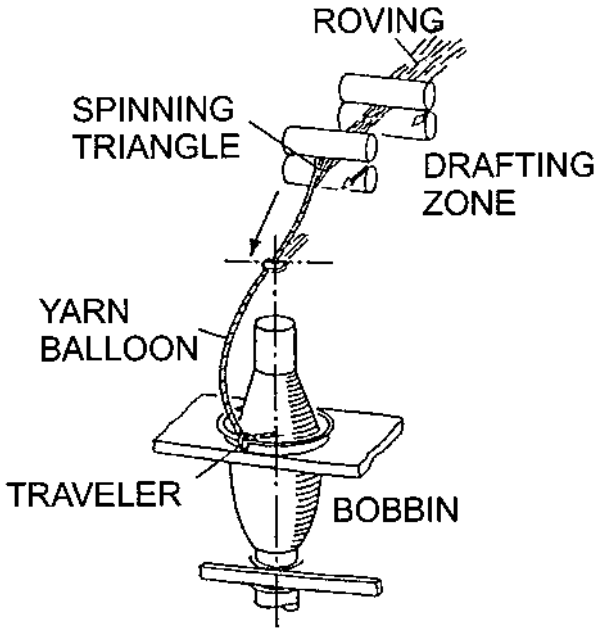


Fig. 2.37 Principles of ring spinning. (From Ref. 87.)

travels around the ring, and then onto the bobbin mounted on the spindle. The spindle rotates at anywhere from 10,000 to 20,000 rpm. The higher speeds have been possible due to the new design of the ring and the individual spindle drive where vibrations due to the tape drive have been eliminated. The yarn rotates between the nip and the traveler by virtue of the movement of the traveler around the ring. The twist so inserted flows to the nip of the front rollers. The differential in speed between the traveler and the spindle controls the rate of winding the yarn onto the bobbin.

Ring spinning has been encountering tough competition from modern spinning systems, which operate at higher throughput rate, provide larger package size, and yield good quality yarns. Consequently, developments have also been taking place continuously in ring spinning. Such developments include balloon breaking devices, better control of yarn tension, an improved top-arm drafting system for better fiber control, and better design of the ring spindle

and bolster. Recent developments have included doffing and donning mechanisms to automate the operations to reduce human involvement and thereby increase spindle allocation. The successful linking of the ring spinning frame to the winding unit has made the two processes continuous, thereby eliminating the need to have manual transportation of the materials between them. The use of an individual motor-driven spindle has helped eliminate the package-to-package irregularity which is commonly encountered in tape-driven spindles. However, further developments of the ring frame to increase speed have reached their limits, and further radical changes in the basic spinning systems are not anticipated.

As already understood, the biggest limitation to increasing the speed of ring spinning lies in the speed of twist insertion; the whole package has to be rotated, which consumes extremely high amounts of energy, especially at higher speeds. This upsets the economics of yarn production and makes the increase in spindle speed beyond 25,000 rpm prohibitive. Furthermore, the yarn tension increases with the square of the spindle speed, thus causing very high end breakage rates at higher speeds. With an increase in spindle speed, the traveler speed also increases, and as a consequence the heat generated at the ring–traveler interface may cause the traveler to overheat. The ring spinning speeds depend upon the size, the shape, and the contour of the ring. The ring, having lower center of gravity and larger contacting surface, dissipates the generated heat much faster. A good combination to attain higher speeds may be elliptical travelers and antiwedge rings.

A new system for ring spinning is reported in Russia where the ''super-traveler'' technology is used. With this technology, a ring with a rolling traveler is used instead of the traditional gliding traveler as commonly used in conventional ring spinning. It is claimed that with this rolling traveler system, the speed of the traveler can be increased to up to 100 m/s due to the associated reduction in friction [89]. A schematic view of the new ''super-traveler'' spinning system is shown in Fig. 2.38. The technology is claimed to offer a solution to a whole range of problems related to the spinning/twisting process, such as lowering energy consumption, improving life of the rings, and reducing wear of the travelers, resulting in a concomitant reduction in end breakage rate and the cost of spinning. Practical trials on cotton, with a yarn count range of 10 to 75 tex, have been reported [89].

2.3.4 Open-End Spinning

The theoretical basis of the open-end spinning principle is the introduction of a ''break'' in the otherwise continuous process of drafting, fiber transportation,

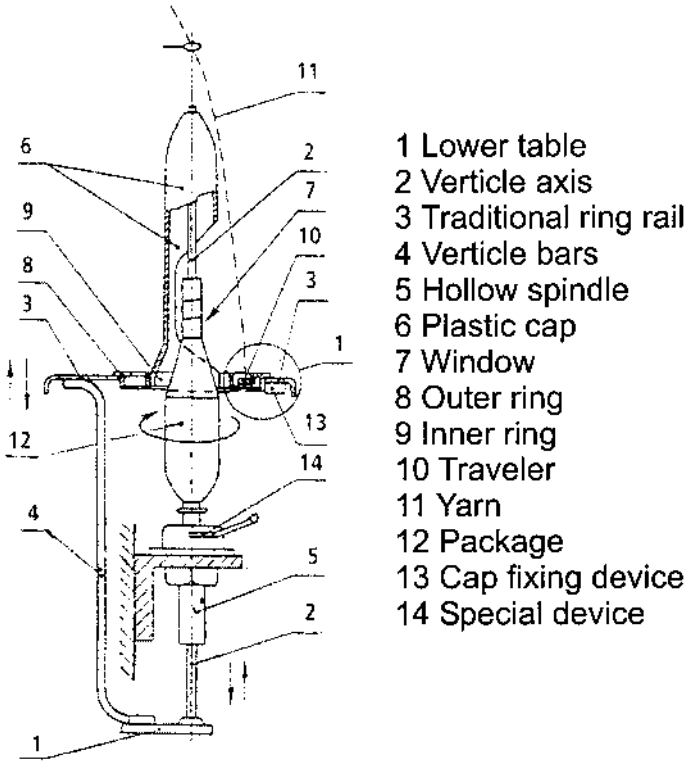


Fig. 2.38 Schematics of a ''super-traveler'' spinning system. (From Ref. 89.)

twisting, and winding. The schematic diagram illustrating the underlying principle is shown in Fig. 2.39. As the fibers flow from the supply strand, commonly a sliver, discontinuity is introduced at point A before transporting them to point B, where they are collected before being subjected to the twisting element. This creates a small open end of the yarn. It is much easier and more economical to rotate this open end to impart twist than to rotate the whole yarn package as occurs in the conventional ring-spinning system. A characteristic of

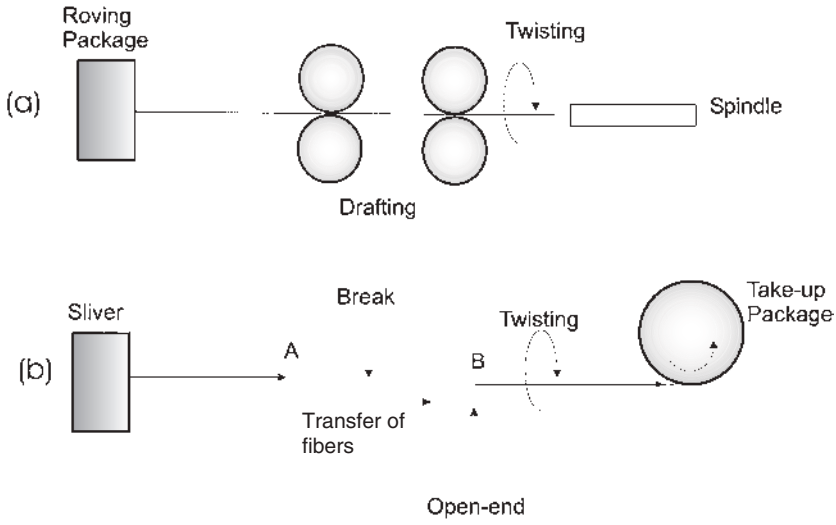


Fig. 2.39 Schematic of (a) ring spinning and (b) open-end spinning principles. (From Refs. 91 and 93.)

this process is the separation of the process of twisting and winding, which enables an increase in spinning speed and a reduction in the production cost of the yarn per unit weight. The yarn is then withdrawn at the necessary rate to obtain the desired twist and linear density in the resultant strand.

To introduce the open end (or break) during the process of spinning, it is required to reduce the fiber flow to just a few fibers in the cross section, which necessitates a very high draft to ensure individual fiber separation. Ideally, the individual fiber separation before being reassembled at point B is necessary for preventing the twist from running back to the fiber supply to avert otherwise false twisting. This system of yarn formation has several advantages, such as the elimination of the effects of air drag and no balloon formation. The need to revolve the take-up package at high speed is completely averted because of the introduction of a break in the flow of fibers and thereby forming a small open end. Ideally, the device employed to rotate such a small open end is also small and light, so the power required to rotate is also low. The function of the take-up package, which rotates at lower speed, is just to collect the yarn, and it can therefore be reasonably large so as to avoid the

rewinding process and thereby yield a long and continuous length of knot-free yarn.

Rotor Spinning

Among the many different forms of open-end spinning developed, rotor spinning has been the most successful and commercially exploited. The early developments were too cumbersome to operate at high speeds. The chronological developments of the various open-end systems and their classification have been extensively reported [90–93]. Rotor spinning was first successfully developed in Czechoslovakia (now the Czech Republic) in the 1960s. The increasing market share of rotor spinning indicates the wide-scale acceptance of the system. The ease of incorporating automation and the possibility of operating at very high speeds (rotor speeds of 150,000 rpm and even beyond) have led to a revolution in the yarn production industries and a serious competition to ring spinning in the coarse and medium count range.

The phases of operations in any rotor spinning system can be divided into six parts, namely, (1) drafting, (2) fiber transport, (3) fiber consolidation, (4) twisting, (5) yarn removal, and (6) winding. The feed sliver with a linear density of 3 to 4 ktex (3–4 g/m) is subjected to drafting by the opening roll containing metallic wires, as shown in Fig. 2.40. The opening roll, operating between 6000 and 8000 rpm subjects the input sliver to a combinglike action to ensure individual fiber separation. The fibers should be completely peeled off from the opening roll and transported to the rotor without disturbing their orientation. This is achieved by means of an air flow with a velocity exceeding that of the velocity of the fibers lying on the surface of the combing roll. This in turn is achieved by the vacuum generated inside the rotor moving at a very high speed. The fiber transport passageway from the opening roll to the rotor should be smooth and straight to ensure deposition of fibers straight on the V-shaped inside wall of the rotor. The fibers entering this collecting surface of the rotor are in a thin stream, and it may take several such streams to make up sufficient mass to make the yarn. The V-shaped groove of the inside wall of the rotor and the centrifugal force generated due to its rotation lay the fibers compactly. The process is similar to that of doubling and drafting, which take place in traditional roller drafting to even out short-term unevenness in the yarn. For every rotation of the rotor, the actions of depositing fibers on the collecting surface of the rotor and the peeling off of the yarn from this collecting surface cause interference. These incoming fibers come into contact with the rotating yarn tail, which facilitates the peeling-off of the fibers and getting them incorporated into the body of the yarn, as shown in Fig. 2.41. Each

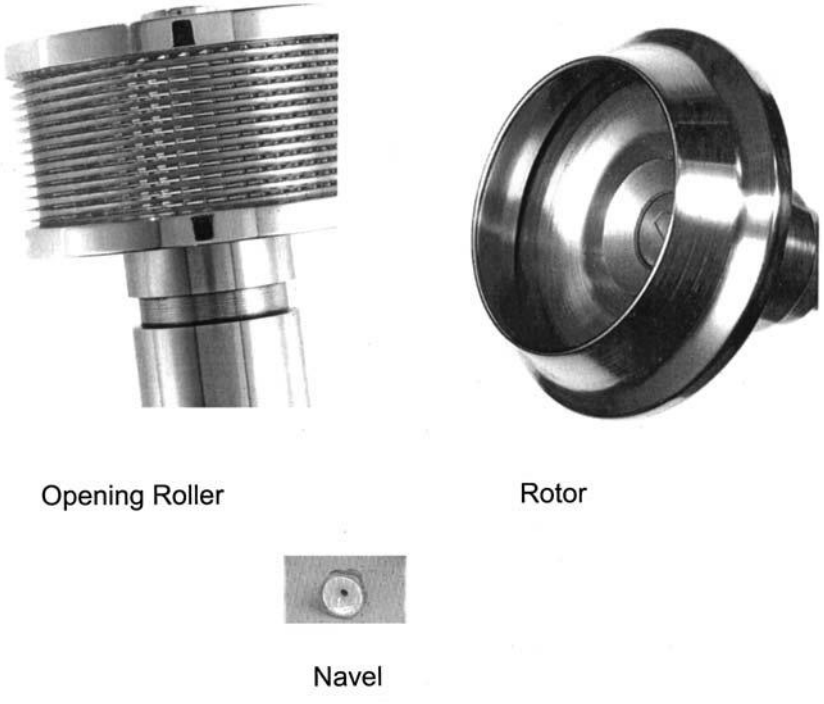


Fig. 2.40 Main elements of rotor spinning. (From Schlafhorst Technical Bulletin.)

rotation of the rotor causes approximately one turn of twist to be inserted and a yarn length equal to one turn of twist to be taken off. The yarn is then withdrawn through the nonrotating doffing tube, more commonly known as a navel (Fig. 2.40), at the center of the rotor and onto the winding package. The withdrawing of the yarn can be performed either in an axial or tangential direction; however, the latter is preferred as it enhances the fiber orientation and parallel arrangement [94]. The winding function of an open-end spinning machine is separated from the twisting, and the yarn is usually taken up at a constant speed as it is delivered from the feed tube. This permits the building up of a large surface-driven yarn package resting on the rotating grooved drum of the yarn winder. The yarn package is generally a cross-wound cheese or cone weighing approximately 3.5 kg.

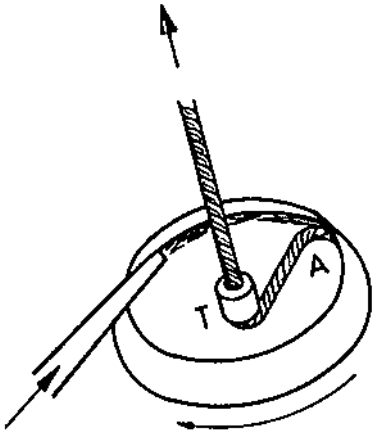


Fig. 2.41 Peeling-off and twisting actions. (From Ref. 93.)

The factors which affect the spinning and yarn quality in rotor spinning are opening roll speed, rotor diameter, yarn tension, and the number of fibers in the yarn cross section. Typical rotor speeds of up to 150,000 rpm are used depending upon the type of fibers and the yarn count being spun. Very high opening roll speed will tend to cause fibers to rupture, thereby adding short fibers giving rise to yarn unevenness. The rotor diameter normally varies between 35 and 50 mm. The lower rotor diameter limit is determined by the staple length of the fiber being processed, and the higher one by the power consumption required to rotate it at high speeds. The rotor diameter and the angular velocity affect the spinning tension, P, which is generated in rotor spinning. This relationship is expressed by

$$P = \frac{t\Omega^2 R^2}{2}$$

where t is the linear density of the yarn, Ω is the angular velocity of the rotor, and R is the radius of the rotor.

The sliver fed to the rotor spinning machine should be well cleaned. Excepting in very coarse count spinning, where strength is not very important, finisher drawn sliver is often used. Some rotor spinning machines have an opening roll equipped with a cleaning edge or cleaning aperture built into it to extract a large proportion of the heavy trash. However, it is still important

that the input fiber mass is well cleaned during the early preparatory processes such as opening, cleaning, and carding. Otherwise the heavy build-up of deposits of dust particles and trash in the rotor wall affect the deposition of incoming fibers and hence the evenness of the outgoing yarn linear density. This poses a significant quality assurance problem in rotor spinning.

The uniformity of the rotor-spun yarn is largely dictated by the number of fibers in the yarn cross section; usually the minimum number required is around 80. The higher the number of fibers, the better the uniformity. However, it is also controlled by fiber fineness depending on the linear density of the yarn being spun, thus demanding the use of better quality fibers for spinning finer counts. Unlike in ring spinning, the problem of uncontrolled floating fibers does not exist. Generally, the opening roll controls both short and long fibers very well. This implies that the fiber stock containing a high proportion of short fibers should also generate comparatively good yarn regularity values. Fig. 2.42 demonstrates that rotor-spun yarns made from the same fiber stock containing a high proportion of short fibers have a better evenness than the corresponding ring-spun yarns. However, the strength and elongation of an open-end rotor yarn is another matter.

2.3.5 Air-Jet Spinning

Air-jet spinning in some ways is similar to ring spinning, although the yarn structure is similar to that of a rotor yarn. The successful development and commercial implementation of this new system is based on a fasciated yarn technology [95,96] in which the sheath fibers are wrapped around the core by a rotating air jet. In the fasciated yarn system developed by Du Pont [95,96], the false twisting zone consists of a pair of drafting rolls, an air jet, and take-up rolls, as shown in Fig. 2.43. The amount of twist inserted in one direction before the air jet is canceled by an equal amount of opposite rotations following the air jet. Du Pont's fasciated yarn technology was not exploited commercially. Consequently, there was a hiatus in the use of air as a media to twist fibers together to form a yarn until the development of the present air-jet spinning system. The fiber strand emerging from the delivery rollers of the drafting system is subjected to the twisting zone. The twisting element constitutes a pair of air-jet nozzles blowing strong air currents in opposing directions. Figure 2.44 shows the schematics of the air-jet spinning principle originally patented by Nakahara and Morihashi [97]. The figure shows the staple fiber sliver being drafted in the drafting system. The parallel and well-oriented drafted fibers emerging from the front rolls of the drafting unit are then passed

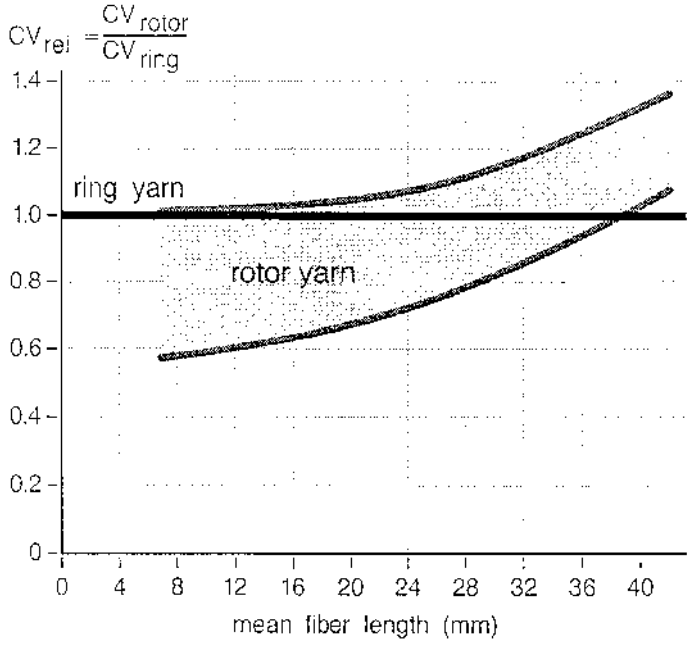


Fig. 2.42 Relative Uster evenness of rotor yarn as a function of the mean fiber length. (From Ref. 101.)

through a pair of nozzles successively placed between the drafting system and a take-up device. The essential elements of the spinning system are

1. Drafting of fibers
2. Intermingling of fibers
3. Yarn take-up

The drafting is performed by a 3 over 3 roller drafting system which is similar to that used in ring spinning. However, the draft ratios and the processing speeds are much higher than those in ring spinning. The problem of controlling fibers and guiding their transport between the drafting zones also remains, similar to that in ring spinning. Consequently, the problem of efficient control of short fibers, acting as floating fibers within the drafting zones, is difficult to solve. The yarn evenness of air-jet yarns deteriorates rapidly with an increase in the short fiber content of the input material. The yarn strength and uniformity

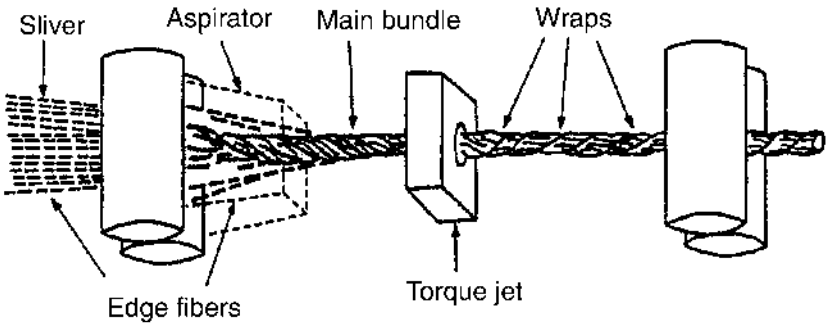


Fig. 2.43 Schematic diagram of the fasciated jet principle. (From Refs. 95 and 96.)

are positively influenced by the efficient control of fiber orientation and the speed of medium and long fibers through the spinning unit.

In the twisting zone, the drafted strand of fibers passes through a pair of air-jet nozzles. The compressed air at high pressure is blown through these nozzles in mutually opposite directions to produce swirling air currents. The first jet—closest to the delivery rolls of the drafting system—imparts twist to the leading ends of protruding fibers from the emerging strand while trailing ends are still gripped by the front rolls. Such fibers, usually lying at the edges of the ribbon, will not be subjected to the full twisting action imparted to the body of the yarn by the second jet and hence receive less twist than those in the body [95]. The second jet imparts false twist to the whole yarn flux in the opposite direction. Because of the higher air pressure used in the second jet, the false twist inserted runs back toward the front roll. As the yarn emerges out of the second jet the false twist is removed, and the body twist is reduced to zero. At this point, the low-twist surface fibers, which were twisted by the first nozzle, are untwisted to a greater degree than their original twist; this results in a true twist in the opposite direction to that of the twist imparted by the first nozzle [98–100]. The twisting nozzle requires a comparatively low yarn tension of the order of 10 cN for achieving good twisting efficiency. A lower yarn tension is beneficial with regard to spinning performance; however, it negatively affects yarn strength because in the twisting process fibers do not pack closely. In a less compact yarn structure, the frictional forces between the fibers are weak, which leads to poor yarn strength as a result of easy fiber slippage [101].

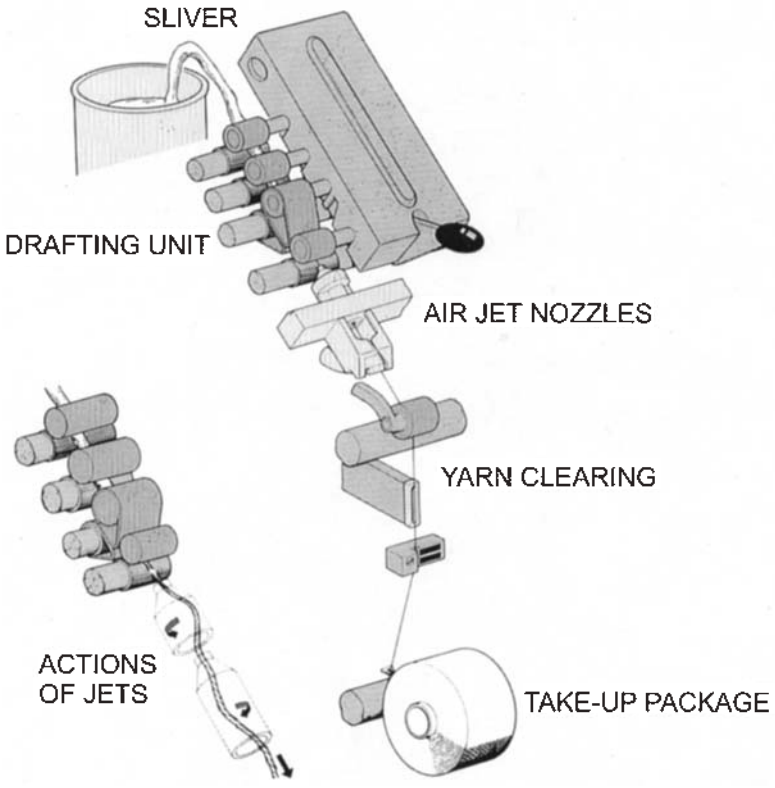


Fig. 2.44 Principles of air-jet spinning. (From Ref. 102.)

The air-jet spinning is very sensitive to the fiber length and fiber length distribution (short fiber content) of the material being processed. The amount of wrapping twist varies depending upon the length of the wrapping fibers as only a part of the total extent is utilized to wrap the core fibers. Wrapping fibers shorter than 12.5 mm practically do not make significant contribution to the strength of the yarn [101]. Air-jet spinning is suitable for processing medium and long staple combed cotton fibers and manmade fibers to produce medium to fine counts. Good fiber control is important in air-jet spinning; therefore, carded cotton sliver containing relatively high amounts of short fibers may not be used to produce fine count yarns.

2.3.6 Vortex Spinning

Vortex spinning is viewed as a natural evolution of the fasciated yarn spinning technology and is in essence an extension of the successful launch of air-jet spinning. It is also considered a major breakthrough in spinning technology because of the very high spinning speed (up to 400 m/min, almost 20 times that of ring spinning) attained with comparable yarn quality. The vortex spinning system marketed by Murata consists of a 4 over 4 drafting system and a yarn formation zone consisting of a stationary spindle around which the fibers are twisted by air currents coming from four nozzles, as shown in Fig. 2.45. The take-up of the yarn occurs through the center of the spindle and it is wound onto a cylindrical package [102]. A finisher drawing sliver goes directly to the drafting device similar in configuration to the air-jet spinner. The drafting system is capable of providing a draft of up to 200. The drafted fiber bundle is passed through an air-jet nozzle and a hollow spindle. The fibers coming out of the front rollers' nip line are sucked into a spiral orifice at the entry end of the jet nozzle, as shown in Fig. 2.46. The fibers are firmly held together when they move toward the tip of the needle, which protrudes from the entry end of the jet nozzle. The force of the airstream twists the bundle of fibers. The propagation of twist tends to flow upward; however, the needle, protruding from the spindle, prevents the upward movement of twists. This action causes the upper portions of some fibers to separate from the nip point of the front rolls and keeps them open. After passing through the orifice of the jet, the fiber ends expand due to the whirling force caused by the airstream, and they twine around the hollow spindle, which in turn get twisted into the fiber core. The yarn winds onto a package after the removal of defects by an electronic clearing device [103,104]. The distance between the nip of the front rollers to the tip of the spindle, as shown by the arrows in Fig. 2.46, is important in determining the characteristics of the yarn being spun. The higher the distance, the more opening of fibers takes place in the upper portion, resulting in a yarn that is closer to real twist characteristics [104]. If this distance is too large, an increase in waste fiber rate is possible. Murata recommends that the optimal distance between the nip of the front rollers and the tip of the spindle is slightly less than the average length of the fibers being processed [102,105].

Due to the unique yarn formation process employed in vortex spinning, the yarn produced exhibits the twist characteristics similar to that of a ring-spun yarn [106]. Vortex spinning also overcomes the problem faced in air-jet spinning, where processing cotton was not feasible.

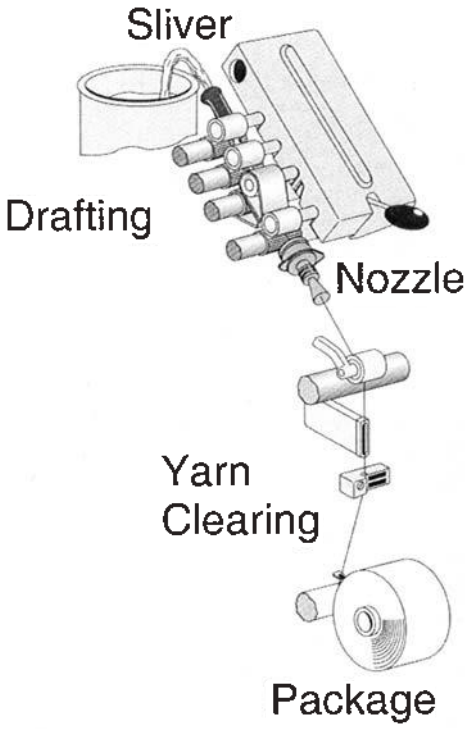


Fig. 2.45 Schematic diagram of Murata Vortex spinning. (From Ref. 102.)

2.3.7 Friction Spinning

Friction spinning is based on the principle of open-end spinning, where the limitation of the twisting speed (in other words productivity) on the winding operation is removed. In friction spinning of staple fiber yarns, the twisting torque is applied directly to the surface of the yarn through frictional contact between relatively slow-moving solid surfaces and the yarn being spun. The yarn rotates about its own axis, thus imparting twist and the spinning tension being relatively low.

The essential features of the friction spinning principle are shown schematically in Fig. 2.47. The input sliver is fed to the spiked opening roll which opens it up. Similar to the opening roller of rotor spinning, here also the opening

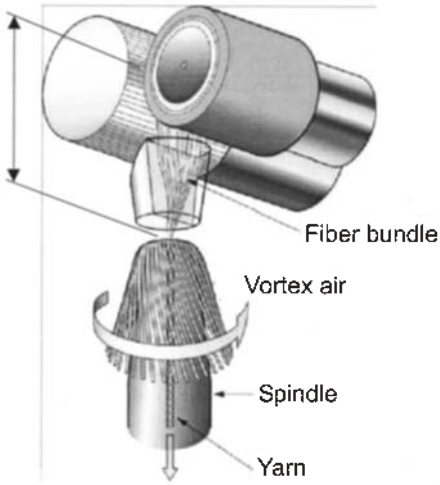


Fig. 2.46 Schematic diagram showing action of a vortex. (From Ref. 104.)

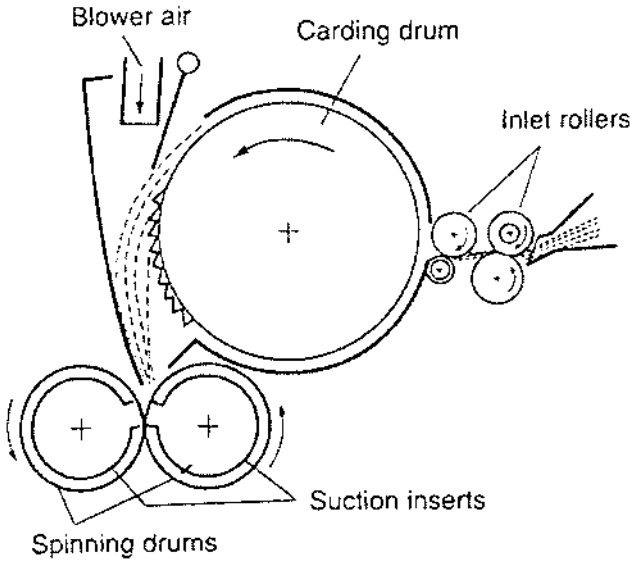


Fig. 2.47 Principles of friction spinning. (From Ref. 109.)

roller treats both short and long staple fibers in the same way. From the opening system, the fibers are carried with an air current through the feed tube toward the collecting surfaces, usually a pair of perforated drums. The yarn formation takes place in this area due to frictional forces between the frictional surfaces and the yarn tail forming an open end. Each revolution of the yarn tail around its own axis inserts one true twist in the yarn. Suction holds the tail end between the V of the pair of rotating drums. The yarn so formed is then withdrawn along the axis of the friction cylinders and wound onto a suitable package.

The fiber control between the opening roll and the friction drums is very poor because of the air currents generated. Consequently, the fibers lose their orientation, a phenomenon similar to what occurs in rotor spinning. Besides, the orientation of the fibers is further disturbed during yarn formation due to the fact that the relatively fast-moving fibers have to be deposited on relatively slow-moving frictional surfaces. The fiber orientation in friction-spun yarn is therefore inferior when compared to that in rotor yarns. This translates into the relatively poor strength of friction-spun yarn [101]. The yarn tension in friction spinning is quite low, ranging between 5 and 15 cN [107]. Such low spinning tensions do not allow proper fiber consolidation, resulting in a not very coherent yarn structure and hence relatively poor strength.

The insertion of twist and the yarn formation process in friction spinning are very complex [108,109]. The actual yarn tail is surrounded by a rotating fiber sleeve, as shown in Fig. 2.48. For spinning finer yarns, the number of fibers in this sleeve is so low that the chances of the yarn tail loosing contact with the flux of fibers in the sleeve and slipping out increase. Excessive ends down may occur even though the spinning tension is very low [109]. Though the strength of friction-spun yarns is lower than that of the equivalent rotor-spun yarns, the differences are smaller for finer yarns than for coarse yarns.

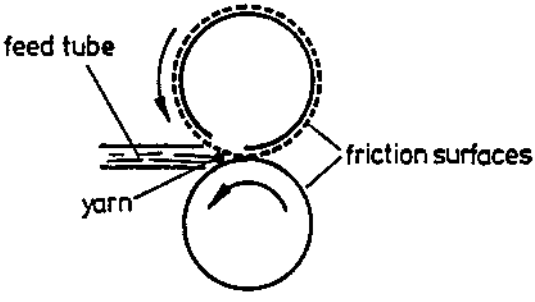


Fig. 2.48 Fiber transfer from feed channel to yarn. (From Ref. 110.)

In a nutshell, friction spinning is fairly flexible with regard to fiber length, but is best suited for handling short and medium staple fibers. Like rotor spinning, friction spinning is more economical and limited to coarse and medium count yarns and for producing specialty fancy yarns for household textiles.

2.3.8 Wrap Spinning

In the wrap spinning system, a continuous filament or another spun yarn is wound around a nontwisted core containing well-drafted parallel staple fibers. Figure 2.49 shows a schematic diagram of the wrap spinning process. The input strand is a roving fed to the drafting zone, which consists of a 3 over 3 roller drafting system. The drafted strand is then passed through a hollow spindle which carries the filament package. By rotating the hollow spindle, the package also rotates, and the filament is wound around the relatively untwisted staple yarn core. For each rotation of the hollow spindle, one wrap is inserted. This physical process resembles ring spinning, in which one rotation of the spindle inserts one turn of twist. The yarn is then taken off onto a package.

The twisting mechanism in wrap spinning is designed such that there is no balloon formation; consequently, the restriction to spindle speed due to traveler speed is eliminated as the system does not require the traveler for inserting a wrap. Due to the absence of a balloon, the yarn tension is also low. However, constraints to increase the spindle speed and therefore the productivity based on energy consideration obviously remain because the mass of filament package has to be rotated. Although the actual spinning speeds are somewhat higher, in the vicinity of 30,000 rpm, than in ring spinning, this may be attributed to the following reasons [110]:

Even though the whole package of the filament yarn is required to be rotated, the energy consumption is relatively low. This is due to the fact that a larger quantity of finer filament yarn can be accommodated on a relatively smaller package.

The filament package is enclosed, which helps to lessen the air drag and therefore the energy consumption.

The drafting system works somewhat faster than in ring spinning, but it is still slower than that of the open-end and air-jet spinning systems.

2.3.9 Compact or Condenser Spinning

All the new spinning systems, particularly rotor and air-jet spinning, considered as breakthroughs, were developed during the past few decades and were

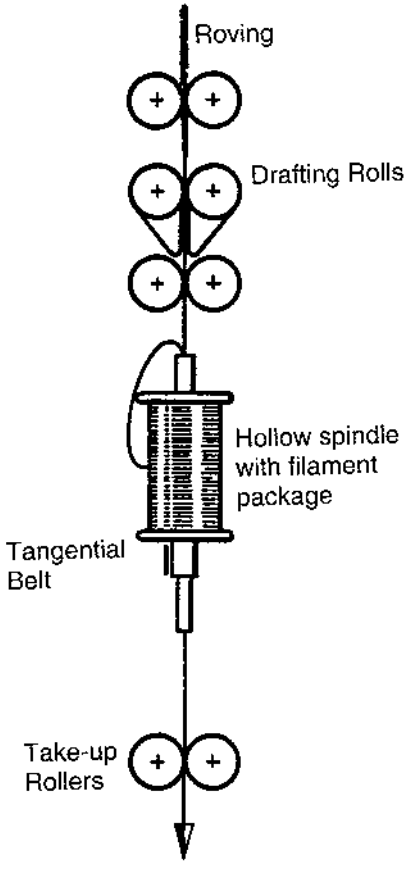


Fig. 2.49 Principles of wrap spinning. (From Ref. 110.)

aimed at improving spinning productivity. However, ring spinning has always remained at the forefront both as the most popular spinning process and as the quality benchmark. Ring-spinning frames produced by different textile machinery manufacturers may differ in respect to their engineering design, which may be evaluated in terms of reliability, spindle speed, power consumption, maintenance and repair characteristics, etc. However, even today little difference can be found in terms of the technological principles employed. Compact spinning represents a new process using the basic components of

the ring spinning system [111–116] but producing better yarn quality through the compacting of the yarn structure. This novel compacted structure produces yarns with higher strength and elongation, and reduced hairiness.

During the process of roller drafting as employed in conventional ring spinning, the effective control of fibers, particularly short fibers, is an essential factor. The short fibers (shorter than the nip to nip distance of the main drafting zone) remain uncontrolled as they leave the grip of the rollers. The speed and movement of short fibers between the nips of the main drafting zone must be controlled so that the fibers get aligned to the core of the yarn and thereby contribute to better yarn strength and evenness. In most modern drafting systems, this task is accomplished by aprons that guide the fibers to the nip of the delivery roller, as shown in Fig. 2.35. This shorter uncontrolled distance between aprons and the delivery roller has led to better yarn uniformity. In practice, during the drafting process the width of the fiber flow is greater than the spinning triangle in conventional ring spinning, as shown schematically in Fig. 2.50. The figure shows the delivery end of the drafting zone with the subsequent yarn formation zone [112]. The spread of the fibers in the drafting system is labeled B, just before the nip of the delivery nip line, in Fig. 2.50. This spread (or width) of fibers, B, which is several times the diameter of the yarn to be spun, depends on various spinning parameters, such as yarn count, roving twist, type of drafting system, and amount of draft. The draft in the

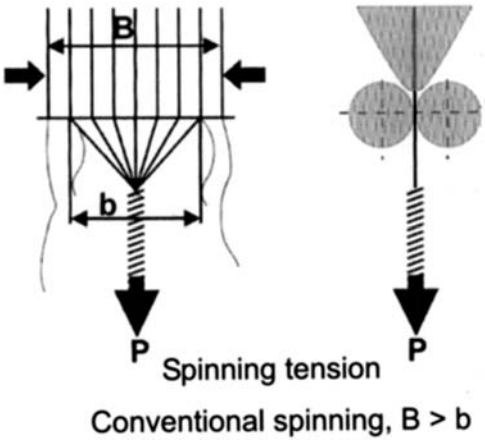
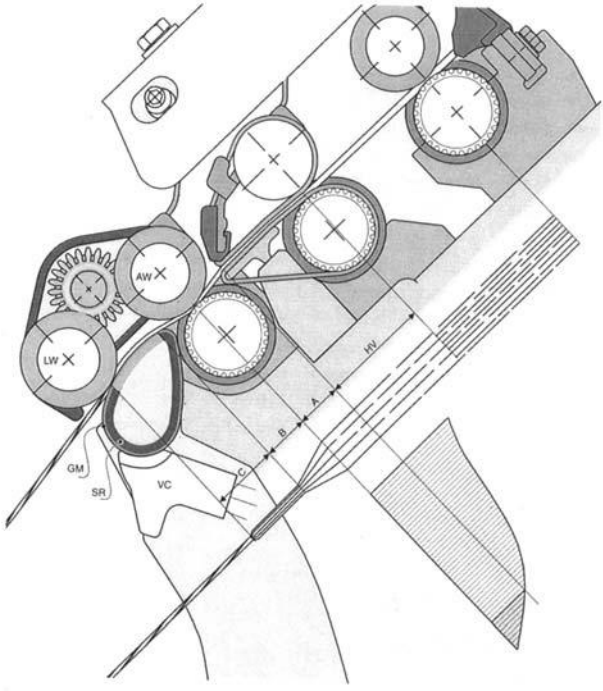


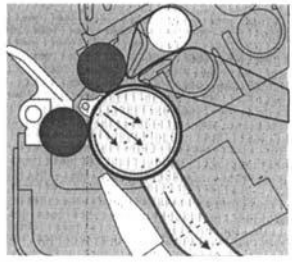
Fig. 2.50 Spinning triangle in conventional ring spinning. (From Ref. 112.)

main drafting zone plays the major role in determining the width of the fiber streams emerging from the delivery end. Immediately after fibers emerge from the nip of the drafting system, the yarn formation process begins. The fibers from the front roll nip are collected in the spinning triangle and integrated into the yarn structure by the twist imparted by the rotating spindle. For a given yarn count, the width of the spinning triangle, b, depends upon the spinning tension, P, exercised by the rotating end, and is in fact inversely proportional to the spinning tension. The higher the spinning tension, the lower the width of the spinning triangle and vice versa. In ring spinning, this difference (B − b) is always greater than zero, and therefore the spinning triangle cannot capture all the fibers delivered by the front nip. As shown in Fig. 2.50, many peripheral fibers emerging from the nip of the delivery rollers are either lost or are so uncontrolled that they are only loosely attached to the yarn being twisted in the spinning zone. Therefore, the structure of the ring-spun yarn is far from ideal, since many such loosely embedded fibers do not contribute to the yarn strength and also increase the yarn unevenness. In general, the strength of the spinning triangle is only about one-third of the strength of the yarn being spun. This is attributed to the fact that the fibers in the center of the spinning triangle are practically without any tension, so they are bound together without suffering any elongation, whereas the fibers from the center of the ribbon to the outer side of the spinning triangle suffer increasing tension. The fibers at the edge of the spinning triangle have to withstand all the spinning tension imposed during the process of yarn formation. Obviously, the short fibers within the spinning triangle do not contribute toward the strength of the spinning triangle. Thus, the spinning triangle is a potential weak spot and adversely affects the process stability [116].

In principle, the problems associated with the spinning triangle in conventional ring spinning should be eliminated if better yarn is to be produced. Some concepts in this direction were advanced by the Fehrer/Rieter and the ITV processes [111]. In the former, the compaction was achieved by suction onto a perforated steel drum and in the latter by means of perforated ribbon aprons. More recently, commercially available compact spinning frames have come to the market such as Rieter's Com4® and Suessen's EliTe®, as shown in Fig. 2.51. Both systems have attempted to eliminate the shortcomings of the yarn formation process in conventional ring spinning by reducing the adverse impact of the spinning triangle. An intermediate condensing or compacting zone is introduced between drafting and yarn formation. In this condensing zone, the drafted fibers are compacted by means of aerodynamic forces, as shown in Fig. 2.52. The condensing of the width of the fiber streams, B, is achieved, and it is converged to the width of the spinning triangle, b, such



Suessen's EliTe System



Rieter's Comfor System

Fig. 2.51 Suessen's EliTe® and Rieter's Comfor® Systems. (Courtesy of Suessen and Rieter, respectively.)

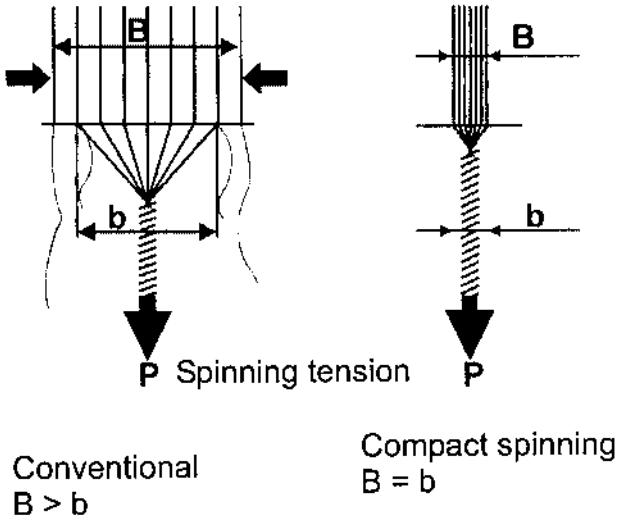


Fig. 2.52 Spinning triangle in conventional and compact spinning. (From Refs. 111 and 112.)

that the difference (B−b) tends to zero. This has led to the formation of a negligibly small spinning triangle or it is virtually eliminated. Therefore, all the fibers delivered by the front nip line are collected by the spinning triangle and thereby fully integrated into the twisting yarn. This has also led to a virtually perfect yarn structure of the compact spun yarn. All fibers are arranged parallel to the core and twisted together, thus contributing fully to the yarn properties.

The technological advantages that resulted from such compact yarn structure are

Improvement in yarn strength and elongation
Drastic reduction in yarn hairiness
Improved abrasion resistance of the yarns

The improved attributes of compact spun yarn provide major advantages for downstream processing, such as the winding, warping, sizing, and weaving operations [113,116].

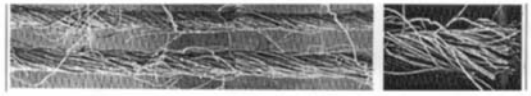
2.4 YARN STRUCTURE

The physical and mechanical properties of yarns are strongly influenced by the properties of the constituent fibers and their disposition in the body of the yarn, i.e., yarn structure [2]. The mechanical resistance of the yarn to tensile, compressive, bending, and shear stresses and physical properties, such as appearance, handle and feel, and dye-uptake, are dependent on the yarn structure. The arrangement of fibers in the yarn matrix, referred to as migration in technical terms, is in turn determined by the processing dynamics, spinning geometry, and the principle of yarn formation used in the specific staple yarn spinning systems. The yarns of identical linear density made from the same raw fiber stock but on different spinning systems are usually different in their mechanical response and physical characteristics.

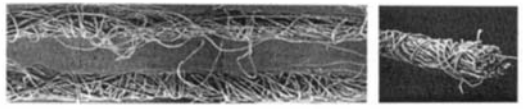
The process of staple yarn spinning involves two stages: (1) fiber drafting and transporting, and (2) twisting, wrapping, entangling, or bonding of a strand of relatively parallel fibers to impart the necessary cohesion between the fibers [86]. The aerodynamic forces imposed on the fibers during drafting and transportation and the nature of fiber control vary in the different spinning systems, such as ring, rotor, friction, and air-jet, owing to the inherently different principles of yarn formation employed.

The interrelationship between fiber properties, spinning process, and the resultant yarn structure is too complex to depict in a simple form. Isolating the effect of each variable influencing the yarn performance from the various complicating factors, though not impossible, is notoriously difficult and time intensive. The complex interrelationship of fiber properties, yarn structure, and the process of spinning has in fact given rise to an altogether separate subject studied under the broad spectrum of the mechanics of staple yarns. Clearly, the elaborate discussion on the subject of yarn mechanics is beyond the scope of this book. Interested readers are referred to the standard texts [3,6,88] and the extensive research efforts of various researchers reported in the published literature. The subject of the structure–property–process interrelationship is extensively investigated elsewhere for ring-spun [2,117], open-end rotor [2,118–120], open-end friction [121,122], and false-twist air-jet spun [2,123–126] yarns. The comprehensive understanding of the yarn structure and its influence on the various yarn properties will lead to a better understanding of this interrelationship, thus leading to the principles of engineering design and the ''engineering'' of yarns for specific end uses.

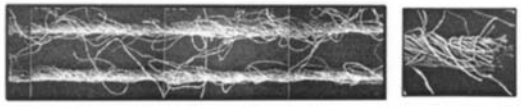
The structures of yarns spun on different spinning systems are shown in Fig. 2.53. The ring-spun yarn has relatively regular and well-defined twisted structure, similar to that found in twisted continuous filament yarn but with



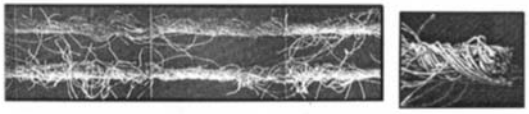
(a) Ring-spun Yarn



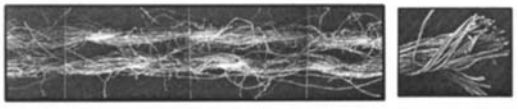
(b) Rotor-spun Yarn



(c) Friction Spun Yarn



(d) Air-jet Spun Yarn



(e) Wrap Spun Yarn

(f) Vortex Spun Yarn

(g) Compact Spun Yarn

Fig. 2.53 Structures of different staple yarns. (From Schlafhorst Technical Bulletin and Refs. 117,120,122, and 125.)

discontinuities at the fiber ends, as shown in Fig. 2.53a. Ring-spun yarns are assumed to have a uniform, homogeneous, coherent, and coaxial helical yarn geometry [127]. The packing density of fibers in the yarn, however, is somewhat irregular, which disturbs the idealized twisted structure. The density of packing of fibers is maximal in the core and steadily decreases toward the periphery of the yarn. The distribution of fibers in a yarn follows a parabolic model [128]. Detailed studies of tracer fiber paths in the yarn matrix have shown that the fiber migrates from the inside to the outside of the yarn, occupying different radial positions within the yarn. Such coherent ring-spun yarn structure is relatively strong but expected to have lesser water absorption capacity, which results in a lower size pick-up during slashing. A thorough knowledge of the relative structural disparities and nuances between different types of yarns is essential for setting up the sizing recipes and assuring sufficient size pick-up and performance on the slasher.

Open-end rotor-spun yarn has a somewhat irregular twist structure displaying two phases, as shown in Fig. 2.53b. A compactly packed core wrapped around by wrapper fibers [120,129]. There is a fairly large number of folded fibers due to hook formation in the spinning process which reduces the effective fiber extent in the yarn, thereby resulting in a relatively weak but bulky yarn structure. The fiber migration is relatively shallow and inferior, which adversely affects the degree of fiber interlocking, and therefore tensile properties of yarns are also poor. Such a weaker structure requires better consolidation and cementing by the sizing agents, and the relatively bulky structure has better moisture absorption, which results in a higher size pick-up.

The friction-spun open-end yarn made on a DREF III machine has a core-sheath structure, as shown in Fig. 2.53c. The core is false-twisted by the collection/twisting cylinders, and the fibers are added to this structure prior to the removal of the false twist [122]. In friction-spun yarns the fiber orientation is not very good, resulting in a relatively poor strength.

The air-jet yarn structure is characterized by parallel core fibers, fasciated by the taut helically wound fibers, called wrapper fibers, as shown in Fig. 2.53d [2,123,125,126]. The air-jet yarn structure varies along its length. The unwrapped core is the weakest place. The fiber migration in the core is not so systematic [123]; consequently, the resultant structure is not very coherent and self-locking. There are many hooked fibers in the yarn, which cause the poor utilization of fiber length. The strength of an air-jet yarn, therefore, depends upon the strength of wrapper fibers and the degree of fasciation [96,100].

The wrapped yarn produced on the hollow-spindle spinning process shows a continuous filament wrapping around a relatively twistless staple fiber

core, as shown in Fig. 2.53e. This structure is intermediate between the two extreme geometries of a staple yarn on the one hand and continuous filament yarn on the other. The strength of such a yarn is mainly dependent on the strength and twist level of the wrapping filament. The wrapping filament prevents the easy sliding apart of the relatively twistless core fibers by generating transverse pressure.

The structure of vortex-spun yarn is achieved in a completely different way when compared to other spinning systems such as ring, rotor, and compact. The yarn structure generated by vortex spinning is very similar to that of ring-spun yarn, as shown in Fig. 2.53f. Recent studies have shown that vortex-spun yarn exhibits a different structure than the jet-spun yarn in respect to wrapper fibers. However, detailed studies on the structure of vortex-spun yarn are still in progress, yet there is no unified structure. It shows a two-part structure if small sections of the yarn are untwisted. The amount of untwisting required to reveal the yarn structure varies along the length of the yarn. Typically, vortex-spun yarn exhibits a core and wrapper fiber based structure.

The structure of compact-spun yarn is similar to ring-spun yarn, but fibers are well packed and integrated, thus yielding very low surface hairiness. The fibers are helically packed in a very neat manner with very few fibers protruding, as shown in Fig. 2.53g. Very small amount of fibers do not get sufficiently integrated in the yarn matrix and consequently do not contribute toward yarn strength. This orderly arrangement of fibers, achieved by the process of compacting, contributes significantly toward improved yarn quality in comparison to ring-spun yarn. The reduction in yarn unevenness, hairiness, and improved strength are expected from such a yarn structure [111–113].

2.5 PROPERTIES OF STAPLE YARNS

2.5.1 Mechanical Properties of Staple Yarns

During the process of textile slashing and weaving, the yarns are subjected to a variety of both simple and complex mechanical deformations, such as tensile, bending, compression, and torsion. The ability of textile yarns to withstand such cyclic tensile, bending, compressive, and torsional stresses is of prime importance for successful slashing and subsequent weaving. An understanding of a yarn's performance during the subsequent processes is therefore never complete without taking into account the mechanical response of the yarn to such deformations. The mechanical behavior of staple fiber yarns is strongly influenced by the properties of the constituent fibers and their relative disposition in the body of the yarn [2,86].

The tensile strength of fibrous materials such as yarns is most commonly used to gauge the quality. Though the strength is of great importance for ensuring the satisfactory processing performance of staple yarns, it should be emphasized that other mechanical properties such as bending modulus and flexibility, resilience, torsional flexibility, elastic recovery, and initial tensile modulus and physical characteristics such as moisture sorption, hairiness, and evenness are also very important. Nevertheless, the measurement of the tensile strength of staple yarns is most common and widely measured in research and industry.

Tensile Strength

The quantities of common interest in the evaluation of tensile strength of staple yarns are the load and elongation at which the yarn specimen breaks when subjected to tension in its axial direction. The testing methods used for strength measurements are divided into two categories depending on the type of specimen and testing instruments used:

1. Lea, or skein, test
2. Single yarn test

Lea, or Skein, Test. Traditionally, this method of tensile testing was commonly used in textile industries such as cotton, wool, and flax, but is increasingly being replaced by the single end strength test method. The instrument used for skein tests operates on the principle of a pendulum lever with constant rate of traverse [11]. The 120-yard-long hank or skein containing 80 loops, each 1.5 yards long, is prepared by knotting both ends. The hank is then placed between two hooks of a lea tester. The lower hook of the tester descends, and the load is developed in the specimen due to the extension induced. When the load developed in the specimen exceeds the strength of the weakest place, the yarn breaks, though the hank still remains unbroken and capable of withstanding further extension. In this way, when the load developed successively exceeds and breaks more yarns in the specimen a point is reached when the hank specimen fails and the breaking strength of the lea is recorded in terms of force (lb or kg) by the swing of the pendulum. Thus the lea strength of the yarn is largely determined by the strength of the weakest places and the frictional forces between the yarns in a specimen. This measure does not give any idea of the absolute yarn strength, but yields relative values, generally useful for day-to-day quality assessment for any particular variety and count of yarn in the industry. To enable meaningful comparison of yarns of different linear densities made from the same or different cotton, a more

useful term used is the count-strength product (CSP), or break factor expressed as the product of the yarn count and the lea strength. The main drawback of this lea strength test is that it does not provide a measure of yarn extension. This poses a formidable problem in evaluating the performance of two yarns having similar lea strength but made from different fiber types, such as cotton and polyester.

Another important quantity of practical interest is the breaking length of the yarn, expressed in kilometers. The breaking length is the length of the specimen breaking under its own weight when suspended vertically. This quantity is usually calculated from the tensile test results obtained on short lengths.

Single Yarn Test. The single yarn test is much more comprehensive and yields more information about the response of a single yarn to axial extension. In this test, the yarn is subjected to a gradually increasing load or extension at uniform rate until it breaks and a complete load–elongation diagram is obtained. From the load–elongation diagram certain useful tensile measures, such as breaking load, breaking extension, initial modulus, elastic limit, yield point, recovery, and breaking energy can be easily calculated. The test is time consuming, however, and is largely useful for the purpose of research where the maximal amount of critical information is needed. Nevertheless, modern testing instruments such as Uster Tensojet can operate at 30,000 tests per hour removing this speed limitation. The modern testing instruments using microprocessors perform the task automatically with all the tensile strength indicators calculated by a personal computer interfaced to it. There is no known direct relationship between lea breaking strength and single yarn strength. The experimental results reported on a large number of yarns have shown that the ratio of lea breaking length to single end breaking length varies from 0.56 to 0.90 [130].

The tensile behavior of a yarn under a gradually increasing load until it breaks can be fully understood from the load–elongation curve, as shown in Fig. 2.54. The load may be expressed in terms of gram-weight or newtons and the elongation in centimeters. In order to compare the tensile behavior of different yarns, the load is expressed in terms of stress which is independent of the specimen dimensions. The stress, in engineering materials, is defined as

$$\text{stress} = \frac{\text{load (N)}}{\text{area of cross section (cm)}}$$

However, in textile materials it is very difficult to practically estimate the cross-sectional dimensions. Besides, the weight (linear density) but not the

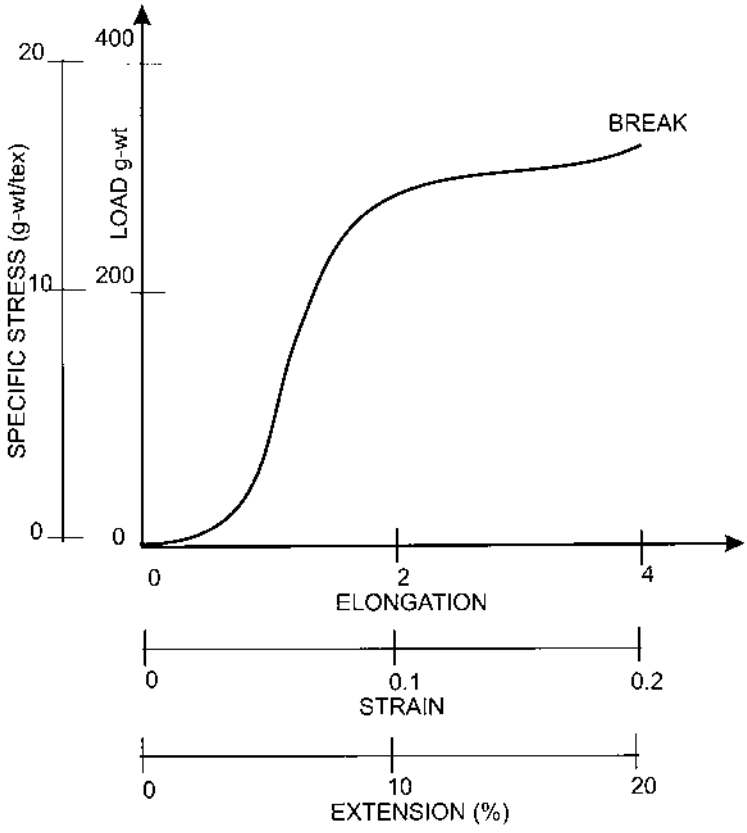


Fig. 2.54 Load–elongation curve of a yarn. (From Refs. 5 and 6.)

cross-sectional dimension is important for textile materials. A more convenient form to express stress is therefore the stress per mass of unit length, expressed as

$$\text{specific stress} = \frac{\text{load (N)}}{\text{mass/unit length (tex)}}$$

The units used for specific stress are grams weight per tex and newtons per tex.

The tensile strain is a nondimensional quantity expressed as the ratio of elongation to initial specimen length, either expressed as a fraction or more commonly as a percentage:

$$\text{tensile strain} = \frac{\text{elongation}}{\text{initial length of specimen}}$$

The load–elongation curve can, therefore, be converted into a stress–strain diagram, as shown in Fig. 2.55. The quantities of practical interest that can be obtained from this stress–strain diagram are:

Strength. Strength is a measure of the force required to rupture a yarn. It is expressed in N/tex and is called specific stress or tenacity at the break point. Alternatively the breaking length is also used to express the tenacity. When the strength is expressed on the basis of cross-sectional area, it is called the ultimate tensile stress, measured in the unit of kg·wt/mm^2 or kPa. However, the use of ultimate tensile stress in textiles is not very common because it is difficult to estimate the diameter of a fiber in a yarn.

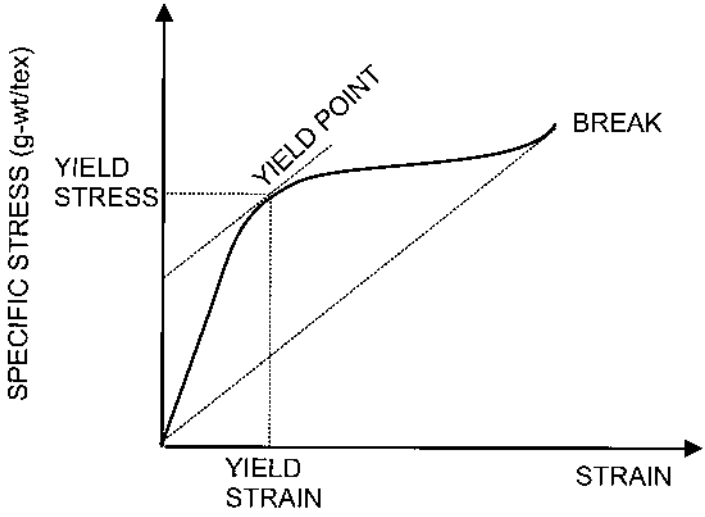


Fig. 2.55 Stress–strain curve of a yarn. (From Refs. 5 and 6.)

Elongation at break. This may be expressed by the ratio of actual increase in length to original specimen length expressed as a fraction or more commonly as a percentage. It is also called the breaking extension.

Work of rupture. This is a measure of the energy required to break the yarn, also called ''toughness.'' The work of rupture is given by the area under the stress–strain curve up to the break point, expressed in kN.cm or kg-wt.cm.

Initial modulus. The initial modulus (initial resistance to extension) is the slope of the initial part of the stress–strain curve at the origin. The initial part of a stress–strain curve is fairly linear, indicating that the ratio of stress to strain remains constant. The quantity is similar to what the engineers express as Young's modulus for solid materials. The modulus gives the measure of initial resistance that the yarn offers before yielding in tension. A highly inextensible yarn will have a high slope, indicating more force is required to produce a small extension, while an easily extensible material will have a low slope indicating that a large deformation is produced even under small stress. The reciprocal of the modulus is called compliance.

Yield point. After overcoming the initial load, the yarn tends to yield on a further increase in stress and produces a relatively large extension for small stress. The yield point is located, as defined by Meredith [131], when a tangent to the curve is parallel to the line joining the origin and the breaking point, as shown in Fig. 2.55. The yield point is also termed the limit of proportionality, beyond which the extension of the yarn ceases to be proportional to the applied stress. The values of stress and strain at the yield point are known as yield stress and yield strain, respectively.

Work of rupture and work factor. The linearly elastic material obeying Hooke's law will have a load–elongation curve represented by a straight line from start to the break point. The work of rupture of such a material will be given by

$$\text{work of rupture} = \frac{\text{breaking load} \times \text{breaking elongation}}{2}$$

However, textile materials, being viscoelastic in nature, do not exhibit such an ideal elastic behavior. The quantity used for such materials is the work factor given as

$$\text{work factor} = \frac{\text{work of rupture}}{\text{breaking load} \times \text{breaking elongation}}$$

The value of work factor for an idealized elastic material will be 0.5. For the curve above and below the straight line, the value of work factor will be greater or smaller than 0.5, respectively, as shown in Fig. 2.56.

Elastic recovery. Elasticity, or elastic recovery, is the property of a material to tend to recover its original size and shape after deformation. Its opposite is plasticity. When a material is allowed to recover from its maximal deformation, the part of the total deformation which is recoverable is called elastic, and the other part that is nonrecoverable is termed plastic, as shown in Fig. 2.57. The quantitative expressions of elastic recovery and work recovery are

$$\text{elastic recovery} = \frac{\text{elastic extension}}{\text{total extension}}$$

$$\text{work recovery} = \frac{\text{work returned during recovery}}{\text{total work done during extension}}$$

2.5.2 Irregularity in Staple Yarns

The principal irregularities in a staple yarn are the variation in linear density and in twist along its length. The variation in strength is largely the result of

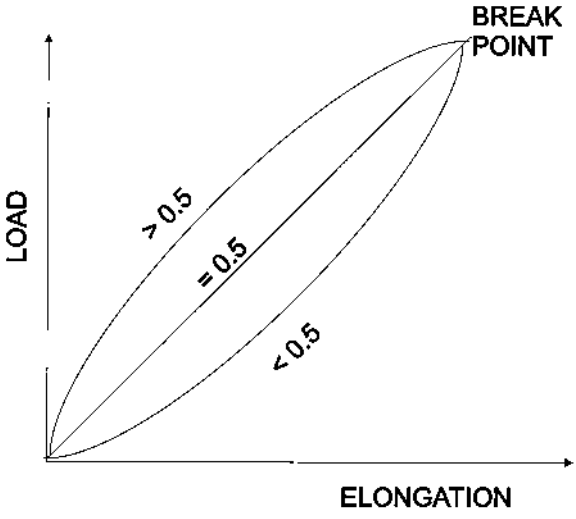


Fig. 2.56 Work factor. (From Ref. 131.)

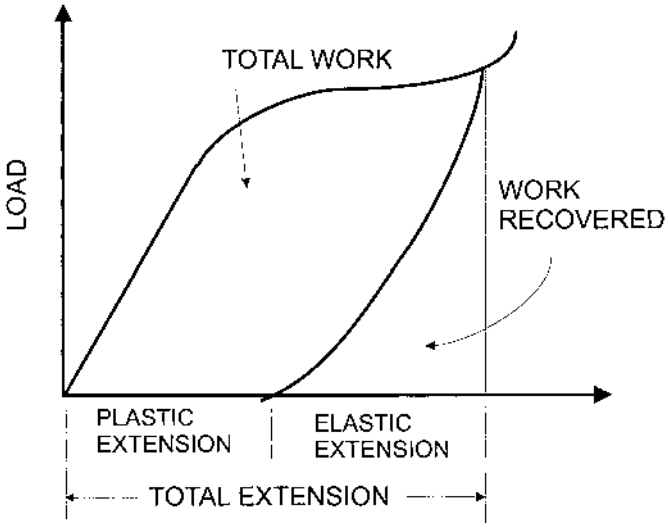


Fig. 2.57 Elastic recovery. (From Ref. 5.)

these two principal variations. The irregularity in staple yarns is attributed to the inherent variation in the input material and the manufacturing process. The variation in fiber characteristics, such as fiber length, fineness, maturity, and trash content; the variation in spinning parameters, such as draft and spindle revolutions per minute; and the random distribution of fibers in the prespinning processes are major factors that cause yarn irregularity. The variation in fiber fineness produces variation in the number of fibers in a cross section and therefore variations in linear density causing characteristic thick and thin places. The twist in the yarn is inserted in a certain yarn length in such a way that the twist factor is kept constant. This implies that the thin places will have more turns per unit length than thick places; therefore thin places are relatively hard whereas thick places are bulky and soft. Besides thin and thick places, the yarn also exhibits faults called ''neps'' often resulting from the immaturity of the cotton fibers.

Importantly, the yarn irregularity affects further processing performance and the appearance of the finished products. Higher yarn variation will exhibit higher breakage rate in subsequent processing and therefore lower productivity. Thick places will be constricted or may be caught in heddle eyes, knitting needles, and travelers and thus cause yarn breakage. Irregular yarns having

nonperiodic variations will cause visible defects such as streaks, and yarns having periodic variations will cause barré and diamond patterns in a fabric, which will be enhanced after dyeing. Yarns not having a high degree of periodic variations but large amounts of nonperiodic variations will produce a patchy, streaky, or cloudy fabric.

2.5.3 Yarn Hairiness

Yarn hairiness occurs because some fiber ends project from the yarn matrix, some fibers form closed loops, and there are some ''wild fibers'' which are loosely attached to the body of the yarn [132–134]. It is reported that the number of protruding fiber ends is approximately the same as the number of fibers in the yarn cros ssection [133,134]. This suggests that the one end of a fiber is gripped in the yarn and the other end is projected out of the body of the yarn [133–135]. Hairiness is generally caused by the shorter fibers, and a large proportion of the hairiness of cotton yarns is due to loops. However, the actual proportion of loop and free fiber ends is variable [133]. The number of fibers which may protrude from the yarn body is independent of the yarn twist; however, the number of loops decreases with an increase in the twist level because of the greater degree of binding [134,136]. The effect of increasing the yarn twist on the reduction of wild fiber is only marginal.

The effect of yarn hairiness on the subsequent processes, such as winding, warping, slashing, weaving, and knitting, and its influence on the characteristics of the product have led to substantial research interest [137–140]. The slashing operation essentially modifies the hairiness by laying the protruding fibers onto the body of the yarn [141]. The reduction in hairiness due to slashing improves the weaving performance due to decreased chaffing and abrasion of yarn with loom parts, such as heddle eyes, reed wires, and the picking element. However, for excessively hairy yarns, slashing alone may not be sufficient to reduce the hairiness adequately. Yarn singeing, for example, prior to slashing produces good results in terms of reducing the number of warp breaks on the loom [142]. Besides performance problems, the fabric made from very hairy yarns will be oozy in appearance and rough in feel. Weft way yarn hairiness causes weft bars in the fabric [143].

The measurement of hairiness is carried out by various methods based on different physical principles. Among the different physical principles of measurement used, the procedures are arranged in the following major groups [133]:

Optical methods
Photographic methods

Photoelectric and related methods
Methods based on electrical conductivity
Methods based on loss of weight by singeing
Methods based on application of laser rays
Methods based on transverse scanning of the yarn image
Miscellaneous methods

For the general description of each of these methods developed and used by various researchers the readers are referred to a review presented by Barella [133].

Sources of Hairiness

The contribution of different spinning stages to yarn hairiness has been studied extensively by researchers [135,143]. More drawframe passages lead to greater parallelization of the fibers with a resultant reduction in the number of hooks and lower hairiness [135]. A reversal of card sliver prior to the drawing operation also reduces hairiness—the effect is equivalent to the effect of an additional drawframe passage [133,135]. The roving operation further reduces hairiness by consolidating the fiber flux in condensers. Yarn spun directly from the drawframe slivers leads to greater yarn hairiness. The combing operation eliminates short fibers and thereby reduces hairiness. The addition of short fibers and comber waste results in an increase in hairiness [135]. Spinning tension, spinning speed, and the weight of traveler have the most profound influence on the hairiness of yarns. An increase in spindle speed generally increases yarn hairiness, this being attributed to the increase in centrifugal force, higher air resistance, and greater friction between the yarn and the ring [135,143,144]. The spinning tension affects the hairiness: the lower the tension, the greater is the yarn hairiness. Eccentricity of the spindle increases yarn hairiness. The hairiness increases almost exponentially with the increase in eccentricity beyond 0.5 mm [143,145]. Besides eccentricity, increased vibrations of the spindle and the ring also tend to increase the hairiness. The effect of an increase in ring weight at a constant spindle speed is a reduction in yarn hairiness, attributable to the combination of the distribution of tension and twist during yarn spinning [133]. The weight of the ring that can be used is limited by the end-breakage rate on spinning frame. The balloon separators also increase the hairiness because the yarn is constantly beaten against them. The traverse cycle of the ring rail also affects the periodic variations in hairiness [4,143,145,146]. The nature and the properties of the fibers being spun, notably fiber length and fineness, affect yarn hairiness, for example, cotton fibers may produce more hairy yarn than the long staple acrylic fiber.

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