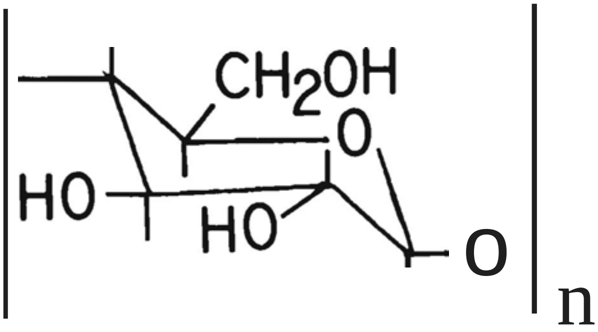
II. Fiber Properties

3. Cellulosic Fibers

Cellulose is a fibrous material of plant origin and the basis of all natural and man-made cellulosic fibers. The natural cellulosic fibers include cotton, flax, hemp, jute, and ramie. The major man-made cellulosic fiber is rayon, a fiber produced by regeneration of dissolved forms of cellulose. The cellulose acetates are organic esters of cellulose and will be discussed in Chapter 4.

Cellulose is a polymeric sugar (polysaccharide) made up of repeating 1,4-8-anhydroglucose units connected to each other by 8-ether linkages. The number of repeating units in cellulosic fibers can vary from less than 1000 to as many as 18,000, depending on the fiber source. Cellulose is a hemiacetal and hydrolyzes in dilute acid solutions to form glucose, a simple sugar.

The long linear chains of cellulose permit the hydroxyl functional groups on each anhydroglucose unit to interact with hydroxyl groups on adjacent chains through hydrogen bonding and van der Waals forces. These strong intermolecular forces between chains, coupled with the high linearity of the cellulose molecule, account for the crystalline nature of cellulosic fibers. It is believed that a gradual transition from alternating areas of greater molecular alignment or crystallinity to more disordered or amorphous areas occurs in cellulose. The number, size, and arrangement of crystalline regions within celluloses determine the ultimate properties of a particular fiber.



CELLULOSE

The predominant reactive groups within cellulose are the primary and secondary hydroxyl functional groups. Each repeating anhydroglucose unit contains one primary and two secondary hydroxyl functional groups which are capable of undergoing characteristic chemical reactions of hydroxyl groups. The primary hydroxyls are more accessible and reactive than secondary hydroxyls; nevertheless, both types enter into many of the chemical reactions characteristic of cellulose.

COTTON

Cotton is the most important of the natural cellulosic fibers. It still accounts for about 50% of the total fiber production of the world, although man-made fibers have made significant inroads into cotton's share during the last three decades. Cotton fibers grow in the seed hair pod (boll) of cotton plants grown and cultivated in warm climates.

Structural Properties

Cotton is very nearly pure cellulose. As many as 10,000 repeating anhydroglucose units are found in the polymeric cellulosic chains of cotton. Studies have shown that all of the hydroxyl hydrogens in cotton are hydrogen bonded. These hydrogen bonds will hold several adjacent cellulose chains in close alignment to form crystalline areas called microfibrils. These microfibrils in turn align themselves with each other to form larger crystalline units called fibrils, which are visible under the electron microscope. In cotton the fibrils are laid down in a spiral fashion within the fiber. Modern fiber theory suggests that each cellulose molecule is present within two or more crystalline regions of cellulose will be held together. Between the crystalline regions in cotton, amorphous unordered regions are found. Voids, spaces, and irregularities in structure will occur in these amorphous areas, whereas the cellulose chains in crystalline regions will be tightly packed. Penetration of dyestuffs and chemicals occurs more readily in these amorphous regions. Approximately 70% of the cotton fiber is crystalline. Individual cotton fibers are ribbonlike structures of somewhat irregular diameter with periodic twists or convolutions along the length of the fiber (Figure 3-1). These characteristic convolutions, as well as the cross-sectional shape of cotton are caused by collapse of the mature fiber on drying.

Three basic areas exist within the cross section of a cotton fiber. The primary outer wall or cuticle of cotton is a protective tough shell for the fiber, while the secondary wall beneath the outer shell makes up the bulk of the fiber. The fibrils within the secondary wall are packed alongside each other aligned as spirals running the length of the fiber. The lumen in the center of the fiber is a narrow canal-like structure running the length of the fiber. The lumen carries nutrients to the fiber during growth, but on maturity the fiber dries and the lumen collapses.

Physical Properties

The high crystallinity and associative forces between chains in cotton result in a moderately strong fiber having a tenacity of 2-5 g/d (18-45 g/tex). The hydrophilic (water-attracting) nature of cotton and the effect of absorbed water on the hydrogen bonding within cotton cause the tensile strength of cotton to change significantly with changes in moisture content. As a result, wet cotton is about 20% stronger than dry cotton. Cotton breaks at elongations of less than 10%, and the elastic recovery of cotton is only 75% after only 2% elongation.

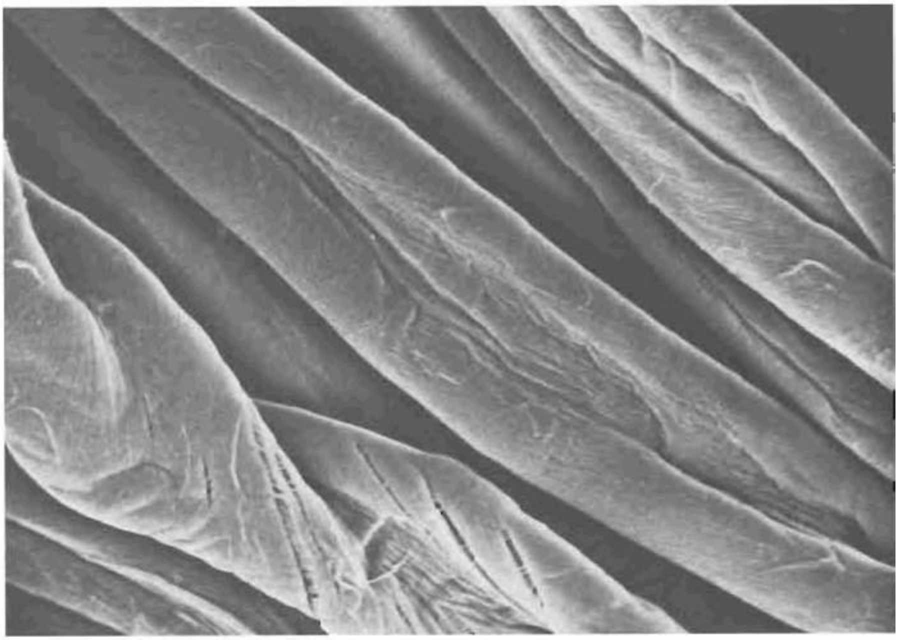


Figure 3-1. Cotton. x1000.

Cotton is a relatively stiff fiber; however, wetting of the fiber with water plasticizes the cellulose structure, and the cotton becomes more pliable and soft. The resiliency of dry and wet cotton is poor, and many finishes have been developed to improve the wrinkle recovery characteristics of cotton.

Cotton is one of the more dense fibers and has a specific gravity of 1.54.

The hydroxyl groups of cotton possess great affinity for water, and the moisture regain of cotton is 7%-9% under standard conditions. At 100% relative humidity, cotton has 25%-30% moisture absorbency.

The heat conductivity of cotton is high, and cotton fabrics feel cool to the touch. Cotton has excellent heat characteristics, and its physical properties are unchanged by heating at 120°C for moderate periods. The electrical resistivity of cotton is low at moderate relative humidities, and the fiber has low static electricity buildup characteristics.

Cotton is not dissolved by common organic solvents. Cotton is swollen slightly by water because of its hydrophilic nature, but it is soluble only in solvents capable of breaking down the associative forces within the crystalline areas of cotton. Aqueous cuprammonium hydroxide and cupriethylenediamine are such solvents.

Chemical Properties

Cotton is hydrolyzed by hot dilute or cold concentrated acids to form hydrocellulose but is not affected by dilute acids near room temperature. Cotton has excellent resistance to alkalies. Concentrated alkali solutions swell cotton, but the fiber is not damaged.

The swelling of cotton by concentrated sodium hydroxide solution is used to chemically finish cotton by a technique called mercerization. In aqueous alkali, the cotton swells to form a more circular cross section and at the same time loses convolutions. If the cotton is held fast during swelling to prevent shrinkage, the cellulose fibers deform to give a fiber of smoother surface. After washing to remove a"lkali, followed by drying, the cotton fiber retains a more cylindrical shape and circular cross section. Although little chemical difference exists between mercerized and unmercerized cotton, mercerization does give a more reactive fiber with a higher regain and better dyeability (Figure 3-2).

Dilute solutions of oxidizing and reducing agents have little effect on cotton; however, appreciable attack by concentrated solutions of hydrogen peroxide, sodium chlorite, and sodium hypochlorite is found.

Most insects do not attack cotton; however, silverfish will attack cotton in the presence of starch. A major problem with cotton results from fungi and bacteria being able to grow on cotton. Mildews feed on hot moist cotton fibers, causing rotting and weakening of the fibers. Characteristic odor and pigment staining of the cotton occurs when mildews attack. Additives capable of protecting cotton are available and commercially applied to cotton fabrics used outdoors. These materials are often metal salts of

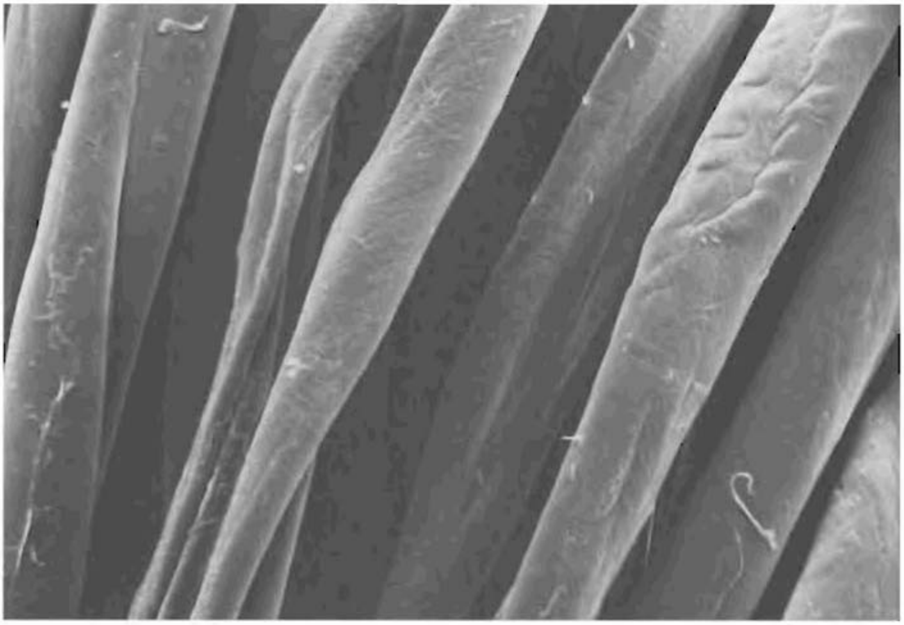


Figure 3-2. Mercerized Cotton. x1000.

organic compounds which are capable of inhibiting growth of mildews and similar organisms.

Cotton is only slowly attacked by sunlight, since cellulose lacks for the most part groups which absorb ultraviolet light between 300 and 400 nm. Over long periods sunlight degrades cotton, causing it to lose strength and to turn yellow. Certain vat dyes tend to accelerate the rate of cotton photodegradation through a sensitization reaction called "phototendering."

Although cotton has excellent heat resistance, degradation due to oxidation becomes noticeable when cotton is heated in the air at 150°C for long periods. Spontaneous ignition and burning of cotton occurs at 390°C. At low humidities in the absence of heat and light, cotton will not deteriorate over long periods of storage.

End-Use Properties

The properties of cotton fiber are such that it serves as nature's utility fiber. Although cotton has some properties which are undesirable from the viewpoint of the consumer, the superior properties of cotton, coupled with its low cost, nevertheless make it a valuable fiber in many applications. Different species of cotton produce fibers of various average lengths. In the United States lengths of cotton staples are designated as follows:

Extra long staple	1 3/8 - 2 inches (3.2 - 4.7 cm)
Long staple	1 1/8 - 1 3/8 inches (2.7 - 3.2 cm)
Medium staple	1 - 1 1/8 inches (2.5 - 2.7 cm)
Short staple	7/8 - 1 inch (2.0 - 2.5 cm)

The two major types of American cotton are American-Upland (including deltapine and acala varieties) and American-Egyptian (including pima).

Cotton has excellent hand, and the drapability of cotton fabrics is quite acceptable. Fabrics of cotton are of satisfactory appearance and have a low luster unless mercerized or resin finished.

The superior absorbency of cotton, coupled with its ability to desorb moisture, makes it a very comfortable fiber to wear. This absorbency permits cotton to be used in applications where moisture absorption is important, such as in sheets and towels. Mildewing of cotton under hot moist conditions and its slowness of drying are undesirable properties associated with its high affinity for water.

The cotton fiber has sufficient strength in the dry and wet states to make it suitable for most consumer textile applications. The increased strength of cotton on wetting adds to its long useful life. Cotton wears well without undue abrasion, and pills do not tend to form as it wears. Cotton's low resiliency and poor recovery from deformation means that it wrinkles easily in both the dry and wet states and exhibits inferior crease retention. Starching of cotton improves these properties, but the effect is only temporary, and it is necessary to renew this finish after each laundering.

The resistance of cotton to common household chemicals, sunlight, and heat makes it durable in most textile applications. Cotton can be dyed successfully by a wide variety of dyes, and the colorfastness of properly dyed cotton is satisfactory.

Fabrics of cotton are maintained with a moderate degree of care. Cotton fabrics launder readily, and its wet strength and alkali resistance mean that cotton is resistant to repeated washings. Stresses which occur during the spinning and weaving process will cause cotton fabrics to undergo relaxation shrinkage during initial launderings. Relaxation shrinkage can be controlled through resin stabilization or through the well known compression shrinkage process called Sanforization.

Cotton can be drip dried or tumbled dry, but in both cases the dry cotton will be severely wrinkled, and ironing will be necessary. Cotton can be ironed safely at temperatures as high as 205°C. Cotton, as well as all cellulosic fibers, is highly flammable and continues to burn after removal from a flame. After extinguishing of the flame the cotton will continue to glow and oxidize by a smoldering process called afterglow. The Limiting Oxygen Index (LO!) of cotton is 18. A number of topical treatments have been developed to lower the flammability of cotton and other cellulosics.

The undesirable properties of cotton can be corrected to varying degrees through treatment of the fiber with special finishes; however, the abrasion resistance of cotton is adversely affected. As a result, blends of cotton with the stronger man-made fibers have become important. Although man-made fibers have made inroads into applications previously reserved for cotton, cotton continues to be the major textile fiber due to its great versatility, availability, and cost.

FLAX

Flax is a bast fiber used to manufacture linen textiles. It is derived from the stem of the annual plant, <u>Linum</u> <u>usitatissimum,</u> which grows in many temperate and subtropical areas of the world. The flax plant grows as high as 4 feet tall, and flax fibers are found below the plant surface held in place by woody material and cellular matter. The flax fibers are freed from the plant by a fermentation process called retting. Chemical retting using acids and bases has been employed with some success; however, such processes tend to be more expensive than natural fermentation techniques. The fibers are then removed from the plant through breaking of the woody core, removal of the woody material (scutching), and combing (hack1ing). The resulting fibers are ready for spinning and are 12-15 inches (30-38 cm) in length.

Structural Properties

Flax is nearly pure cellulose and therefore exhibits many properties similar to cotton. Strands of individual flax fibers may consist of many individual fiber cells--fibrils held together by a natural cellulosic adhesive material. The molecular chains in flax are extremely long, and the average molecular weight of molecules in flax is 3 million. There are swellings or nodes periodically along the fiber which show up as characteristic cross markings. The cell walls of flax are thick, and the fiber cross section is polygonal with a large lumen in the center (Figure 3-3).

Physical Properties

Flax is a strong fiber, and the average tenacity of dry flax is 2-7 g/d (18-63 g/tex); wet flax is 2.5-9 g/d (23-81 g/tex). Like cotton, the wet flax fiber is about 20% stronger than the dry fiber. Flax has a low elongation at break (about 3%); however, the fiber is fairly elastic at very low elongations.

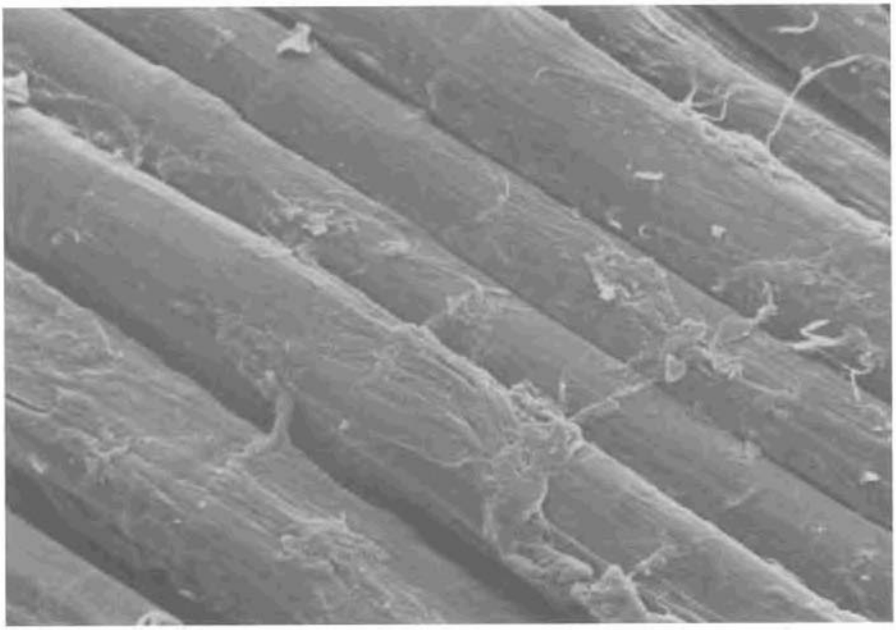


Figure 3-3. Flax. x1000.

Flax has a higher regain than cotton, and a 12% regain is observed at standard conditions. Flax possesses good heat conductivity and is cool to the touch. The heat and electrical properties of flax are similar to those of cotton, and flax possesses solubility characteristics identical to cotton.

Flax is a highly rigid fiber, and it tends to crease on bending due to its poor resiliency. The specific gravity of flax is 1.54, the same as cotton. Flax is a dull fiber, but more lustrous linen fabrics can be obtained by pounding the linen with wooden hammers (beetling). Linen fabrics have good dimensional stability unless stresses have been introduced during the weaving process.

Chemical Properties

The chemical properties of flax are similar to those of cotton. Flax has good resistance to acids, bases, and chemical bleaches. Flax is resistant to insects and microorganisms, and only under severe moist warm conditions will it be attacked by mildews. Flax is only slowly degraded by sunlight, and it decomposes at temperatures similar to that observed for cotton.

End-Use Properties

Flax finds only limited use in modern textiles. The methods used to produce flax involve extensive labor and cost; thus flax usage is reserved for special luxury applications. The strength of flax makes it superior to cotton in certain applications. Flax is resistant to abrasion, but like cotton suffers from lack of crease retention and poor wrinkle recovery. Linen fabric's superior absorbency, coupled with its cool crisp hand, contributes to its desirability as a prestige fiber. The thermal properties and chemical resistance of flax make it suitable for many consumer applications. Linen can be laundered repeatedly without deterioration and ironed safely at temperatures as high as 220°C. Flax is very flammable. Flax is used in prestige items including handkerchiefs, towels, tablecloths, sheets, and certain garments.

OTHER NATURAL CELLULOSIC FIBERS

A large number of natural cellulosic fibers from plant sources exist, including jute, hemp, ramie, kenaf, urena, sisal, henequen, abaca, pina, kapok, coir, and others. Each of the fibers is a plant or seed hair fiber and has properties that make it suitable for selected applications. The major fibers--jute, hemp, and ramie--will be considered here.

Hemp is a bast fiber harvested from the hemp plant and processed in a manner similar to flax. It is a coarser fiber than flax, darker in color and difficult to bleach. The fiber is strong and durable, and the strands of hemp fiber may reach six feet or longer. Individual hemp cells are 1/2-1 inch (1.2-2.5 cm) in length, and the fiber cross section is polygonal. The fiber is very stiff and contains considerable lignin. Although fine fabrics can be produced from select hemps, hemp is used mainly in coarse fabrics, including sack material, canvas, ropes, and twines.

Jute

Jute fiber comes from a herbaceous annual plant which grows as high as 20 feet. The fibers are extracted from the plant stalk in a manner similar to flax. Jute tends to be brown in color due to about 20% lignin present in the fiber, but it does have a silklike luster. The individual cells of jute are very short, being about 0.1 inch (.25 cm) long, and the fiber cross section has five or six sides. Jute is not as strong or as durable as flax or hemp. Jute fibers are stiff, but it does have an unusually high moisture regain. Jute's low cost, moderate strength, and availability make it an important fiber for use in sacks, bags, and packing materials. Fabrics made of jute are called burlap.

Ramie

Ramie is a bast fiber often referred to as china grass. Ramie fiber is removed from the plant by peeling or removing the bark and soaking the fibers in water, followed by scraping. The fiber must be further degummed by treatment in base before spinning. Ramie is a white fiber with excellent strength and luster. The fiber is stiff and fairly coarse. The cells of the fiber are very long, and the cross section irregular in shape. Ramie is useful in industrial applications and is being used in furnishings where rough, irregular fabrics are desired.

RAYON

Rayon was the first man-made fiber to be produced commercially, and several types of rayon fibers are produced. Rayon is regenerated cellulosic material produced by solution of a cellulose source (wood pulp, cotton waste, etc.), followed by forcing of the solution through a spinneret and subsequent regeneration to form the fiber. The Federal Trade Commission defines rayon as a manufactured fiber composed of regenerated cellulose in which substituents have not replaced more than 15% of the hydroxyl hydrogens. Rayon is produced by three methods to give the viscose rayons, cuprammonium rayon, and saponified cellulose acetate. Of these, viscose rayon is the most important and the most inexpensive to produce.

Structural Properties and Formation of Rayon

Viscose Rayon: Viscose rayon fibers are produced by the viscose process, which involves formation of soda cellulose, reaction with carbon disulfide to form cellulose xanthate, and spinning into dilute acid to regenerate the cellulose as rayon fiber. In practice the cellulose pulp is steeped in warm concentrated sodium hydroxide and pressed to remove excess sodium hydroxide. After aging, during which some degradation and breaking of cellulose chains occurs, the soda cellulose crumbs are mixed with carbon disulfide, and orange sodium cellulose xanthate is formed. The xanthate is then dissolved in dilute sodium hydroxide. At this point titanium dioxide is added to the solution if a delustered fiber is desired. The solution is aged and ripened until a proper viscosity is reached; the solution is then forced through the spinneret into dilute sulfuric acid to decompose the xanthate and regenerate the cellulose by the wet spinning process. In addition to acid, the following additives are often found in the spinning bath: sodium sulfate (15%-20%), zinc sulfate (1%-5%), and glucose (2%). Initially, the outer portion of the xanthate decomposes in the acid bath and a cellulose skin forms on the fiber. The sodium and zinc sulfates affect the rate of xanthate decomposition and fiber formation, while the action of zinc sulfate is confined to crosslinking the outermost portion of the fiber. The glucose tends to slow the rate of regeneration of the fiber and tends to make the fiber more pliable. The concentration and type of additives in the bath and the nature of the original cellulose will affect the physical properties of the rayon. By careful control of the coagulation bath followed by mechanical stretching, crimp can be produced in the fiber. Slow regeneration and stretching of the rayon will tend to introduce greater areas of crystallinity within the fiber. High-tenacity rayons are formed in this manner. Also, the fiber can be modified through addition of other crosslinking agents to the spinning bath.

High-wet-modulus rayons (polynosic rayons) have been developed in recent years. These fibers are produced from high-grade cellulose starting materials, and the formation and decomposition of cellulose xanthate is carried out under the mildest of conditions to prevent degradation of the cellulose chains.

After initial skin formation, the core of the fiber decomposes, hardens, and shrinks, causing wrinkling on the fiber skin. The final fiber cross section of viscose rayon appears serrated and irregular, and the nature of the crystallites in the skin and core will differ (Figure 3-4). This skin effect can be controlled sufficiently to give nearly round fiber cross sections where carefully controlled coagulation occurs.

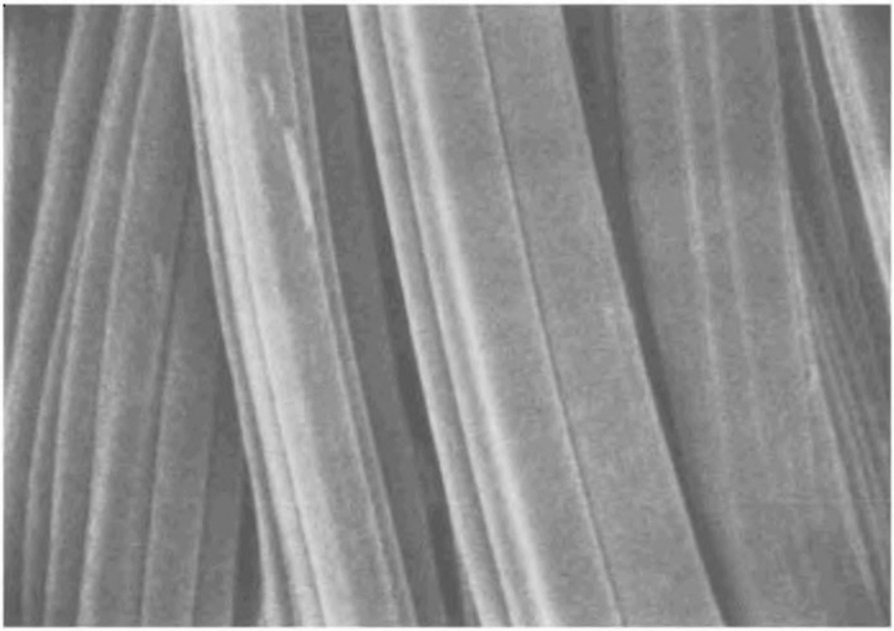


Figure 3-4. Viscose rayon. x2000.

The majority of viscose rayons have serrated and irregular cross sections due to the skin effect. The viscose rayon fiber is long and straight unless the fiber has been crimped, and striations due to the irregular cross section will run the length of the fiber. If the fiber has been delustered or spun dyed during fiber formation, particles of pigment will appear in the fiber. Normal viscose fibers will generally consist of 25%-30% crystalline areas within the fiber, and the average degree of polymerization of glucose units in the cellulose chains will be 200-700. The crystallites in viscose rayon are somewhat smaller than those found in cotton. Higher-tenacity rayons and high-wet-modulus rayons tend to be more crystalline, and higher degrees of polymerization are found. The cross sections of these rayons tend to be more nearly round. The degree of crystallinity of high-wet-modulus rayons can reach 55%.

Cuprammonium Rayon: Cuprammonium rayon is produced by solution of cellulosic material in cuprammonium hydroxide solution at low temperature under nitrogen, followed by extrusion of the solution through a spinneret into water and then sulfuric acid to decompose the cuprammonium complex and regenerate the cellulose. Cuprammonium rayon is more silklike than any of the other celluloses, but the cost of production is correspondingly higher. Cuprammonium rayon has a smooth surface, and no markings or striations are found on the fiber (Figure 3-5). The fiber cross section is nearly round.

Saponified Cellulose Acetate: Rayon can be produced from cellulose acetate yarns by hydrolysis in base, a process called saponification. Cellulose acetate molecules are unable to pack closely within the fiber due to lack of hydrogen bonding and the presence of bulky acetate side chains within the molecule. Since cellulose acetate is more plastic in nature, it can therefore be drawn and extended to give a high degree of orientation to the fiber. On hydrolysis the highly oriented cellulosic chains form hydrogen bonds with adjacent chains to give a rayon of high orientation and crystallinity. Saponified cellulose acetate has a nearly round but lobed cross section. The indentations caused by the lobes appear as light striations running the length of the filament.

Physical Properties

Since rayons are essentially pure cellulose, they would be expected to have physical properties similar to cellulosic fibers of natural origin. Differences in properties would be expected to depend on the degree of polymerization, crystallinity, and orientation within the fiber. The dry and wet tenacities of the rayons vary over a wide range dependent on the degree of polymerization and crystallinity with tenacities of 2 to 6 g/d (18 to 54 g/tex) dry and 1 to 4 g/d (9 to 36 g/tex) wet. For the more crystalline and oriented rayons, the drop in tenacity observed on wetting of the fiber is lower; however, none of the rayons exhibit higher wet strength than dry strength, as found with cotton. The great loss in strength of wet regular tenacity rayon makes it subject to damage during laundering.

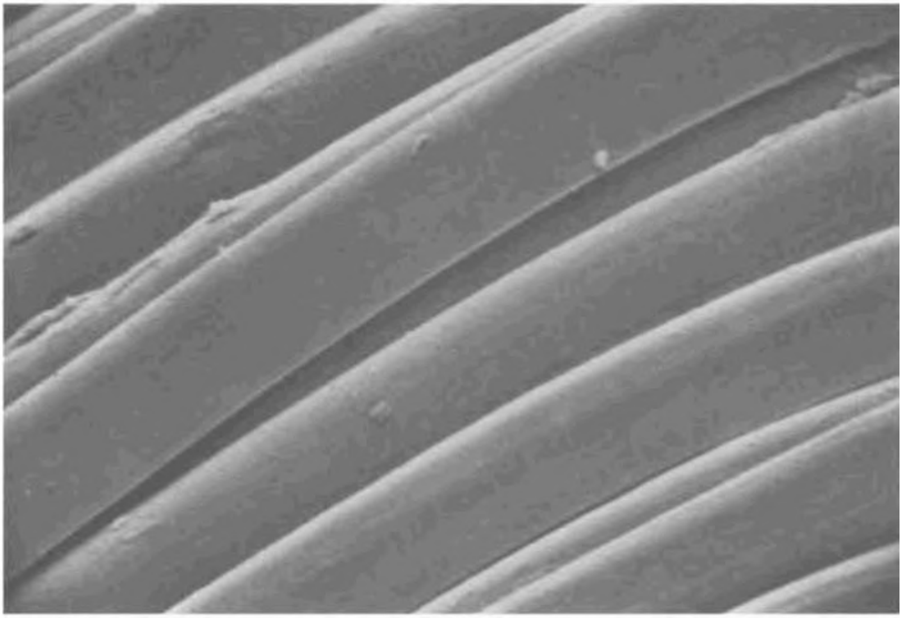


Figure 3-5. Cuprammonium rayon. x1100.

The percentage elongation at break varies from 10 to 30% dry and 15 to 40% wet. The recovery at 2% elongation ranges from 70 to 100%. In general, the rayons have significantly higher elongations at break than observed for cotton. As the degree of crystallinity and orientation of the rayon increases, the elongation at break is lower. Rayons generally have somewhat better elastic properties at low elongations than is found for cotton.

The rayons possess greater luster than cotton, and often delusterants are added to rayon prior to spinning to give a more subdued fiber. Since the rayons are less crystalline and oriented than cotton, they tend to swell more in water and undergo greater elongation under tension in both the wet and dry states. During weaving and wet finishing considerable stresses can be introduced into many rayon fabrics, and relaxation of these stresses will be necessary before a dimensionally stable fabric is obtained.

Owing in part to the more extensive networks of amorphous regions found in rayons, the moisture regain of rayon is significantly higher than that of cotton. The regains of rayons under standard conditions range from 11% to 13%. The lower crystallinity and degree of polymerization of rayons also affect the way water acts on the fibers. Rayons as a consequence are swollen to varying degrees due to increased susceptibility to water penetration. During wetting rayon may increase up to 5% in length and swell up to double its volume.

The heat conductivity and electrical properties are the same as those found for cotton. Rayon is cool to the touch, and static charges do not build up in the fiber at humidities greater than 30%.

Although rayon swells in water, it is not attacked by common organic solvents. It does dissolve in cuprammonium solutions.

The rayons are moderately stiff fibers with poor resiliency and wrinkle recovery properties. As in the case of cotton, resin treatments will effectively increase the resiliency of rayon. Often such treatments will tend to be more effective on rayon than on cotton due to the greater accessibility of the interior of rayon to the resin. The specific gravities of viscose and cuprammonium rayons are the same as cotton and vary between 1.50 and 1.54. Only saponified cellulose acetate has a markedly different specific gravity (1.30).

Chemical Properties

The chemical properties of the rayons are essentially the same as those found for cotton. Cold dilute or concentrated base does not significantly attack rayon, but hot dilute acids will attack rayon at a rate faster than found for cotton. Although generally resistant to oxidizing bleaches, rayon is significantly attacked by hydrogen peroxide in high concentrations. Although silverfish are known to attack rayon, microorganisms which cause mildew do not readily attack rayon, except under more severe hot and moist conditions. Prolonged exposure of rayon to sunlight causes degradation of the cellulose chains and loss of strength of the fibers. The rayons are not thermoplastic, and they, like cotton, decompose below their melting point. Regular-tenacity rayon begins to decompose and lose strength at 150°C for prolonged periods and decomposes rapidly at 190°-210°C. High-tenacity rayons tend to decompose at slightly higher temperatures.

End-Use Properties

Rayon fibers found in consumer goods are known by numerous trade names. Regular- and high-tenacity viscose rayons are marketed as rayon or with names like Zantrel, Avril, Enkaire, and Fibro. Cuprammonium rayon and saponified cellulose acetate are not longer in production in the U.S. Regular- and medium-tenacity viscose rayons are among the least expensive of the man-made fibers, whereas high-strength, cuprammonium, and saponified cellulose acetate rayons are more expensive due to the greater care and additional steps necessary in manufacture of these fibers.

Although the properties of rayons are very nearly those of cotton, a greater range of properties exist within the various types of rayons available. Being an inexpensive fiber, rayon plays a role similar to that of cotton; however, rayon differs from cotton in that it can be modified to some degree during manufacture and is not as subject to world economic and climatic conditions.

The dry strength of regular-tenacity viscose and cuprammonium rayons are lower than that found for cotton, whereas high-tenacity viscose, polynosic, and saponified cellulose acetate rayons are significantly stronger than cotton. All rayons lose strength when wet and are more susceptible to damage while wet.

The abrasion resistance of rayon is fair, and abrasion of rayon fabrics becomes noticeable after repeated usage and launderings. The rayons are resistant to pill formation. Rayon fabrics wrinkle easily and without chemical treatment show poor crease recovery and crease retention. Durable press and wash-and-wear finishes tend to cause less degradation of rayon than found with cotton. Rayon possesses excellent moisture absorbency characteristics, but the weaker rayons swell and deform somewhat in the presence of moisture.

The hand of lower-strength viscose rayons is only fair, whereas the hand of cuprammonium and high-wet-modulus rayons is crisp and more desirable. Fabrics of rayon are generally comfortable to wear and are of acceptable appearance.

The rayons are resistant to common household solvents and to light and heat except under extreme conditions or prolonged exposures. Rayons can be dyed readily by a wide variety of dyes, and the colorfastness of dyed rayons is satisfactory. Rayons are moderately resistant to deterioration by repeated laundering, and a moderate degree of care is necessary for maintenance of rayon fabrics. The lower-strength rayons exhibit poor dimensional stability during laundering. Rayons are affected significantly by detergents or other laundry additives. Greater care must be taken when ironing rayon fabrics than would be necessary with cotton. Viscose and cuprammonium rayons may be safely ironed at 176°(, while saponified cellulose acetate can be ironed at 190°(. The rayons possess poor flammability characteristics and ignite readily on contact with a flame, as is the case for natural cellulosics.

The versatility of rayons, coupled with their lower price, makes them suitable for many textile applications. Rayon is used in clothing and home furnishings. Disposable nonwoven garments and products of rayon have been introduced to the consumer in recent years. The stronger rayons have been used in tire cord for several decades but have lost a significant portion of this important market in recent years. Rayon has been used more and more in blends with synthetic fibers, since rayon undergoes less degradation than cotton with durable press and wash-and-wear finishes.

4. Cellulose Ester Fibers

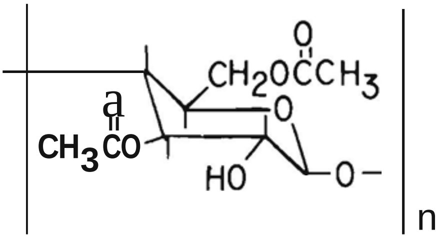
ACETATE AND TRIACETATE

The cellulose esters triacetate and acetate (secondary acetate) are the two major fibers of this type. The production of acetate fibers resulted from an attempt to find a new outlet for cellulose acetate used as aircraft "dope" in World War 1. By 1921, the first acetate fibers were being produced. Although small quantities of cellulose triacetate fibers were produced before World War I, it was not until after 1954 that cellulose triacetate fibers were produced commercially in large quantities.

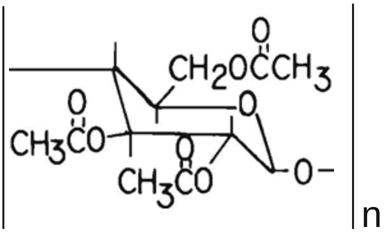
The Federal Trade Commission defines the acetate fibers as manufactured fibers in which the fiber-forming substance is cellulose acetate. Triacetate fibers are those cellulose fibers in which more than 92% of the hydroxyl groups are acetylated. The term secondary acetate has been used in the past in reference to the acetates being less than 92% acetylated. In recent years, these fibers have simply gone by the designation acetate. Although triacetate and acetate are very similar structurally, this slight difference in degree of esterification provides significant differences in properties for these fibers.

Structural Properties and Formation

The cellulose esters triacetate and acetate are formed through acetylation of cotton linters or wood pulp using acetic anhydride and an acid catalyst in acetic acid. At this point the cellulose is fully acetylated.



ACETATE



TRIACETATE

The triacetate is precipitated from solution by addition of water and dried. The cellulose triacetate is normally dissolved in methylene chloride to form about a 20% solution and forced through the spinneret into a stream of hot air to evaporate the solvent to form triacetate fibers by dry spinning. Acetate is formed by allowing the water-precipitated cellulose triacetate solution above to stand as long as 20 hours in aqueous solution. During this ripening process, some of the acetyl groups are hydrolyzed or removed from the cellulose. The acetate is then washed, dried, and dissolved in acetone to form the spinning "dope." The "dope" is forced through a spinneret into hot air to form the acetate fiber by dry spinning. Triacetate and acetate fibers can also be formed by wet spinning processes.

In triacetate, essentially all hydroxyl groups of the cellulose have been acetylated, whereas 2.3-2.5 hydroxyl groups per anhydroglucose unit have been acetylated in cellulose acetate. In both triacetate and acetate, hydrogen bonding between cellulose chains for the most part is eliminated. Also, the bulky acetate group discourages close tight packing of adjacent cellulosic chains. As would be expected, these changes in molecular structure greatly affect the physical properties of triacetate and acetate.

Although limited hydrogen bonding occurs between molecules within acetates, triacetate is incapable of forming hydrogen bonds. Van der Waals forces caused by the interaction of adjacent acetate and triacetate chains are the major associative forces between the acetylated cellulose molecular chains. The average number of acetylated anhydroglucose units in chains of acetates and triacetates usually varies between 250 and 300 units.

The microscopic structures of triacetate and acetate are similar (Figures 4-1 and 4-2). The fiber cross section of each fiber is irregular, with as many as five or six lobes. The longitudinal views of these fibers show striations running the length of the fiber. Small particles of delusterant will be visible in these fibers if they have been added to the fiber prior to spinning. Acetate and triacetate fibers are very similar in appearance to the regular-tenacity viscose rayons.

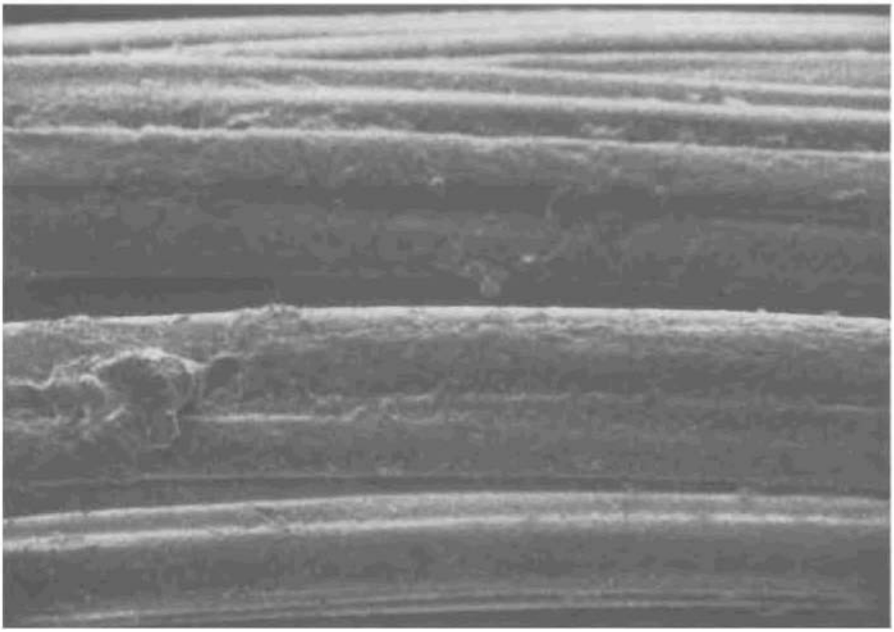


Figure 4-1. Acetate. x1200.

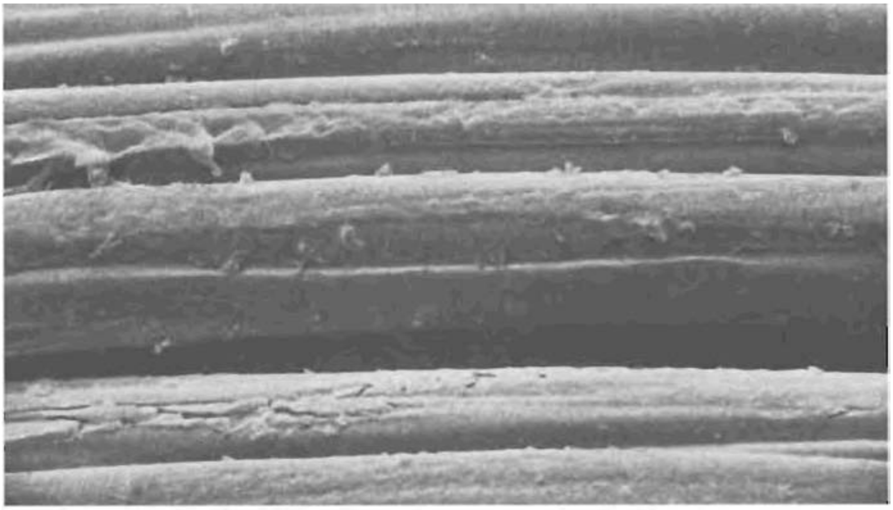


Figure 4-2. Triacetate. x1200.

Physical Properties

Since acetate and triacetate have only limited associative forces between molecular chains, they are considerably weaker than most of the cellulosic fibers. The tenacity of acetate and triacetate falls in the range 1-1.5 g/d (9-14 g/tex). On wetting, their tenacities fall to 0.8-1.2 g/d (7.2-10.8 g/tex). The elongations at break for acetate and triacetate are 25%-40%. On wetting, acetate breaks at 35%-50% elongation, whereas triacetate breaks at 30%-40% elongation. These fibers possess good recoveries at low elongations (80%-100% at 2% elongation). Above 5% elongation, plastic deformation of the fibers occurs and subsequent recovery is poor.

Acetates and triacetates are moderately stiff fibers and possess good resiliency on bending and deformation, particularly after heat treatment. The specific gravities of acetate and triacetate range from 1.30 to 1.35.

The moisture regains of these fibers are markedly lower than found for rayon and cotton. Acetate and triacetate have moisture regains of 6.0% and 4.5%, respectively. On heating, the moisture regain of triacetate drops further to 2.5%.

Acetate and triacetate fibers conduct heat readily and are cool to the touch. Being thermoplastic, acetate and triacetate fibers soften at 200°C and 225°C and melt at 232°C and 300°C, respectively. Triacetate can be heat set more readily than acetate, and permanent pleats can be satisfactorily heat set into triacetate fabric. Heat treatment of triacetate will change the character of the fiber and give a more dense molecular structure. Acetate and triacetate possess excellent electrical characteristics and can be used as insulating materials. As a consequence, static buildup is a problem on these fibers unless antistatic treatments are applied. Acetates and triacetates are attacked by a number of organic solvents capable of dissolving esters. Acetate swells or dissolves in acetone, ethyl acetate, phenol, chloroform, and methylene chloride, whereas triacetate dissolves in formic acid, acetic acid, methylene chloride, or chloroform.

Chemical Properties

Acetate and triacetate are resistant to dilute acids but are attacked by concentrated acids causing hydrolysis and removal of the acetate ester groups. While resistant to dilute alkalies, acetate is more susceptible to attack by alkalies than triacetate. Dilute alkali solutions attack acetate causing saponification and removal of the acetate groups on the fibers. Acetate is attacked by strong oxidizing agents, while triacetate has somewhat better resistance to attack by these reagents. Both fibers, however, can be bleached under proper conditions. Both acetate and triacetate are not attacked by insects or microorganisms. Acetate and triacetate are resistant to attack by sunlight, with greater resistance found for triacetate. Acetate and triacetate will withstand long periods at elevated temperatures below their melting points without significant loss of strength.

End-Use Properties

Acetates and triacetates are relatively inexpensive and have certain properties which are desirable in selected end-use applications. Acetate is marketed under trade names such as Airloft, Estrom, and Loftura, while triacetate fibers bear the trade names Tricel and Arnel.

Both acetate and triacetate are weak fibers having low tenacities, and they cannot be used in applications where high strength is required unless they are blended with other fibers. The high elongations at break found for acetate and triacetate help compensate for these fibers' low strengths to some extent, and the fibers exhibit good recoveries at low extensions.

The abrasion resistance of acetate and triacetate is poor, and these fibers cannot be used in applications requiring high resistance to rubbing and abrasion; however, the resistance of these fibers to pilling is excellent. While acetate and triacetate are moderately absorbent, their absorbencies cannot compare with the pure cellulosic fibers. The hand of acetate fabrics is somewhat softer and more pliable than triacetate, which possesses a crisp firm hand. Fabrics of both fibers possess excellent draping characteristics. Fabrics of acetate and triacetate have a pleasing appearance and a high degree of luster, but the luster of these fabrics can be modified through addition of delusterants.

Both acetate and triacetate are susceptible to attack by a number of household chemicals. Acetate and triacetate are attacked by strong acids and bases and by oxidizing bleaches. Acetate has only fair sunlight resistance, whereas the sunlight resistance of triacetate is superior. Both fibers have good heat resistance below their melting points.

Acetate and triacetate cannot be dyed by dyes used for cellulosic fibers. These fibers can be satisfactorily dyed with disperse dyes at moderate to high temperatures to give even, bright shades. The laundry colorfastness of triacetate is excellent; however, dyed acetate fabrics generally have moderate to poor colorfastness.

The acetate fibers generally require a certain degree of care in laundering, although they exhibit greater wrinkle recovery on drying than cellulosic fibers. Both acetate and triacetate fabrics do not shrink or lose their shape readily during laundering and can be laundered satisfactorily under mild laundry conditions. Both acetate and triacetate may be satisfactorily dry cleaned in Stoddard solvents, but certain other solvents must be avoided due to fiber solubility.

Acetate and triacetate dry quickly and may be tumble dried or drip dried. During tumble drying of these materials it is essential that the dryer be cool during the final tumbling.

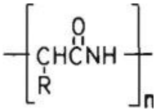
Both acetate and triacetate can be safely ironed, but direct contact of the fabric with the iron is not recommended. Acetate must be ironed at a lower temperature than triacetate, and the maximum safe ironing temperature for these fabrics is 175°C and 200°C, respectively. The flammability characteristics of these fibers are similar to those of the cellulosic fibers, and they have LOIs of 18.

Acetate is used in dresses, blouses, foundation garments, lingerie, garment linings, some household furnishings, and certain specialty fabrics. Triacetate is used in sportswear, tricot fabrics, and in garments where pleats and pleat retention is important, as well as in certain specialty fabrics.

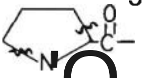
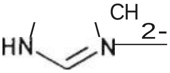
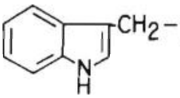
5. Protein Fibers

The protein fibers are formed by natural animal sources through condensation of a-amino acids to form repeating polyamide units with various substituents on the a-carbon atom. The sequence and type of amino acids making up the individual protein chains contribute to the overall properties of the resultant fiber. Two major classes of natural protein fibers exist and include keratin (hair or fur) and secreted (insect) fibers. In general, the keratin fibers are proteins highly crosslinked by disulfide bonds from cystine residues in the protein chain, whereas secreted fibers tend to have no crosslinks and a more limited array of less complex amino acids. The keratin fibers tend to have helical portions periodically within protein sequence, whereas the secreted fiber protein chains are arranged in a linear pleated sheet structure with hydrogen bonding between amide groups on adjacent protein chains. Keratin fibers are extremely complex in structure and include a cortical cell matrix surrounded by a cuticle sheath laid on the surface as overlapping scales. The cell matrix of some coarser hair fibers may contain a center cavity or medulla. The keratin fibers are round in cross section with an irregular crimp along the longitudinal fiber axis which results in a bulky texturized fiber. Secreted fibers are much less complex in morphology and often have irregular cross sections. Other fibrous protein materials include azlon fibers, spun from dissolved proteins, and a graft protein-acrylonitrile matrix fiber.

In general, protein fibers are fibers of moderate strength, resiliency, and elasticity. They have excellent moisture absorbency and transport characteristics. They do not build up static charge. While they have fair acid resistance, they are readily attacked by bases and oxidizing agents. They tend to yellow in sunlight due to oxidative attack. They are highly comfortable fibers under most environmental conditions and possess excellent aesthetic qualities.



PROTEIN

R	AMINO ACID	R	AMINO ACID
H-	GLYCINE	$HOCH_2$-	SERINE
CH_3-	ALANINE	$CH_3\underset{OH}{CH}$-	THREONINE
$(CH_3)_2CH$ -	VALINE	-CH_2SSCH_2-	CYSTINE
$(CH_3)_2CHCH_2$-	LEUCINE	$CH_3SCH_2CH_2$-	METHIONINE
$CH_3CH_2\underset{CH_3}{CH}$-	ISOLEUCINE	$NH_2\overset{NH}{C}NH(CH_2)_3$-	ARGININE
	PROLINE		HISTIDINE
	PHENYLALANINE	$NH_2(CH_2)_4$	LYSINE
$HOOCH_2$ -	TYROSINE	$HOOCCH_2$-	ASPARTIC ACID
	TRYPTOPHAN	$HOOC(CH_2)_2$	GLUTAMIC ACID

WOOL

Wool is a natural highly crimped protein hair fiber derived from sheep. The fineness and the structure and properties of the wool will depend on the variety of sheep from which it was derived. Major varieties of wool come from Merino, Lincoln, Leicester, Sussex, Cheviot, and other breeds of sheep. Worsted wool fabrics are made from highly twisted yarns of long and finer wool fibers, whereas woolen fabrics are made from less twisted yarns of coarser wool fibers.

Structural Properties

Wool fibers are extremely complex, highly crosslinked keratin proteins made up of over 17 different amino acids. The amino acid content and sequence in wool varies with variety of wool. The average amino acid contents for the major varieties of wool are given in Table 5-1.

Table 5-1. Amino Acid Contents in Wool Keratins

Amino Acid	Content in Keratin (g/100 g Wool)
Glycine	5-7
Alanine	3-5
Valine	5-6
Leucine	7-9
Isoleucine	3-5
Proline	5-9
Phenylalanine	3-5
Tyrosine	4-7
Tryptophan	1-3
Serine	7-10
Threonine	6-7
Cystine	10-15
Methionine	0-1
Arginine	8-11
Histidine	2-4
Lysine	0-2
Aspartic acid	6-8
Glutamic acid	12-17

The wool protein chains are joined periodically through the disulfide crosslinked cystine, a diamino acid that is contained within two adjacent chains. About 40% of the protein chains spiral upon themselves and internally hydrogen bond to form an α-helix. Near the periodic cystine crosslinks or at points where proline and other amino acids with bulky groups occur along the chain, the close packing of chains is not possible and a less regular nonhelical structure is observed. The crosslinked protein structure packs and associates to form fibrils, which in turn make up the spindle shaped cortical cells which constitute the cortex or interior of the fiber. The cortex is made up of highly and less cross-linked ortho and para cortex positions. The cortex is surrounded by an outer sheath of scalelike layers or cuticle, which accounts for the scaled appearance running along the surface of the fiber (Figures 5-1 and 5-2).

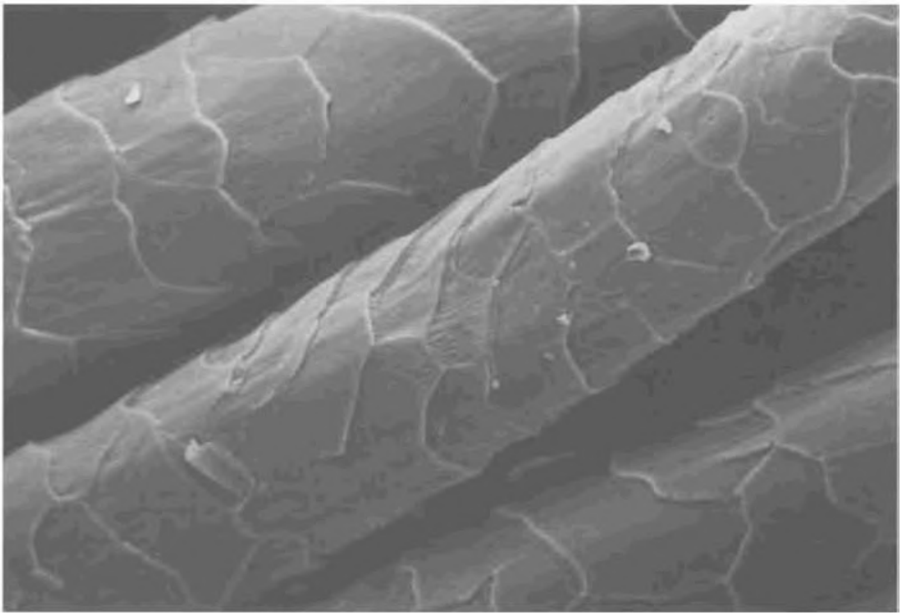


Figure 5-1. Wool. x900.

Physical Properties

Wool fibers possess low to moderate strength with tenacities of 1-2 g/d (9-18 g/tex) dry and 0.8-1.8 g/d (7-16 g/tex) wet. Elongations at break vary from 25% to 40% dry and 25% to 60% wet. At 2% extension, wool shows 99% recovery, and even at 20% extension a recovery as high as 65% is observed. Wool fibers have excellent resiliency and recover readily from deformation except under high humidities. The stiffness of wool varies according to the source and the diameter of the individual fibers. The moisture regain of wool is very high and varies between 13% and 18% under standard conditions. At 100% RH, the regain approaches 40%. Wool fibers have specific gravities of 1.28-1.32. Wool is insoluble in all solvents except those capable of breaking the disulfide crosslinks, but it does tend to swell in polar solvents. Wool is little affected by heat up to 150°C and is a good heat insulator due to its low heat conductivity and bulkiness, which permits air entrapment in wool textile structures. At moderate humidities, wool does not build up significant static charge.

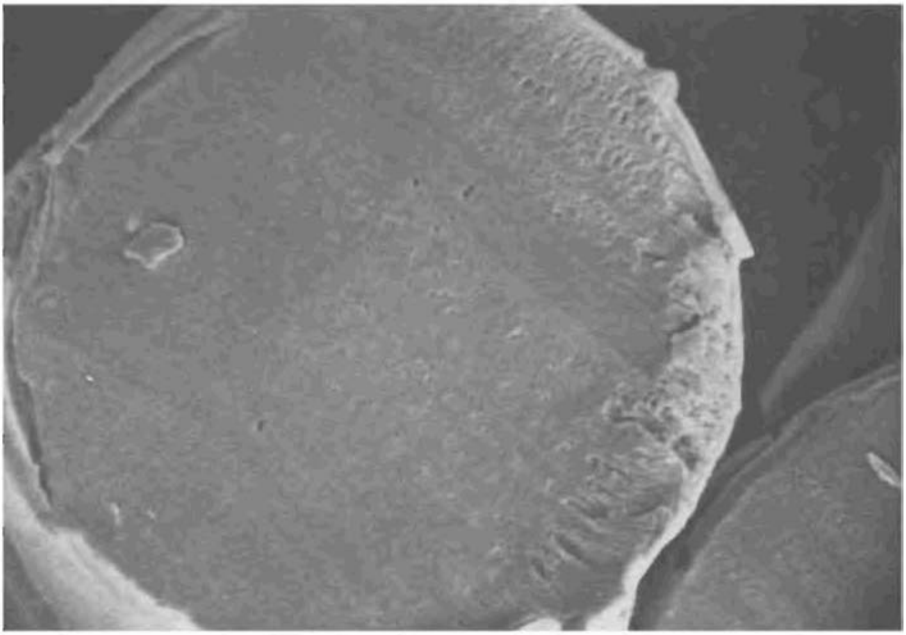


Figure 5-2. Wool cross-section. x2400.

Chemical Properties

Wool is resistant to attack by acids but is extremely vulnerable to attack by weak bases even at low dilutions. Wool is irreversibly damaged and colored by dilute oxidizing bleaches such as hypochlorite. Reducing agents cause reductive scission of disulfide bonds within the wool, eventually causing the wool to dissolve. Under controlled conditions, reducing agents can be used to partially reduce the wool and flat set or set permanent pleats in the wool. Unless chemically treated, wool is susceptible to attack by several species of moths able to dissolve and digest wool fibers. Wool is quite resistant to attack by other biological agents such as mildew. Wool is attacked by short wavelength (300-350 nm) ultraviolet light, causing slow degradation and yellowing. On heating, wool degrades and yellows above 150°C and chars at 300°C.

End-Use Properties

Wool varieties include Merino, lincoln, leicester, Sussex, Cheviot, Ramboullett, and Shetland, as well as many others. Wool is a fiber of high to moderate luster. Fabrics of wool possess a soft to moderate hand and exhibit good drapability. Wool fibers are highly absorbent and have excellent moisture transmission properties.

The low to moderate strength of wool fibers is compensated for by its good stretch and recovery properties. Wool is fairly abrasion resistant and does not tend to form pills due to its low strength. It resists wrinkling except under warm, moist conditions. Its crease retention is poor unless creases have been set using chemical reducing agents.

Wool is attacked by alkalies and chlorine bleaches and is progressively yellowed by the short ultraviolet wavelengths in sunlight. Wool dyes readily, and the dyed wools exhibit good colorfastness. Owing to its felting action, wool cannot be laundered in hot water with agitation, but it can be dry-cleaned or washed in warm water with a mild detergent if no agitation is used.

Due to its affinity for water, wool is slow drying. Wool may be ironed at 150°C or below without steaming. Wool is a self-extinguishing fiber and burns very slowly even in contact with a flame. It has an lOI of 25.

Wool is extensively used in textile applications where comfort and aesthetics are important. It is used in men's and women's apparel, outer wear and cold weather clothing, suits, blankets, felts, and carpeting. It is often used in blends with cellulosic and man-made fibers.

SILK

Silk is a natural protein fiber excreted by the moth larva Bombyx mori, better known as the common silkworm. Silk is a fine continuous monofilament fiber of high luster and strength and is highly valued as a prestige fiber. Because of its high cost, it finds very limited use in textiles. A minor amount of wild tussah silk is produced for specialty items. Attempts have been made to commercialize silk from spiders over the years, but all ventures have met with failure. Domestic and wild silks are essentially uncrosslinked and relatively simple in amino acid composition compared to the keratin fibers. The properties for silk listed here are for silk formed by Bombyx mori moth larvae.

Liquid silk protein is extruded from two glands in the head of the silkworm. The fibers emerge from a common exit tube or spinneret and harden into a single strand by a protein gum called sericin. The completed silk cocoons are soaked in hot water to loosen the sericin, and the silk filaments are unwound. After unwinding, the silk filaments are washed in warm detergent solutions to remove the sericin. The fibroin silk fibers are more simple in structure than keratin and are composed predominantly of glycine, alanine, tyrosine, and serine. The average range of composition for silk is given in Table 5-2.

With no cystine present in the fibroin protein, little crosslinking is observed between protein chains. The degree of polymerization of silk fibroin is uncertain, with DPs of 300 to 3000+ having been measured in different solvents. In the absence of crosslinks and with limited bulky side chains present in the amino acids, fibroin molecules align themselves parallel to each other and hydrogen bond to form a highly crystalline and oriented "pleated-sheet" or "beta" structure. Silk fibers are smooth surfaced and translucent with some irregularity in diameter along the fiber (Figure 5-3). The fibers are basically triangular in cross section with rounded corners.

Physical Properties

Silk fibers are strong with moderate degrees of recovery from deformation. Silk has a dry tenacity of 3-6 g/d (27-54 g/tex) and a wet tenacity of 2.5-5 g/d (23-45 g/tex). Silk exhibits a recovery of 90% from 2% elongation and of 30%-35% from 20% elongation. Silk fibers are moderately stiff and exhibit good to excellent resiliency and recovery from deformation, depending on temperature and humidity conditions. Silk has a specific gravity of 1.25-1.30 and a moisture regain of 11% under standard conditions. Silk is soluble in hydrogen bond breaking solvents such as aqueous lithium bromide, phosphoric acid, and cuprammonium solutions. It exhibits good heat insulating properties and is little affected by heat up to 150°C. Silk has moderate electrical resistivity and tends to build up static charges.

Table 5-2. Amino Acid Contents in Fibroin

Amino Acid	Content in Fibroin (g/IOO g Fibroin)
Glycine	36-43
Alanine	29-35
Tyrosine	10-13
Serine	13-17
Valine	2-4
Leucine	0-1
Proline	0-1
Phenylalanine	1-2
Tryptophan	0-1
Threonine	1-2
Cystine	0
Methionine	0
Arginine	0-2
Histidine	0-1
Lysine	0-1
Aspartic acid	1-3
Glutamic acid	1-2

Chemical Properties

Silk is slowly attacked by acids but is damaged readily by basic solutions. Strong oxidizing agents such as hypochlorite rapidly discolor and dissolve silk, whereas reducing agents have little effect except under extreme conditions. Silk is resistant to attack by biological agents but yellows and loses strength rapidly in sunlight. Silk is often weighted with tin and other metal salts. These salts make silk even more sensitive to light-induced oxidative attack. Silk undergoes charring and oxidative decomposition when heated above 175°C in air over a prolonged period of time.

Figure 5-3. Silk. x900.

End-Use Properties

Silk possesses a combined set of aesthetic properties that make it useful for high-fashion luxury textile goods. Silk has a high luster and is translucent. Silk fabrics have pleasing appearance and drapability, and a characteristically pleasing crisp hand. Silk is highly moisture absorbent and has good to excellent resistance to wrinkling. It is a moderately strong fiber with moderate recovery properties. It exhibits fair abrasion resistance and good resistance to pilling. Silk is sensitive to chlorine bleaches and to alkalies and is easily damaged by sunlight. The fiber may be dyed with a wide variety of dyes to give dyed fibers with high colorfastness. Silk may be laundered under mild, nonalkaline conditions and dry cleans readily. Because of its high affinity for water, it dries slowly but may be dried or ironed safely up to 150°C. Silk burns slowly and self-extinguishes when removed from a flame. Silk is used extensively in luxury fabrics and apparel and home furnishings, and in accessories such as scarfs.

OTHER NATURAL AND REGENERATED PROTEIN FIBERS

The other major hair (keratin) fibers include mohair, cashmere, llama, alpaca, and vicuna, as well as many others. Regenerated Azlon fibers are derived from soluble proteins that can be spun into fibers, insolubilized, and regenerated. Soluble proteins also may be grafted to form a copolymer, dissolved, and then spun into fibers.

Mohair

Mohair is a very resilient hair fiber obtained from the angora goat. The two primary classifications for mohair are the finer kid mohair and the coarser adult mohair. In many respects, mohair resembles wool in structure and possesses properties including the characteristic scale structure of the fiber. The average length of mohair fibers is longer than wool, with 4-12 inch fiber lengths being typical. It is a much stronger fiber than wool, but its other tensile properties resemble wool. Mohair is remarkably resistant to wear and is used in applications where such durability is essential. Mohair possesses a beautiful natural luster and is used in blends to provide luster. Mohair fibers also provide a characteristic, resilient, and slightly scratchy hand in even small quantities blended with other fibers.

Cashmere

Cashmere is the fine, soft inner coat of down obtained from the cashmere goat found on the inner plateaus of Asia. In many ways the properties of cashmere resemble those of wool, but cashmere fibers are extremely fine and soft compared to wool. Cashmere is used in luxury applications where a soft, warm, fine fiber with beautiful drape is desired.

Llama, Alpaca, and Vicuna

These fibers come from a group of related animals found in South America. They are fine fibers that are white to tan and brown in color. They are longer than most wool fibers and generally stronger, with a finer scale structure. They are generally used only in the expensive luxury items of textiles and apparel.

Regenerated Protein Fibers

Azlon is the generic name given to manufactured fibers composed of a regenerated natural protein. Azlon is produced by dissolving proteins like casein from milk, soya bean protein, and zein from corn in dilute alkali and forcing these solutions through a spinneret into an acid-formaldehyde coagulating bath. Many of the properties of these fibers resemble the natural protein fibers, but they suffer from low dry and wet strength and sensitivity to alkalies. Although no longer produced in the U.S., azlon fibers are produced in Europe and used in blends with natural and man-made fibers.

Protein-Polyacrylonitrile Graft Copolymer

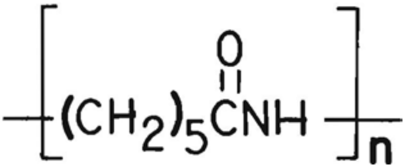
A fiber consisting of a copolymer of casein protein (25%-60%) grafted with 40%-75% acrylic monomers, of which at least half is acrylonitrile, has been developed in Japan under the tradename Chinon. The casein dissolved in aqueous zinc chloride and grafted with acrylonitrile is wet or dry spun into fibers. The fiber has a tenacity of 3.5-5 g/d (32-45 g/tex) dry and 3-4.5 g/d (27-40 g/tex) wet and an elongation at break of 15%-25% wet or dry. It recovers 70% from 5% elongation. The fiber has a moisture regain of 4.5%-5.5% and a specific gravity of 1.22. It dyes readily with acid dyes, but basic and reactive dyes can be used also. The fiber is marketed as a substitute for silk.

6. Polyamide Fibers

The polyamide fibers include the nylons and the aramid fibers. Both fiber types are formed from polymers of long-chain polyamides. In nylon fibers less than 85% of the polyamide units are attached directly to two aromatic rings, whereas in aramid fibers more than 85% of the amide groups are directly attached to aromatic rings. The nylons generally are tough, strong, durable fibers useful in a wide range of textile applications. The fully aromatic aramid fibers have high temperature resistance, exceptionally high strength, and dimensional stability. The number of carbon atoms in each monomer or comonomer unit is commonly designated for the nylons. Therefore the nylon with six carbon atoms in the repeating unit would be nylon 6 and the nylon with six carbons in each of the monomer units would be nylon 6,6.

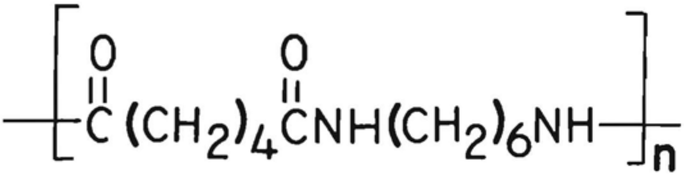
NYLON 6 AND 6,6

Nylon 6 and 6,6 are very similar in properties and structure and therefore will be described together. The major structural difference is due to the placement of the amide groups in a continuous head-to-head arrangement in nylon 6, whereas in nylon 6,6 the amide groups reverse direction each time in a head-to-tail arrangement due to the differences in the monomers and polymerization techniques used:



$$\left[(CH_2)_5\overset{O}{\overset{\|}{C}}NH \right]_n$$

NYLON 6



$$\left[\overset{O}{\overset{\|}{C}}(CH_2)_4\overset{O}{\overset{\|}{C}}NH(CH_2)_6NH \right]_n$$

NYLON 6.6

Nylon 6,6 was developed in the United States, whereas nylon 6 was developed in Europe and more recently Japan. These nylon polymers form strong, tough, and durable fibers useful in a wide variety of textile applications. The major differences in the fibers are that nylon 6,6 dyes lighter, has a higher melting point, and a slightly harsher hand than nylon 6.

Structural Properties

Nylon 6 is produced by ring-opening chaingrowth polymerization of caprolactam in the presence of water vapor and an acid catalyst at the melt. After removal of water and acid, the nylon 6 is melt spun at 250°C-260°C into fibers. Nylon 6,6 is prepared by step growth polymerization of hexamethylene diamine and adipic acid. After drying, the nylon 6,6 is melt spun at 280°C-290°C into fibers. Both nylon 6 and 6,6 are drawn to mechanically orient the fibers following spinning.

The degree of polymerization (OP) of nylon 6 and 6,6 molecules varies from 100 to 250 units. The polyamide molecular chains lay parallel to one another in a "pleated sheet" structure similar to silk protein with strong hydrogen bonding between amide linkages on adjacent molecular chains. The degree of crystallinity of the nylon will depend on the degree of orientation given to the fiber during drawing. Nylon fibers are usually rodl ike with a smooth surface or trilobal in cross section (see Figures 6-1 and 6-2). Multilobal (star) cross sections and other complex cross sections are also found. Side-by-side bicomponent fibers with a round cross section are also formed. Following orientation and heating, these bicomponent fibers form small helical crimps along the fiber to give a texturized fiber useful in many applications including women's hosiery. Cantrece nylon is such a fiber. Also, sheath-core nylons with differing melting characteristics are formed for use as self-binding fibers for nonwovens.

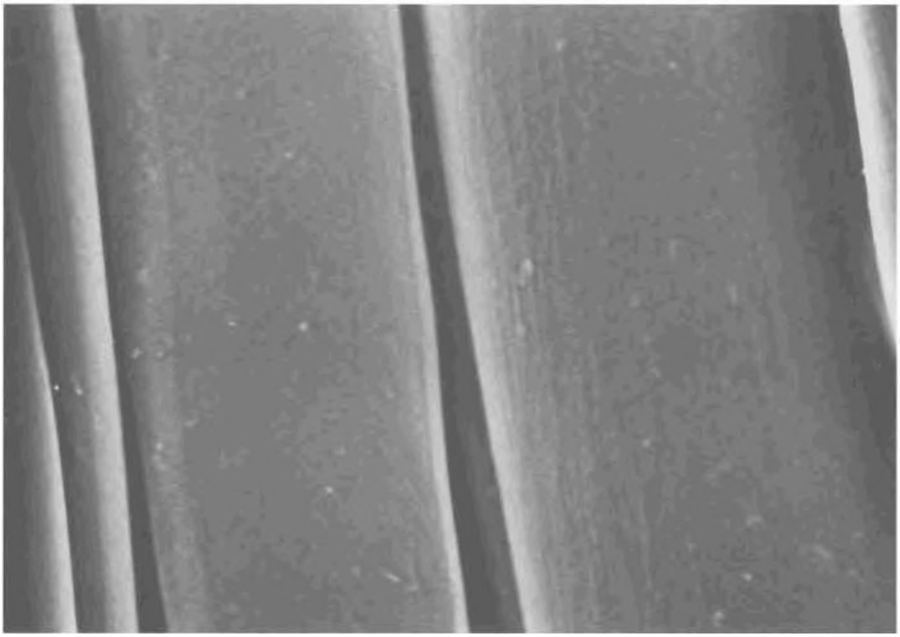


Figure 6-1. Nylon 6,6, round. x1900.

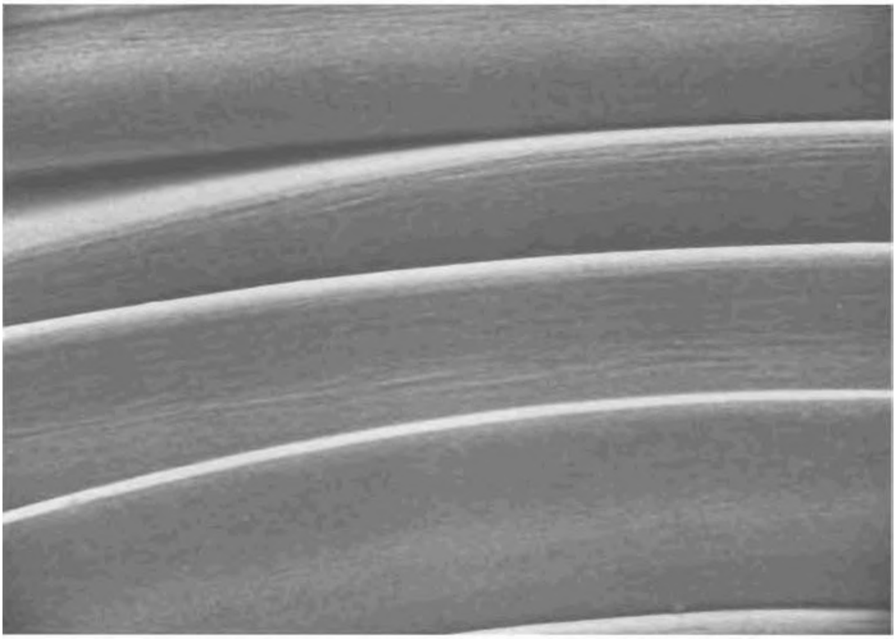


Figure 6-2. Nylon 6,6, trilobal. x1200.

Physical Properties

Nylon 6 and 6,6 fibers are strong, with a dry tenacity of 4-9 g/d (36-81 g/tex) and a wet tenacity of 2.5-8 g/d (23-72 g/tex). These nylons have elongations at break of 15%-50% dry, which increase somewhat on wetting. Recovery from stretch deformation is very good, with 99% recovery from elongations up to 10%. The nylons are stiff fibers with excellent resiliency and recovery from bending deformation. They are of low density, with a specific gravity of 1.14. They are moderately hydrophilic with a moisture regain of 4%-5% under standard conditions and a regain of 9% at 100% relative humidity. Nylon 6 and 6,6 are soluble in hydrogen bond breaking solvents such as phenols, 90% formic acid, and benzyl alcohol. They have moderate heat conductivity properties and are unaffected by heating below 150°C. The nylons have a high resistivity and readily build up static charge.

Chemical Properties

The nylons are fairly resistant to chemical attack. They are attacked by acids, bases, and reducing and oxidizing agents only under extreme conditions. They are unaffected by biological agents, but at elevated temperatures or in the presence of sunlight they will undergo oxidative degradation with yellowing and loss of strength.

End-Use Properties

Nylon 6 and 6,6 are marketed under several trade names. In fact, nylon was originally used as a trade name for duPont polyamide fiber, but as a result of common usage the term nylon came to be the generic term for these polyamide fibers. Common trade names for these nylons include Anso, Antron, Cadon, Cantrece, Cordura, Caprolan, duPont nylon, and Enkalure. Nylon 6 and 6,6 are extremely strong fibers with excellent recovery and resiliency properties. Nylon fabrics have a fair hand, with nylon 6 having a somewhat softer hand than nylon 6,6. Nylon fabrics have high luster unless delustered. They have moderate to excellent draping properties depending on the denier of the fiber. Unless bleached and dyed, nylons have a slightly yellow color. The nylons are wrinkle resistant and have good crease resistance **if** heat set. The fiber is tough and has good abrasion resistance. In fact, nylon is reported to abrade other fibers in a fiber blend. The fiber has good resistance to household chemicals but exhibits poor resistance to attack by sunlight unless treated with antioxidants. The fibers have excellent dyeability with excellent colorfastness properties. Nylon 6 is somewhat deeper dyeing than nylon 6,6.

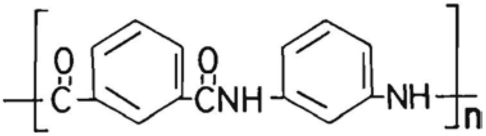
The fiber has good laundering and dry cleaning properties but tends to scavenge dyes bleeding from other fibers. The fibers have moderate moisture uptakes and dry readily at temperatures up to 150°C. Nylon 6 can be safely ironed up to 140°C, whereas nylon 6,6 can be safely ironed up to 180°C. The nylons are less flammable than cellulosics, with an LOI of 20. They melt and drip and tend to self-extinguish on burning. Nylons are extensively used in hosiery, lingerie, underwear, sweaters, and other knitted goods. They have been used extensively in light and sheer apparel articles such as windbreakers. Nylons are used in home furnishings and industrial applications including carpets, upholstery, tie cord, para-" chutes, sails, ropes, thread, and outdoor wear.

ARAMID FIBERS

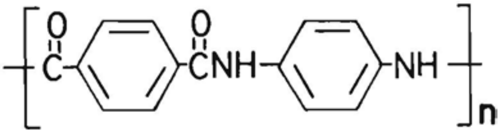
The aramid polyamide fibers are formed from a long chain of synthetic polyamides in which at least 85% of the amide linkages are attached to aromatic rings. These essentially fully aromatic polyamides are characteristically high melting and have excellent property retention at high temperatures and excellent durability. They are unaffected by moisture and most chemicals and are inherently flame retardant. The fibers have high strength and can be used in a number of unique high-strength applications.

Structural Properties

Aramids are formed through step growth polymerization of aromatic diacid chlorides with aromatic diamines in a polar aprotic solvent such as *N*,*N*-dimethylformamide (DMF) to a DP of 100-250. The *meta-* and *para-substituted* benzene dicarboxylic acid chlorides and diamines are characteristically used for aramid fibers presently in production, but other fully aromatic ring systems are possible future sources of aramid polymers for fibers:



NOMEX



KEVLAR

ARAMID

The resultant aramid polymers are spun in suspension through a spinneret into hot air (dry spinning) or a coagulating of both (wet spinning) to form the fibers, followed by fiber stretching and orientation. The aromatic units along aramid polyamide chains confer stiffness to the polymeric chains and limit their flexibility and mobility. Hydrogen bonding between amide groups on adjacent chains and extremely strong van der Waals interactions between aromatic rings planar to adjacent aromatic rings provide a tightly-packed, strongly held molecular structure and account for the strength and thermal stability of the aramids. The aramids are usually spun in round or dumbbell cross section.

Physical Properties

The aramids are the strongest of the man-made fibers, with the strength depending on the polymer structure, spinning method used, and the degree of orientation of the fiber. Dry tenacities of 4-22 g/d (36-198 g/tex) are found for the aramids, and wet tenacities of 3-18 g/d (27-162 g/tex) have been recorded. The elongation at break of the fibers decreases with increasing tenacity over a range of 3%-30% dry and wet. Recovery from low elongations of 5% or less is 98%-100%. The fibers are stiff, with excellent resiliency and recovery from bending deformation. The specific gravities of these fibers vary from 1.38 to 1.44. The aramids have a moisture regain comparable to the other polyamide fibers and are in the 3.5%-7% range. The fibers are swollen and dissolved in polar aprotic solvents or strong acids. The aramids have high heat and electrical resistivities, have excellent insulative capabilities, and are unaffected by heat up to 250°C.

Chemical Properties

The aramids are extremely resistant to chemical or biological attack. Only under extreme conditions and at elevated temperatures will concentrated acids or strong oxidizing agents attack aramids. Aramid fibers undergo initial oxidative attack in sunlight, causing discoloration and slight strength loss, but further exposure has little additional effect. The aramids also act as effective screens to high-energy nuclear radiation due to their ability to trap and stabilize radical and ionic species induced by radiation. The aramids undergo oxidative degradation on prolonged heating above 370°C.

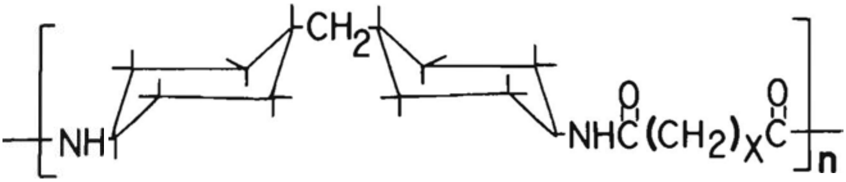
End-Use Properties

Common trade names for aramid fibers include Nomex and Kevlar (duPont). Aramid fibers are extremely strong and heat resistant. Fabrics from the aramids have a high luster with a fair hand and adequate draping properties. The fibers are light yellow unless bleached and exhibit moderate moisture absorption characteristics. The fibers recover readily from stretching and bending deformation and are extremely abrasion resistant. They do tend to pill due to the high strength of the fiber. The aramids are extremely resistant to attack by household chemicals and exhibit good resistance to sunlight. The fibers are difficult to dye except by special dyeing techniques with disperse dyes. Dyed aramids are reasonably colorfast. They have good launderability and dry-cleanability and are moderately easy to dry. The fibers are extremely heat stable and can be ironed up to 300°C. The fibers are of low flammability and self-extinguish on removal from a flame. They have an LOI of 30. Aramid fibers are used in fabric applications where high strength and low flammability are important, including protective clothing, electrical insulation, filtration fabrics, specialized military applications, and tire cord.

OTHER POLYAMIDES

Several other polyamides have been introduced for use as fibers in specialty applications where certain combinations of properties are desired. The major specialty nylons include Qiana, nylon 4, nylon 11, nylon 6,10, and biconstituent nylon-polyester. Their particular characteristics are outlined below.

Qiana is a trade name (duPont) for the luxury nylon fiber formed through step growth polymerization of trans,trans-di(4-aminocyclohexyl) methane and a dibasic acid having 8-12 carbon atoms:



QIANA

Qiana resembles nylon 6 and 6,6 in many of its properties but also has a unique silklike texture, a lustrous appearance, excellent form retention, and an overall superior performance level which makes it useful in prestige textile products and in the sophisticated fashion apparel market.

Qiana has a tenacity of 3-3.5 g/d (27-32 g/tex) and an elongation at break of 20%-30%. It is reported to recover from strain better than nylon 6,6 or polyester. It has a specific gravity of 1.03 and a moisture regain of 2%-2.5%, which are much lower values than nylon 6 or 6,6. Qiana melts at 275°C and is stable up to 185°C. The cross section of the fiber is trilobal (Figure 6-3). It shows good chemical stability and is readily dyeable to fast colors. The excellent aesthetic qualities and drapability of Qiana have contributed greatly to its success.

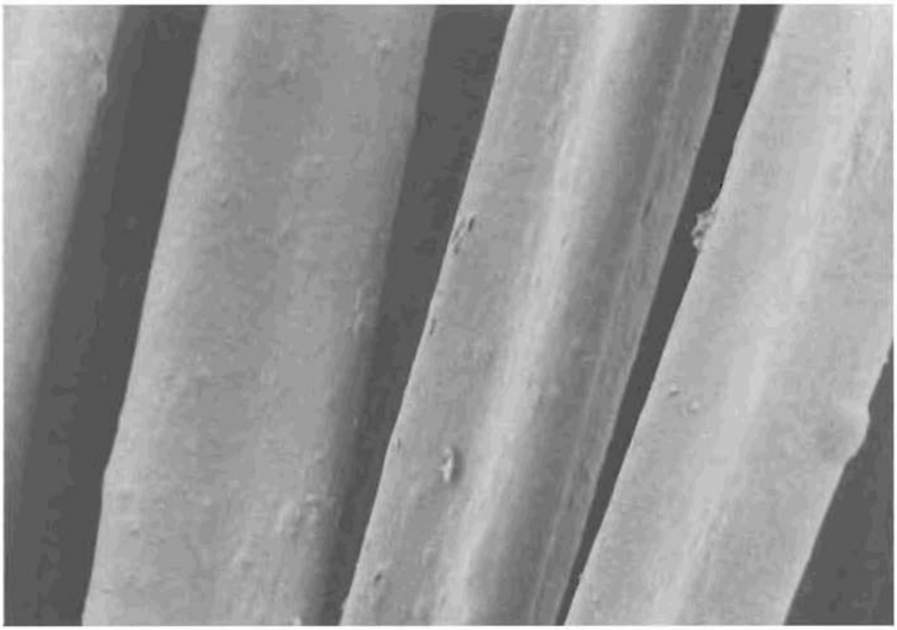


Figure 6-3. Qiana. x900.

Nylon 4

Nylon 4 is produced by polymerization of pyrrolidone using carbon dioxide catalyst. Nylon 4 is melt spun (melting point 273°C) to give a fiber of about 60% crystallinity. The fiber is of moderate dry strength (4.5 g/d) and slightly higher wet strength, with a higher specific gravity (1.25) than nylon 6 and 6,6. The fiber has excellent elongation and recovery properties and a water regain comparable to cotton (8% at 21°C and 65% RH). Nylon 4 is easily laundered and can be dyed easily to give colorfast shades but has limited wrinkle recovery properties and is sensitive to hypochlorite bleaches. Although a major attempt was made to commercialize nylon 4, market conditions limited the penetration of this new fiber type and production was discontinued. Nylon 4 is no longer being produced.

Nylon 11

Nylon II is produced by self-condensation of ll-aminoundecanoic acid in Europe and marketed under the name Rilsanite. It is melt spun (mp 189°C) into fiber and possesses essentially the same properties as nylon 6 and 6,6. It has high strength (5-7.5 g/d), low specific gravity (1.04), and low water regain (1.2%). Nylon II has excellent electrical properties and is used in electrical products as well as in brush bristles, tire cord, lingerie, and hose.

Nylon 6,10

Nylon 6,10 is produced by condensation polymerization of hexamethylene diamine and sebacic acid and is melt spun (mp 216°C) into fibers. It resembles nylon 6 and 6,6 in many ways but has a lower moisture regain (2.6%). It is primarily used in brush bristles.

Biconstituent Nylon-Polyester

Biconstituent fiber of nylon 6 with polyester microfibrils dispersed throughout the fiber matrix has been marketed under the trade name Source (Allied). The fiber is reported to have unique optical and dyeing properties and a higher strength and lower regain than nylon 6,6 and is used primarily in carpets. A sheath-core bicomponent fiber containing a nylon 6 sheath and a polyester core has been reported also. It is said to have properties that are intermediate between both fibers.

7. Polyester Fibers

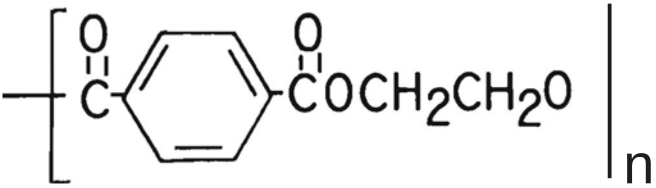
Polyesters are those fibers containing at least 85% of a polymeric ester of a substituted aromatic carboxylic acid including but not restricted to terephthalic acid and f-hydroxybenzoic acid. The major polyester in commerce is polyethylene terephthalate, an ester formed by step growth polymerization of terephthalic acid and the diol ethylene glycol. Poly-1,4-cyclohexylenedimethylene terephthalate is the polyester of more limited usage and is formed through the step growth polymerization of terephthalic acid with the more complex diol 1,4-cyclohexylenedimethanol. A third polyester fiber is actually the polyester ether PolY(f-ethyleneoxybenzoate) and is formed through step growth polymerization of £-hydroxybenzoic acid with ethylene glycol; it is no longer in commercial production, however. The polyester fibers all have similar properties, are highly resilient and resistant to wrinkling, possess high durabilily and dimensional stability, and are resistant to chemical and environmental attack.

POLYETHYLENE TEREPHTHALATE

Polyethylene terephthalate polyester is the leading man-made fiber in production volume and owes its popularity to its versatility alone or as a blended fiber in textile structures. When the term "polyester" is used, it refers to this generic type. It is used extensively in woven and knitted apparel, home furnishings, and industrial applications. Modification of the molecular structure of the fiber through texturizing and or chemical finishing extends its usefulness in various applications. Polyester is expected to surpass cotton as the major commodity fiber in the future.

Structural Properties

Polyethylene terephthalate is formed through step growth polymerization of terephthalic acid or dimethyl terephthalate with ethylene glycol at 250°-300°C in the presence of a catalyst to a DP of 100-250:



POLYETHYLENE TEREPHTHALATE
POLYESTER

The resultant polymer is isolated by cooling and solidification and dried. Polyester fibers are melt spun from the copolymer at 250°-300°C, followed by fiber orientation and stretching. The polyester molecular chains are fairly stiff and rigid due to the presence of periodic phenylene groups along the chain. The polyester molecules within the fiber tend to pack tightly and are held together by van der Waals forces. The polyesters are highly crystalline unless comonomers are introduced to disrupt the regularity of the molecular chains. Polyester fibers are usually smooth and rodlike with round or trilobal cross sections (Figure 7-1).

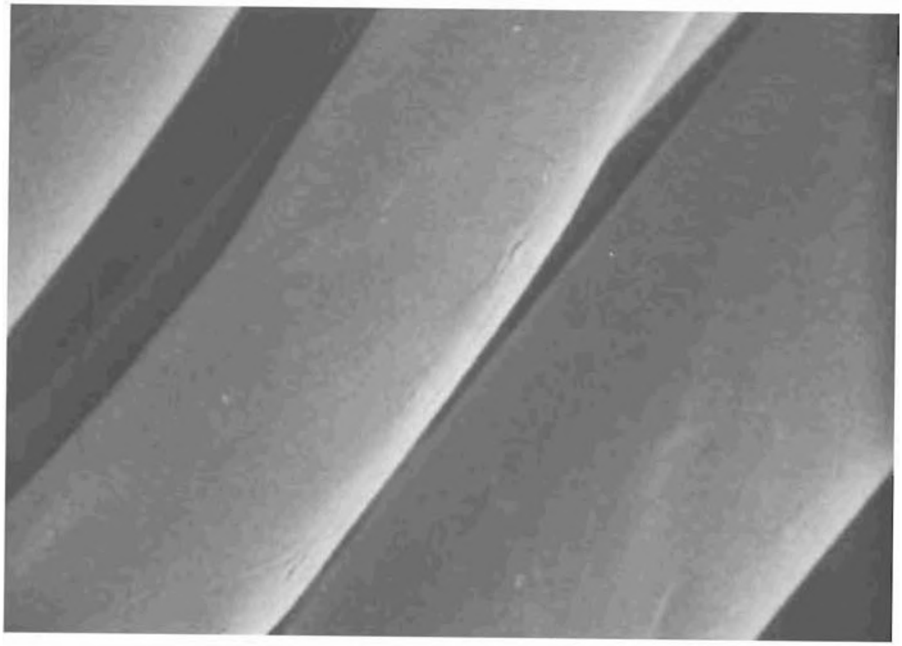


Figure 7-1. Polyester. x1000.

Physical Properties

Polyester from polyethylene terephthalate is an extremely strong fiber with a tenacity of 3-9 g/d (27-81 g/tex). The elongation at break of the fiber varies from 15% to 50% depending on the degree of orientation and nature of crystalline structure within the fiber. The fiber shows moderate (80%-95%) recovery from low elongations (2%-10%). The fiber is relatively stiff and possesses excellent resiliency and recovery from bending deformation. The fiber has a specific gravity of 1.38. The fiber is quite hydrophobic, with a moisture regain of 0.1%-0.4% under standard conditions and 1.0% at 21°C and 100% RH. It is swollen or dissolved by phenols, chloroacetic acid, or certain chlorinated hydrocarbons at elevated temperatures. The fiber exhibits moderate heat conductivity and has high resistivity, leading to extensive static charge buildup. On heating, the fiber softens in the 210°-250°C range with fiber shrinkage and melts at 250°-255°C.

Chemical Properties

Polyethylene terephthalate polyester is highly resistant to chemical attack by acid, bases, oxidizing, or reducing agents and is only attacked by hot concentrated acids and bases. The fiber is not attacked by biological agents. On exposure to sunlight, the fiber slowly undergoes oxidative attack without color change with an accompanying slow loss in strength. The fiber melts at about 250°C with only limited decomposition.

End-Use Properties

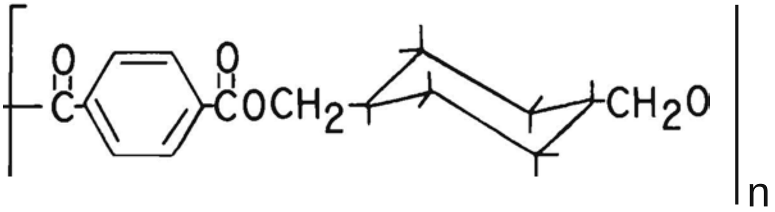
Common trade names for polyethylene terephthalate polyester are Monsanto, Dacron, Encron, Kadel IV, Polar Guard, Trevira, Fortrel, and Vycron. This polyester is an inexpensive fiber with a unique set of desirable properties which have made it useful in a wide range of end-use applications. It has adequate aesthetic properties and bright translucent appearance unless a delusterant has been added to the fiber. The hand of the fiber is somewhat stiff unless the fiber has been texturized or modified, and fabrics from polyester exhibit moderate draping qualities.

The fiber is hydrophobic and nonabsorbent without chemical modification. This lack of absorbency limits the comfort of polyester fabrics. Polyester possesses good strength and durability characteristics but exhibits moderate to poor recovery from stretching. It has excellent wrinkle resistance and recovery from wrinkling and bending deformation. Polyester shows only fair pilling and snag resistance in most textile constructions. Heat setting of polyester fabrics provides dimensional stabilization to the structure, and creases can be set in polyester by heat due to its thermoplastic nature. It has excellent resistance to most household chemicals and is resistant to sunlight-induced oxidative damage, particularly behind window glass.

Due to its hydrophobicity and high crystallinity, polyester is difficult to dye, and special dyes and dyeing techniques must be used. When dyed, polyester generally exhibits excellent fastness properties. Polyester has good laundering and dry-cleaning characteristics but is reported to retain oily soil unless treated with appropriate soil release agents. Owing to its low regain, polyester dries readily and can be safely ironed or dried at temperatures up to 160°C. It is a moderately flammable fiber that burns on contact with a flame but melts and drips and shrinks away from the flame. It has a LOI 21. Polyester is used extensively as a staple and filament fiber in apparel and as a staple fiber in blends with cellulosic fibers for apparel of all types. Polyester is also used extensively in home furnishings and as fiberfill for pillows, sleeping bags, etc. Polyester is used in threads, rope, and tire cord and in sails and nets as well as other industrial fabrics.

POLY-l,4-CYCLOHEXYLENEDIMETHYLENE TEREPHTHALATE

Poly-l,4-cyclohexylenedimethylene terephthalate resembles polyethylene terephthalate in most properties:



POLY-I.4-CYCLOHEXYLENEDIMETHYLENE TEREPHTHALATE POLYESTER

The cyclohexylene group within this fiber provides additional rigidity to the molecular chains, but the packing of adjacent polymer chains may be more difficult due to the complex structure (Figure 7-2). As a result, the fiber has a lower tenacity than polyethylene terephthalate. It has a tenacity of 2.5-3 g/d (22-27 g/tex) and exhibits lower elongations than polyethylene terephthalate. It has a lower specific gravity (1.22-1.23) than polyethylene terephthalate. The fiber melts at 290°-295°C and is attacked and shrunk by trichloroethylene and methylene chloride. The fiber has good chemical resistance. The major trade name for this polyester is Kodel II. The fiber is somewhat superior to polyethylene terephthalate in certain end-use properties including better recovery from stretch and better resistance to pillin9. The fiber has superior resiliency and is particularly suited for use in blend with cellulosics and wool, as a carpet fiber, and as fiberfill.

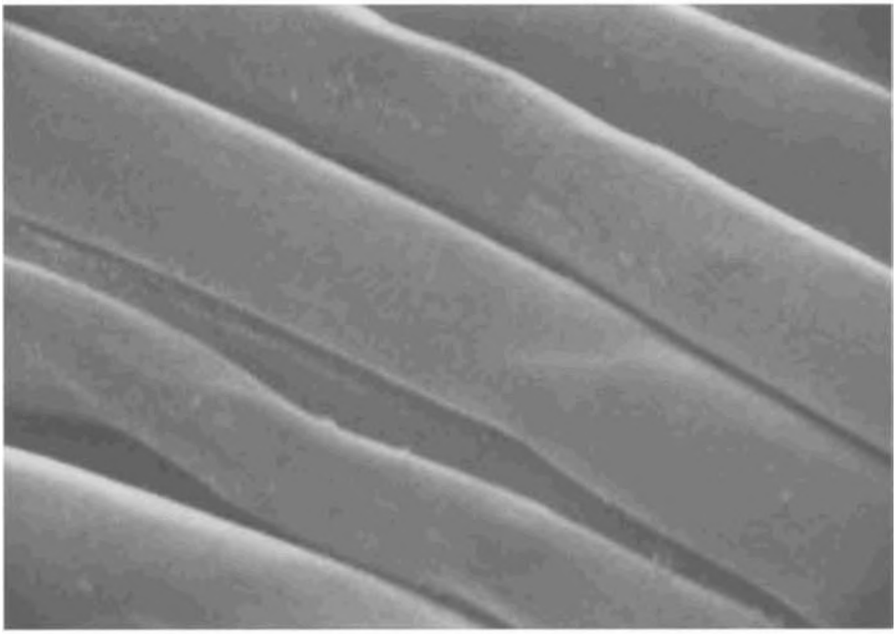


Figure 7-2. Poly-l,4-cyclohexylenedimethylene terephthalate polyester. x1300.

OTHER POLYESTERS

Poly-p-ethyleneoxybenzoate

This fiber was introduced by a Japanese firm as A-Tell. The properties of the fiber are very similar to the polyesters containing terephthalate units in most respects including tensile properties, specific gravity, melting point, chemical resistance, and sunlight resistance. As a result, the FTC expanded the polyester category to include the polymeric p-ethyleneoxybenzoate esters. The fiber is produced by reaction of ethylene oxide with £-hydroxybenzoic acid, followed by melt spinning.

The fiber has a tenacity of 4-5.5 g/d (36-50 g/tex) and an elongation at break of 15%-30% with nearly complete recovery from low elongation. Its specific gravity of 1.34 and moisture regain of 0.4%-5.0% are nearly the same as that of polyethylene terephthalate polyester. The fiber melts at 224°C and softens at about 200°C. The fiber is reported to be even more resistant to attack by acids and bases than terephthalate-based polyesters. The properties of this fiber were not sufficiently different from other polyesters to achieve reasonable market penetration, and the fiber has been discontinued.

Modified Terephthalate Polyesters

Poor dyeability and the moderate flammability of polyester have resulted in formulation of modified terephthalate esters to improve the dyeability and the flame retardant properties of the fiber. Introduction of amino or sulfonic acid groups on the benzene ring of terephthalate leads to fibers that are more dyeable with cationic or acid dyes. Bromine, other halogen, or phosphonate groups substituted within the structure provide flame retardant characteristics to the fiber, especially if antimony oxide is present in the fiber matrix. Appropriate nonterephthalate comonomers replacing some of the terephthalate groups introduced into the polyester can improve dyeability and/or flammability of the fibers.

8. Acrylic Fibers

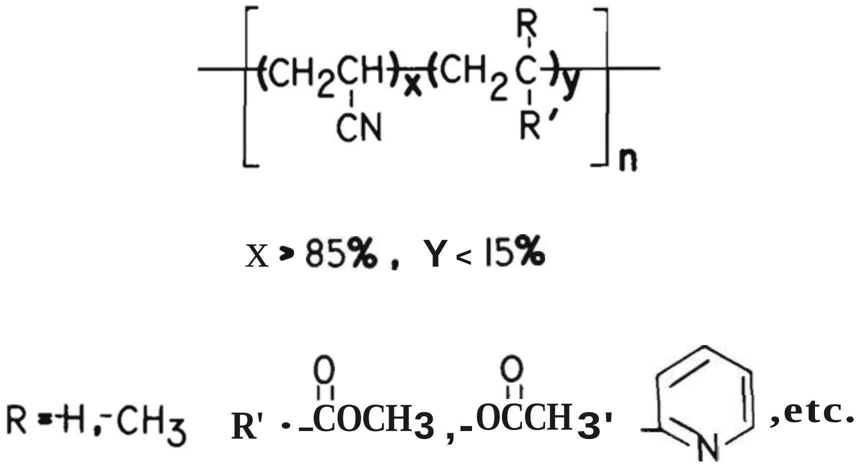
The acrylic fibers include acrylic, modacrylic, and other vinyl fibers containing cyanide groups as side chains. Among the major acrylic fibers used in commerce, acrylonitrile is the comonomer containing a cyanide group. Acrylic fibers are formed from copolymers containing greater than 85% acrylonitrile monomer units, whereas modacrylic fibers contain 35%-85% acrylonitrile units. lastrile fibers contain 10%-50% acrylonitrile units copolymerized with vinylidene chloride monomer, whereas nytril fibers are made from copolymers containing at least 85% vinylidene dinitrile units. In general, these fibers possess a warm bulky hand, good resiliency and wrinkle resistance, and overall favorable aesthetic properties.

ACRYLIC

Acrylic fibers are formed from wet or dry spinning of copolymers containing at least 85% acrylonitrile units. After texturizing, acrylic fibers have a light bulky wool-like hand and overal wool-like aesthetics. The fibers are resilient and possess excellent acid resistance and sunlight resistance. Acrylics have been used extensively in applications formerly reserved for wool or other keratin fibers.

Structural Properties

Acrylic fibers are made up of copolymers containing at least 85% acrylonitrile units in combination with one or more comonomers including methyl methacrylate, vinyl acetate, or vinyl pyridine:



$$-\left[(CH_2\underset{CN}{CH})_x(CH_2\overset{R}{\underset{R'}{C}})_y\right]_n-$$

$X > 85\%$, $Y < 15\%$

$R = -H, -CH_3$ $R' = -\overset{O}{\overset{\|}{C}}OCH_3, -O\overset{O}{\overset{\|}{C}}CH_3,$,etc.

ACRYLIC

The copolymer is formed through free radical emulsion polymerization. After precipitation the copolymer is dried and dissolved in an appropriate organic solvent and wet or dry spun. The degree of polymerization of the copolymers used for fiber formation varies from 150 to 200 units. Pure polyacrylonitrile will form satisfactory fibers. Owing to the extensive tight packing of adjacent molecular chains and the high crystallinity of the fiber, comonomers must be introduced to lower the regularity and crystallinity of the polymer chains to make the fiber more dyeable. Extensive hydrogen bonding occurs between a-hydrogens and the electronegative nitrile groups on adjacent polymer chains, and strong van der Waals interactions further contribute to the packing of the acrylic chains. The periodic comonomer units interfere with this packing and therefore decrease the overall crystallinity of acrylic fibers. Acrylic fibers are usually smooth with round or dog-bone cross sections (Figure 8-1). Many bicomponent acrylic fibers are produced in order to provide a bulky texturized structure on drawing.

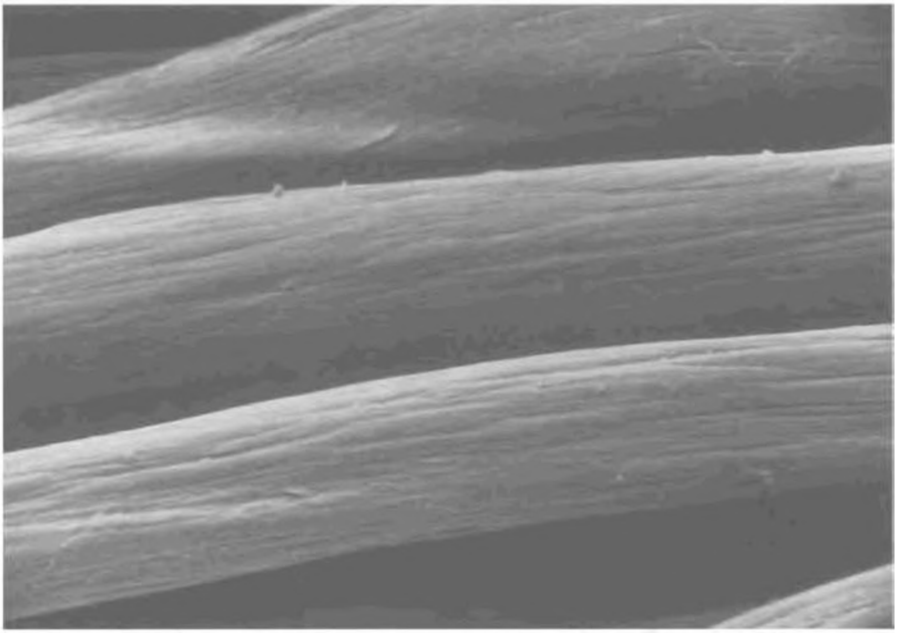


Figure 8-1. Acrylic. x1300.

Physical Properties

Acrylic fibers are fibers of moderate strength and elongations at break. The tenacity of acrylic fibers varies from 2 to 4 g/d (18-36 g/tex). On wetting, the tenacity drops to 1.5-3 g/d (13-27 g/tex). The elongation at break varies from 20% to 50% for the various acrylic fibers. At 2% elongation the recovery of the fiber is 99%; however, at 5% elongation the recovery is only 50%-95%. The fiber is moderately stiff and has excellent resiliency and recovery from bending deformation. The fibers have low specific gravities of 1.16-1.18 and low moisture regains of 1.0%-

2.5% under standard temperature and humidity conditions. The fiber is soluble in polar aprotic solvents such as N,N-dimethylformamide. The fiber exhibits good heat and electrical insulation properties. Acrylic fibers do build up moderate static charge and soften at 190°-250°C.

Chemical Properties

Acrylic fibers exhibit good chemical resistance. The fibers are only attacked by concentrated acids and are slowly attacked and hydrolyzed by weak bases. Acrylics are unaffected by oxidizing and reducing agents except for hypochlorite solutions at elevated temperatures. Acrylic fibers are unaffected by biological agents and sunlight. On heating above 200°C, acrylic fibers soften and undergo oxidative attack by a complex mechanism with formation of condensed unsaturated chromophoric (colored) groups in the fiber.

End-Use Properties

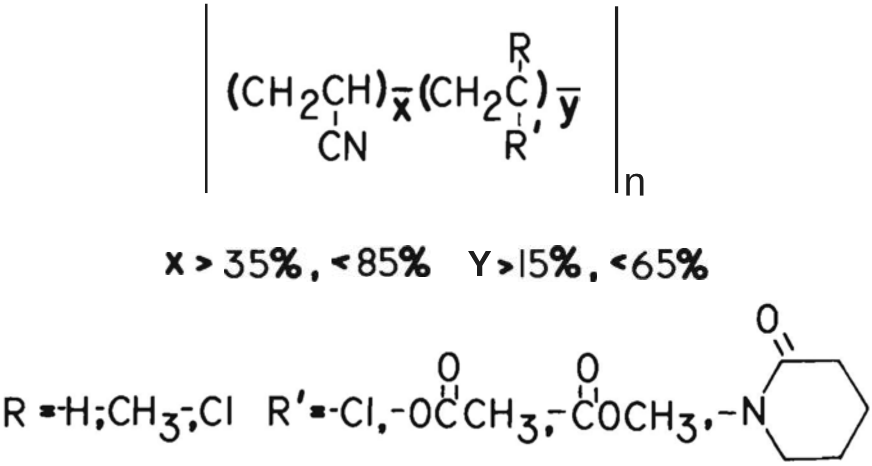
Common trade names for acrylic fibers include Acrilan, Creslan, Orlon, Sayelle, and Zefran. Since the acrylic fibers are usually texturized, they have a bulky wool-like hand and possess a moderate degree of luster. The fibers are of moderate strength but exhibit poor recovery from elongation. They possess fair abrasion and pilling resistance. The fiber has good wrinkle resistance and crease retention if properly heat set. The fiber possesses good resistance to household chemicals and sunlight and is moderately resistant to heat-induced oxidation and discoloration. The fiber undergoes laundering and dry-cleaning very well and may be dried readily due to its low affinity for moisture. The fiber may be ironed safely up to 150°C. Owing to the introduction of comonomer, acrylic fibers are generally dyeable and give fast colors with a wide range of dyes including acid, basic, or disperse dyes. The comonomer present determines the type of dye(s) that may be effectively used. The acrylic fibers are moderately flammable with a LOI of 18. The fibers burn with melting and continue to burn on withdrawal from the flame. On extinguishing, the fiber leaves a hard black bead. Acrylic fibers have found a wide spectrum of use where soft, warm, wool-like characteristics are desired. Such uses would include sweaters, skirts, dresses, suits, outerwear and knitted wear, blankets, socks, carpets, drapes, upholstery, and pile fabrics.

MODACRYLIC

Modacrylic fibers are formed from copolymers consisting of 35%-85% acrylonitrile and a suitable vinyl comonomer or comonomers such as vinyl chloride, vinylidene chloride, vinyl acetate, vinyl pyrollidone, or methyl acrylate. The modacrylics generally resemble acrylics and have a warm pleasing hand and good drapability, resiliency and wrinkle resistance. They are more heat sensitive but more flame resistant than acrylics and have generally been used in specialty applications. Modacrylic fiber exhibits a more thermoplastic character than the related acrylic fibers.

Structural Properties

Modacrylic fibers are wet or dry spun from copolymers of acrylonitrile (35%-85%) and an appropriate comonomer or comonomers:



$$\left|\,(\mathrm{CH_2}\underset{\mathrm{CN}}{\mathrm{CH}})_{\bar{x}}\,(\mathrm{CH_2}\underset{\mathrm{R'}}{\overset{\mathrm{R}}{\mathrm{C}}})_{\bar{y}}\,\right|_n$$

MODACRYLIC

The copolymer is formed through free radical chain growth emulsion or solution polymerization to a DP of 150-500. The copolymer is isolated and dissolved in acetone or a similar low-boiling-point solvent and wet or dry spun to a fiber of round, dog-bone, crescent, or polylobal cross section (Figure 8-2). The oriented fiber possesses a low crystallinity due to the irregularity and heterogeneity of the copolymer structure. Limited hydrogen bonding and van der Waals interactions are possible due to the limited regularity of adjacent polymer chains.

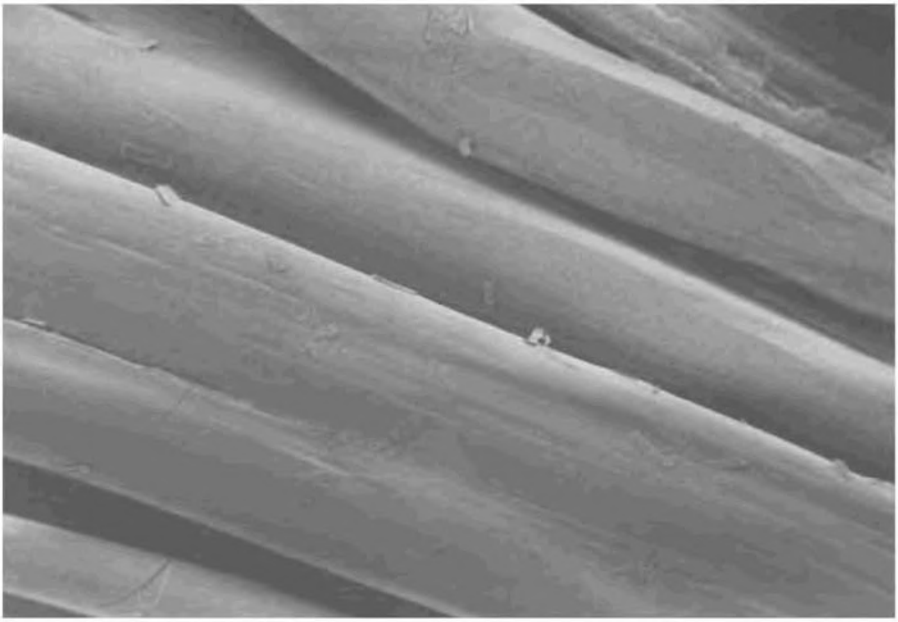


Figure 8-2. Modacrylic. x1000.

Physical Properties

The modacrylic fiber is of moderate strength with a dry tenacity of 1.5-3 g/d (14-27 g/tex) and a slightly reduced wet tenacity of 1-2.5 g/d (9-23 g/tex). The fiber has a high elongation at break of 25%-45% and excellent recovery (95%-100%) from low degrees of stretching «5%). The fibers possess excellent resiliency and moderate stiffness and have specific gravities of 1.30-1.37. Modacrylic fibers exhibit a wide range of moisture regains, from 0.4% to 4%, depending on the nature and composition of comonomers making up the copolymer. Modacrylic fibers are soluble in ketone solvents such as acetone and in aprotic polar solvents including N,N-dimethylformamide. The fibers are good heat and electrical insulators but tend to build up static charge. The fibers soften in the 135°-160° range with accompanying heat shrinkage.

Chemical Properties

The modacrylic fibers exhibit excellent resistance to chemical agents. They exhibit good stability to light and biological agents. Modacrylic fibers melt at 190°-210°C with slight decomposition. SEF modacrylic fibers possess somewhat greater heat stability than the other modacrylics.

End-Use Properties

Modacrylic fiber trade names include Elura, SEF, Verel, and Zefran. Production of Dynel modacrylic fibers was discontinued in 1975. Modacrylics possess warm wool-like aesthetics and a generally bright luster. The fiber exhibits fair pilling and abrasion resistance. It has good wrinkle resistance and crease retention if the fiber has been properly heat set. The fiber has moderate strength and good recovery from low elongations. Modacrylics are resistant to attack by household chemicals and have excellent sunlight resistance. The laundry and dry-cleaning characteristics of the fiber are good if the temperature is held at moderate levels. The fibers are more difficult to dye with acid and/or basic dyes than acrylics. They have better affinity for disperse dyes and give dyeings of good colorfastness. Owing to the low moisture regain of modacrylics, they dry readily, but the drying temperature must be kept low «100°C) to prevent damage and shrinkage. Consequently, modacrylics must be ironed below 135°C. Modacrylic fibers are flame retardant and self-extinguishing on removal from a flame, with a LOI of 27. Modacrylic fibers are used in a number of special products including deep pile carpets, fleece and fur fabrics, blankets, scatter rugs, wigs and hair pieces, stuffed toys, and more recently children's sleepwear.

OTHER ACRYLICS

Nytril fibers are made up of polymers containing at least 85% vinylidene dinitrile units, which appear at least every other unit in the polymer chain. The comonomer used in Nytril synthesis is vinyl acetate. The two monomers are polymerized in benzene using peroxide catalyst. The polymer is precipitated, washed, and dissolved in N,N-dimethylformamide and then passed through a spinneret into an aqueous coagulating bath to form Nytril fibers. The properties of the Nytril fiber are similar to the other acrylic fibers. The fiber possesses moderate tensile, regain, and thermal properties. The fiber is chemical and sunlight resistant but is as flammable as cellulosic fibers. Darvan Nytril fibers were produced in the U.S. until 1961.

Lastrile

Lastrile fibers are fibers formed from copolymers of acrylonitrile and a diene such as butadiene and contain 10%-50% acrylonitrile units. Lastrile fibers have not been commercially produced. The major proportion of butadiene within the copolymer suggests that the fiber would have extensive elastomeric character.

9. Polyolefin Fibers

POLYETHYLENE AND POLYPROPYLENE

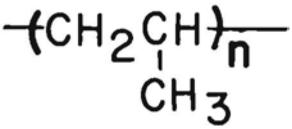
Polyolefin fibers are those fibers produced from polymers formed by chain growth polymerization of olefins (alkenes) and which contain greater than 85% polymerized ethylene, propylene, or other olefin units. In general, linear high-density stereoregular polyethylene and polypropylene are used in textile applications, with polypropylene predominating due to its superior temperature stability. These fibers have good strength and toughness, have good abrasion resistance, and are inexpensive. The fibers are difficult to dye and have relatively low melting points, but they are effectively used in a wide variety of textile applications.

Structural Properties

Linear polyethylene and polypropylene are polymerized from their corresponding monomers to a DP of 1000-3000 using complex metal (Ziegler-Natta) catalysts at 40°-100°C and at moderate pressures. Using this initiation technique, branching of the polyolefin due to free radical chain transfer is avoided and a linear unbranched structure is formed. With polypropylene, catalyst systems are selected that will lead to regular isotactic placement (>90%) of the optically active methyl-substituted carbon on the backbone to give a structure capable of high crystallinity:

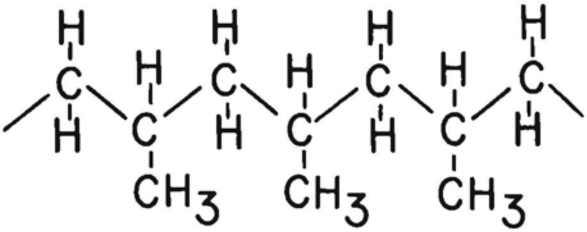
$-(CH_2CH_2)_n-$

POLYETHYLENE



$$-(CH_2\underset{\displaystyle CH_3}{\underset{|}{C}}H)_n-$$

POLYPROPYLENE



ISOTACTIC POLYPROPYLENE

The resultant polymers are dried, compounded with appropriate additives, melt spun into fibers, and drawn to orient. The highly linear chains of these polyolefins can closely pack and associate with adjacent chains through van der Waals interactions and possess crystallinities in the 45%-60% range, The surface of these fibers is usually smooth, and the fiber cross section is round (Figure 9-1). Also, polyolefin films can be split (fibrillated) using knife edges to form flat ribbonlike fibers with a rectangular cross section.

Physical Properties

Polypropylene and polyethylene are strong fibers with good elongation and recovery properties. The tenacity of fibers varies from 3.5 to 8 g/d (31-81 g/tex), with an elongation at break of 0%-30%. The fibers recover well from stress, with 95% recovery at 10% elongation. The fibers are moderately stiff and have moderate resiliency on bending. Moisture does not affect these properties, since polyolefins are hydrophobic and have a moisture regain of 0%. The polyethylene fibers have specific gravities of 0.95-0.96 and polypropylene specific gravities of 0.90-0.91. As a consequence these fibers float on water and are the lightest of the major fibers in commerce.

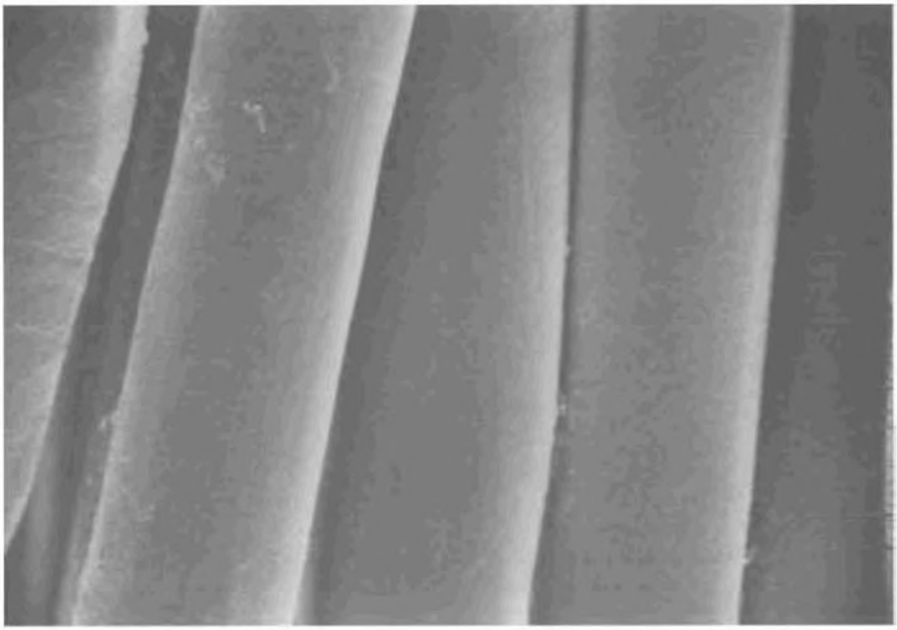


Figure 9-1. Polypropylene. x1000.

The fibers are unaffected by solvents at room temperature and are swollen by aromatic and chlorinated hydrocarbons only at elevated temperatures. They exhibit excellent heat and electric insulation characteristics and are extensively used in these applications. The fibers are heat sensitive. Polyethylene softens at 130°C and melts at 150°C, while polypropylene softens at about 150°C and melts at about 170°C.

Chemical Properties

The polyolefins are extremely inert and resistant to chemical attack. They are unaffected by chemical and biological agents under normal conditions. They are sensitive to oxidative attack in the presence of sunlight due to formation of chromophoric keto groups along the hydrocarbon chain. These groups act as photosensitizers for further decomposition. The fiber only slowly undergoes oxidative decomposition at its melting point.

End-Use Properties

Common trade names for polyolefin fibers include Herculon, Marvess, and Vectra. Polyolefins are lustrous white translucent fibers with good draping qualities and a characteristic slightly waxy hand. They have excellent abrasion resistance and exhibit fair wrinkle resistance. They are essentially nonabsorbent, but reportedly exhibit wicking action with water. The polyolefins are strong, tough fibers which are chemically inert and resistant to oxidative attack except that induced by sunlight. Stabilizing chemicals must be incorporated into the fibers to lower their susceptibility to such light-induced attack. The polyolefins have high affinity for oil-borne stains, which are difficult to remove on laundering. The fibers are dry-cleanable with normal dry-cleaning solvents if the temperature is kept below 50°C. Since the fibers have no affinity for water, they dry readily, but care must be taken to keep the drying temperature below 70°C for polyethylene and 120°C for polypropylene to prevent heat-induced thermoplastic shrinkage and deformation. The fibers are flammable, burn with a black sooty flame, and tend to melt and draw away from the flame.

The polyolefins--particularly polypropylene--have found a number of applications particularly in home furnishings and industrial fabrics. Uses include indoor-outdoor carpeting, carpet backing, upholstery fabrics, seat covers, webbing for chairs, nonwovens, laundry bags, hosiery and knitwear (particularly as a blended fiber), fishnet, rope, filters, and industrial fabrics.

10. Vinyl Fibers

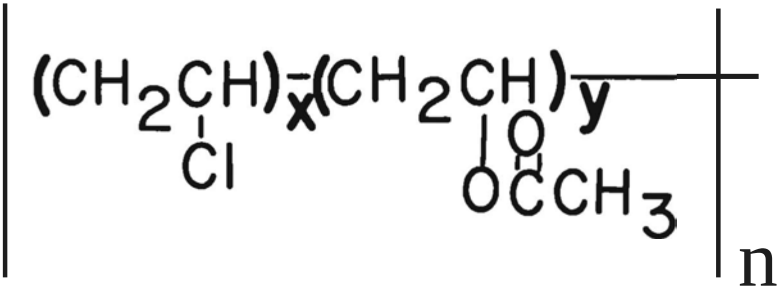
Vinyl fibers are those man-made fibers spun from polymers or copolymers of substituted vinyl monomers and include vinyon, vinal, vinyon-vinal matrix (polychlal), saran, and polytetrafluoroethylene fibers. Acrylic, modacrylic and polyolefin--considered in Chapters 8 and 9--are also formed from vinyl monomers, but because of their wide usage and particular properties they are usually considered as separate classes of fibers. The vinyl fibers are generally specialty fibers due to their unique properties and uses. **All** of these fibers have a polyethylene hydrocarbon backbone with substituted functional groups that determine the basic physical and chemical properties of the fiber.

VINYON

Vinyon is defined as a fiber **in** which at least 85% of the polymerized monomer units are vinyl chloride. Vinyon fibers have high chemical and water resistance, do not burn, but do melt at relatively low temperatures and dissolve readily **in** many organic solvents, thereby limiting their application.

Structural Properties

Vinyon is formed by emulsion polymerization of vinyl chloride or by copolymerization of vinyl chloride with less than 15% vinyl acetate in the presence of free radical catalysts to a DP of 200-450:



$$\left[(\mathrm{CH_2}\underset{\mathrm{Cl}}{\mathrm{CH}})_x-(\mathrm{CH_2}\underset{\mathrm{O\overset{O}{\overset{\|}{C}}CH_3}}{\mathrm{CH}})_y\right]_n$$

$x > 85\%$. $y < 15\%$

VINYON

The polymer is precipitated and isolated by spray drying and then dissolved in acetone; the polymer solution is dry spun to form the fiber. Comonomers such as vinyl acetate are added to reduce the crystallinity of the drawn fiber and to increase the amorphous areas within the fiber. Weak hydrogen bonding between chlorine and hydrogen on adjacent vinyon chains would be expected with tight packing of the molecular chains in the absence of comonomer. The fibers are spun in nearly round or dog-bone cross section (Figure 10-1).

Physical Properties

Vinyon fibers have a strength of 1-3 g/d (9-27 g/tex) in both the wet and dry states; elongations at break vary between 10% and 125%. At low elongations vinyon fibers recover completely from deformation. Vinyon fibers are soft and exhibit good recovery from bending deformation. The fiber has moderate density, with a specific gravity of 1.33-1.40. Vinyon is extremely hydrophobic, having a moisture regain of 0.0%-0.1% under standard conditions. Vinyon is readily dissolved in ketone and chlorinated hydrocarbon solvents and is swollen by aromatic solvents. The fiber is a poor heat and electrical conductor and possesses potential in insulation applications. Unfortunately, the oriented fiber softens and shrinks at temperatures above 60°C, thereby limiting the applications in which it may be used.

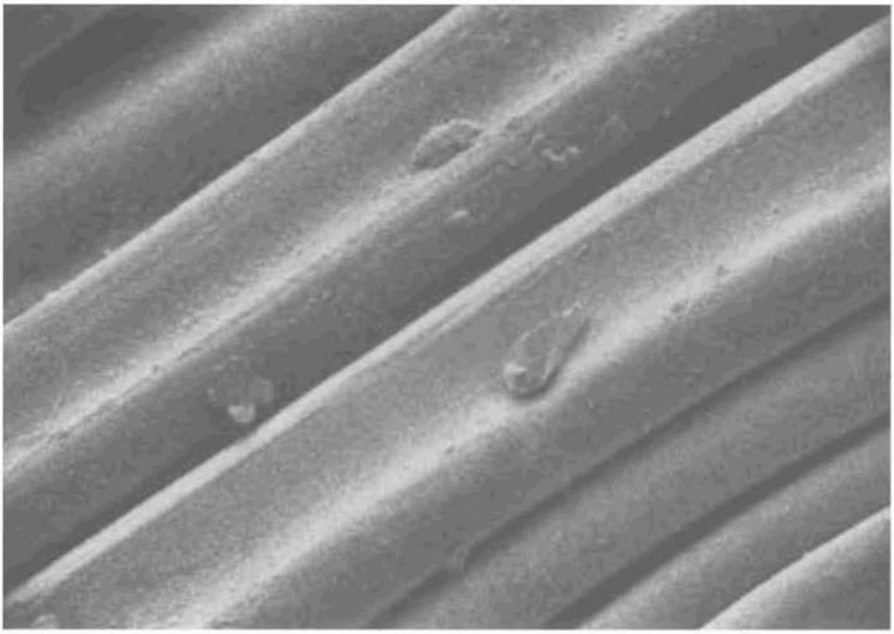


Figure 10-1. Vinyon. x1400.

Chemical Properties

Vinyon fiber is chemically inert and possesses chemical properties similar to polyolefin fiber. Vinyon is only slowly attacked by ultraviolet rays in sunlight. Vinyon fiber melts with decomposition at 135°-180°C, with vinyon containing comonomer having a lower melting/decomposition temperature.

End-Use Properties

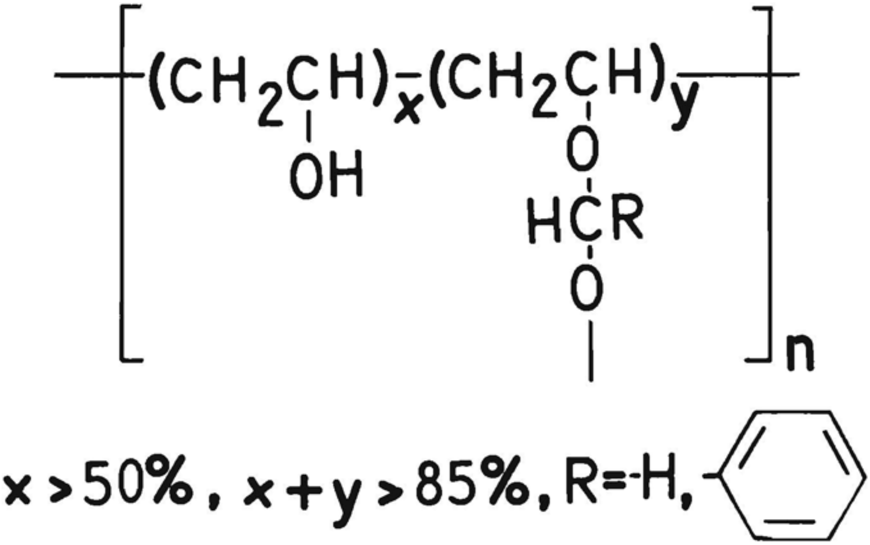
Vinyon as pure polyvinyl is marketed as PVC-Rhovyl, while vinyon HH is a copolymer. The fiber is of low strength but has properties that make it useful in apparel where heat is not a factor. It is difficult to dye. It may be laundered readily, but it is attacked by common dry-cleaning solvents. Since the fiber may not be heated above 60°C, it may be tumble dried only at the lowest heat settings. The fiber is nonflammable and does not support flaming combustion (LOI of 37). Vinyon finds its major use in industrial fabrics including filters, tarps, and awnings, in protective clothing, and in upholstery for outdoor furnishings. It is also used as a bonding fiber in heat bonded nonwovens and as tire cord in specialty tires.

VINAL

Vinal fibers are made from polymers containing at least 50% vinyl alcohol units and in which at least 85% of the units are combined vinyl alcohol and acetal crosslink units. The fiber is inexpensive, resembles cotton in properties, and is produced in Japan.

Structural Properties

Vinal fibers are formed from inexpensive starting materials through a complex process. Vinyl acetate monomer is solution polymerized to polyvinyl acetate using free radical initiation techniques. The polyvinyl acetate is hydrolyzed to polyvinyl alcohol in methanol under basic conditions. Aqueous polyvinyl alcohol solution is wet or dry spun followed by exposure to an aldehyde such as formaldehyde or benzaldehyde and heat (240°C) to form acetal crosslinks between chains to insolubilize the fiber. The polyvinyl alcohol chains are tightly packed except near the juncture of the acetal crosslinks. Extensive hydrogen bonding between hydroxyl groups on adjacent chains occurs, which contributes to its highly packed structure, and the fiber is about 50% crystalline:



VINAL

The fiber surface is somewhat rough with lengthwise striations and possible periodic twists. The fiber may be nearly round or U-shaped in cross section with a noticeable skin and core.

Physical Properties

Vinal fiber is moderately strong with a dry tenacity of 3-8.5 g/d (27-77 g/tex) and possesses a moderate extension at break of 10%-30%. On wetting the strength of the fiber decreases and the elongation at break increases slightly. The fiber exhibits poor to moderate (75%-95%) recovery from elongations as low as 2%. The fiber is moderately stiff, but does not recover readily from dry or wet deformation. The fiber has a specific gravity of 1.26-1.30. Vinal fiber has a moisture regain of 3.0%-5.0% under standard conditions, and is swollen and attacked by aqueous phenol and formic acid solutions. The fiber is a moderate heat and electrical conductor. On heating to 220°-230° the fiber undergoes 10% or more heat-induced shrinkage.

Chemical Properties

Vinal is somewhat sensitive to acids and alkalies. It is attacked by hot dilute acids or concentrated cold acid solutions with fiber shrinkage and is yellowed by strong aqueous solutions of alkali. Oxidizing, reducing, and biological agents have little effect on vinal. Sunlight causes vinal to slowly lose its strength with perceptible changes in color. At 230°-250° vinal shrinks and softens with decomposition.

End-Use Properties

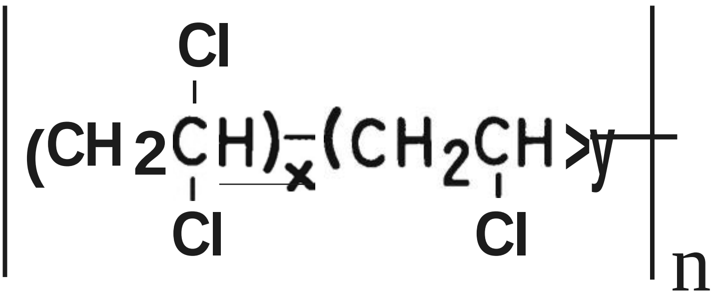
Vinal resembles cotton and other cellulosics in end-use properties. Kuralon and Manryo are names under which vinal fibers are marketed. Vinal fiber has good strength and excellent abrasion and pilling resistance. Like cellulosics, vinal breaks at low elongations, exhibits poor recovery from small deformations, and wrinkles readily unless treated with durable press resins of the type used for cellulosics. Fabrics of vinal have a warm comfortable hand, are absorbent, and exhibit good drapability. The fiber has a silklike appearance and luster. It has excellent sunlight resistance and fair heat resistance. It dyes readily with dyes for cellulosics. Its launderability and dry-cleanability are very good, and it dries more readily than cellulosics. Vinal may be ironed dry up to 120°C, but undergoes severe deformation if ironed wet below 120°C. Vinal burns readily like a cellulosic fiber and has a LOI of 20. Vinal is used in apparel as well as industrial applications where an inexpensive fiber of moderate strength and properties is desired. It is useful in fiber blends to increase comfort and aesthetic properties.

VINYON-VINAL MATRIX FIBER

In response to the need for a fiber of low flammability (LOI of 31) and low toxic gas formation on burning, Kohjin company developed and marketed a vinyon-vinyl (50:50) matrix (polychlal) fiber under the trade names Cordela and Cordelan. The fiber is believed to be formed through grafting of vinyl chloride to polyvinyl alcohol followed by mixing of the resultant copolymer with additional polyvinyl alcohol. The polymer mixture is wet spun, oriented, and crosslinked with aldehydes. The fiber has a kidney-shaped cross section, and no outer skin is evident. The fiber is moderately strong with a dry tenacity of about 3 g/d (27 g/tex) and wet tenacity of 2.2 g/d (20 g/tex). The elongation at break is 15%-20% wet or dry, with poor recovery from even low elongations. It has a specific gravity of 1.32 and moisture regain of 3.0%. Besides its low flammability, it has good chemical resistance except under extreme conditions. The fiber is heat sensitive above 100°C, but it may be dyed at lower temperatures with a large range of dyes for cellulosics as well as man-made fibers. Vinyon-vinyl matrix fiber is used primarily in applications where low flammability in apparel is desired and has been used extensively in children's sleepwear.

SARAN

Saran is the generic name for fibers made from synthetic copolymers that are greater than 80% vinylidene chloride. The fiber is formed through emulsion copolymerization of vinylidene chloride with lesser amounts of vinyl chloride using a free radical catalyst, and the precipitated copolymer is melt spun into the fiber:



$$\left[(\mathrm{CH_2}\overset{\mathrm{Cl}}{\underset{\mathrm{Cl}}{\mathrm{C}}}\mathrm{H})_x - (\mathrm{CH_2}\underset{\mathrm{Cl}}{\mathrm{C}}\mathrm{H})_y \right]_n$$

$$x > 80\% \bullet y < 20\%$$

SARAN

The fiber is of moderate crystallinity and resembles vinyon in properties. The fiber has wet and dry strength of 1-3 g/d (9-27 g/tex), elongation at break of 15%-30%, and good recovery from less than 10% elongation. The fiber has a specific gravity of 1.7 and has excellent resiliency. It has essentially no affinity for water, but it is soluble or attacked by cyclic ethers, ketones, and aromatic solvents. It is a good heat and electrical insulator, but it softens at 115°-150°C and melts at 170°C. The fiber is chemically inert and only slowly affected by the ultraviolet rays in sunlight. The fiber is of low flammability. Saran is marketed as saran or under the trade name Rovana. The fiber has high resiliency and low water absorbency and is chemically inert and used in applications where these qualities are desirable and where heat sensitivity is not a problem. The fiber is generally not used in apparel but rather in automobile upholstery, outdoor fabrics, home furnishings, and industrial applications.

POLYTETRAFLUOROETHYLENE

Tetrafluoroethylene is better known by its trade name--Teflon--and is widely used in many applications including specialty fibers. Polytetrafluoroethylene fiber is extremely hydrophobic and chemically and thermally stable and is used in applications where such stability and inertness is needed. Polytetrafluoroethylene fibers are produced through polymerization of tetrafluoroethylene under conditions of high temperature and pressure using peroxide catalysts. The polymer is spun as a dispersion to form a weak fiber which is then heated at 385°C to fuse the individual fiber particles. The fiber must be bleached to give a white fiber. The highly electronegative fluorine atoms in the fiber result in an extremely tight packing of adjacent molecular chains tightly held by van der Waals forces and with a high degree of crystallinity. The fibers are smooth with a round cross section.

The fiber has a tenacity of 1-2 g/d (9-18 g/tex) and elongations at break vary from 15% to 30%. It is a soft flexible fiber of high density (specific gravity 2.1), and it is totally hydrophobic. It is unaffected by solvents except for perfluorinated hydrocarbons above 300°C. It is an excellent electrical and heat insulator and is not affected by heat up to 300°C. It is chemically inert and may be used in numerous industrial end-use applications including protective clothing. Its hydrophobicity has permitted is to be used to form breathable but water repellant composite materials for textile usage, particularly in outdoor and rainwear.

$$-\!\!\left(CF_2CF_2\right)_n\!\!-$$

TETRAFLUOROETHYLENE

11. Elastomeric Fibers

Elastomeric fibers are those fibers that possess extremely high elongations (400%-8001) at break and that recover fully and rapidly from high elongations up to their breaking point. Elastomeric fibers are made up of molecular chain networks that contain highly amorphous areas joined together by crosslinks. On elongation, these amorphous areas become more oriented and more crystalline in nature. Elongation continues until the crosslinks in the structure limit further molecular movement. If additional force is placed on the elastomeric fibers at this point, molecular scission occurs, causing a reduction in properties and ultimate breaking of the fiber. Elastomeric fibers include the crosslinked natural and synthetic rubbers, spandex fibers (segmented polyurethanes), anidex fibers (crosslinked polyacrylates) and the side-by-side biconstituent fiber of nylon and spandex (Monvelle). The fibers are all used in specialized applications where high elasticity is necessary within the textile structure.

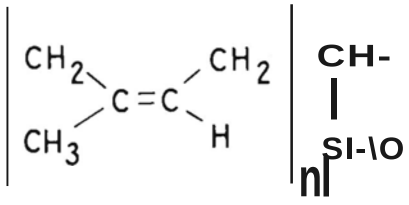
RUBBER

Rubber fibers from natural sources have been known for over 100 years. Natural rubber in commerce is derived from coagulation of Hevea brasiliensis latex and is primarily cis-polyisoprene, a diene polymer. Most synthetic rubbers were developed during and following World War II. They are crosslinked diene polymers, copolymers containing dienes, or amorphous polyolefins. Both the natural and synthetic rubbers must be crosslinked (vulcanized) with sulfur or other agents before true elastomeric properties are introduced. In addition, accelerators, antioxidants, fillers, and other materials are added to the polymeric rubber prior to fiber formation.

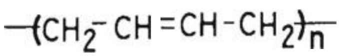
Rubber fibers exhibit excellent elastic properties but are sensitive to chemical attack, thereby limiting their usefulness.

Structural Properties

Rubber fibers are derived from the sources outlined above and structurally are crosslinked polyisoprene, polybutadiene, diene-monomer copolymers, or amorphous polyolefins. Less common or special use rubbers include the acrylonitrile-diene copolymer Lastrile and the chloroprene polymer Neoprene. Structural formuli of typical rubbers follow:

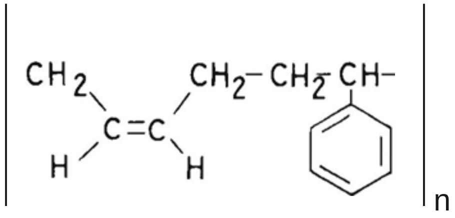


CROSSLINKED cis-POLYISOPRENE (VULCANIZED NATURAL RUBBER)



$-(CH_2-CH=CH-CH_2)_n-$

POLYBUTADIENE (BUTYL RUBBER)



cis-POLYBUTADIENE-STYRENE COPOLYMER RUBBER

The rubber polymers emulsified as a latex are blended with vulcanizing agents, chemical accelerators, antioxidants, fillers, and other materials. The polymer blend is extruded or coagulated and cut into fibers and heated to crosslink the structure. Of necessity, the rubber fibers are large in cross section and have a higher linear density compared to other man-made fibers. The hydrocarbon chains in the crosslinked rubbers are in a highly folded but random and amorphous configuration, but they are attached periodically to adjacent polymer chains through multiple sulfur or other crosslinks. On stretching, the molecular chains in the amorphous region untangle and straighten and orient into parallel, more crystalline structures, up to the elastic limit determined by the crosslinks present. On relaxation, the molecular chains return to their lower-energy amorphous state. Rubber fibers tend to possess a square or round cross section depending on whether the fibers were extruded or cut.

Physical Properties

Rubber fibers possess tenacities of only 0.5-1 g/d (4.5-9 g/tex) wet or dry. Elongation at break for these elastomeric fibers varies between 700% and 900%, with nearly complete elastic recoveries even at higher elongations. Because of their size, rubber fibers are moderately stiff but resilient. They are light, having a specific gravity of only 0.95-1.1.

Certain environmental properties of rubber limit its usefulness. Being hydrocarbon material, rubber fibers do not absorb moisture and have a regain of 0.0% under standard conditions. The fiber is a poor heat conductor and a good heat and electrical insulator. The fiber is readily swollen by ketones, alcohol, hydrocarbons, and oils and softens if heated above 100°C.

Chemical Properties

Rubber fibers are quite susceptible to attack by chemicals both in solutions and in the environment due to the presence of extensive unsaturation in the molecule. Rubber is readily attacked by concentrated sulfuric and nitric acids and by oxidizing agents such as hydrogen peroxide and sodium hypochlorite at elevated temperatures. Although biological agents don't readily attack rubber, heating above 100°C or exposure to sunlight accelerates its oxygen-induced decomposition. Rubber fibers are particularly susceptible to attack by atmospheric ozone (0_3), a major component of smog.

End-Use Properties

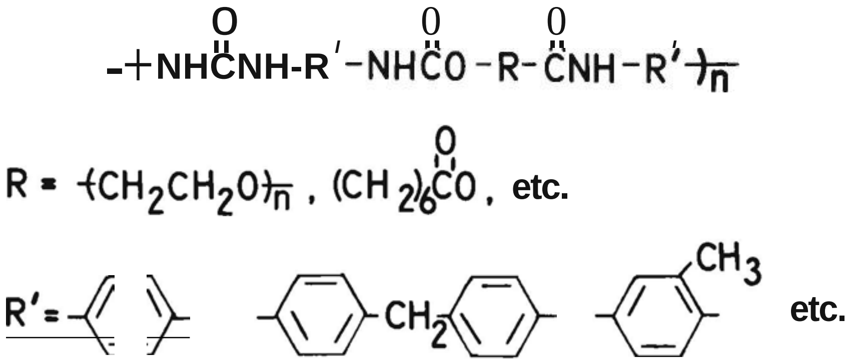
Rubber fibers are manufactured by several companies as rubber fiber or under trade names such as Buthane, Contro, Hi-Flex, Lactron, Lastex, and Laton. Rubber fibers show good elastomeric properties and reasonable aesthetic properties particularly as the core of a textile yarn structure. Rubber fibers usually have a dull luster due to the additives and fillers within the fiber. The fiber has poor resistance to household chemicals, sunlight, heat, and atmospheric contaminants. It cannot be dyed readily, and the polymer must be colored prior to fiber extrusion and curing. The fiber possesses only fair launderability and poor dry-cleanability. Owing to its low moisture absorbance, it dries readily, but care must be taken to dry or iron the fiber below 100°C. Rubber fibers burn readily but tend to be self-extinguishing. Rubber fibers are used extensively in applications where elastomeric fibers are desired, such as in swimwear, foundation garments, outerwear, and underwear, hosiery, and surgical bandages. The use of rubber fibers has decreased in recent years as more stable elastomeric fibers such as spandex have been introduced.

SPANDEX

Spandex fibers are elastomeric fibers that are >85% segmented polyurethane formed through reaction of a diisocyanate with polyethers or polyesters and subsequent crosslinking of polyurethane units. The spandex fibers resemble rubber in both stretch and recovery properties, but are far superior to rubber in their resistance to sunlight, heat, abrasion, oxidation, oils, and chemicals. They find the widest use of any of the elastomeric fibers.

Structural Properties

Spandex is a complex segmented block polymer requiring a complex series of reactions for formation. Initially, low molecular weight polyethers and polyesters (oligomers) containing reactive terminal hydroxyl and/or carboxyl groups are reacted with diisocyanates by step growth polymerization to form a capped prepolymer. This polymer is melt spun or solvent spun from *N,N*-dimethylformamide into a fiber; then the fiber is passed through a cosolvent containing a reactive solvent such as water that reacts with the terminal isocyanite groups to form urethane crosslinks. Typical structures for spandex with urethane crosslinks follow:



SPANDEX

The polyether or polyester segments in spandex are amorphous and in a state of random disorder, while urethane groups segmenting the polyether or polyester segments can form hydrogen bonds and undergo van der Waals interactions with urethane groups on adjacent chains. Chain ends will be cross-linked or joined to other chains through urea groups. On stretching, the amorphous segments of the molecular chains become more ordered up to the limit set by the urea linkages. On relaxation, the fiber returns to its original, less ordered state. Spandex fibers are long, opaque fibers available in many cross sections including round, lobed, or irregular (Figure 11-1).

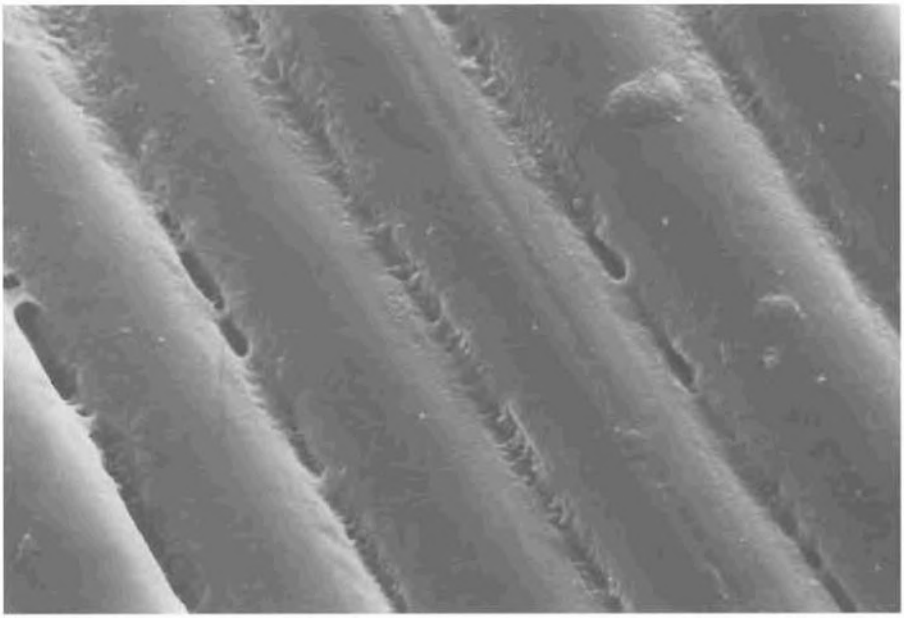


Figure 11-1. Spandex. x1200.

Physical Properties

Spandex fibers are weak but highly extensible fibers with tenacities of 0.5-2 g/d (4.5-18 g/tex) dry with slightly weaker wet tenacities, and elongations at break of 400%-700%. Spandex exhibits nearly complete recovery from high elongations and is quite resilient. The fibers have specific gravities of 1.2-1.4 and are somewhat more dense than rubber fibers. Owing to the more hydrophilic nature of spandex, its moisture regain varies between 0.3% and 1.3% under standard conditions. Although spandex is swollen slowly by aromatic solvents, it is generally unaffected by other solvents. Spandex is a heat insulating material and shows poor heat conductivity. It softens between 150°C and 200°C and melts between 230°C and 290°C. It has moderate electrical resistivity and builds up some static charge under dry conditions.

Chemical Properties

Spandex fibers are much more stable to chemical attack than rubber. Spandex is attacked by acids and bases only at higher concentrations and under more extreme reaction conditions. Reducing agents do not attack spandex, but chlorine bleaches such as sodium hypochlorite slowly attack and yellow the fiber. Spandex generally resists attack by organic solvents and oils and is unaffected by biological agents. Sunlight causes slow yellowing and deterioration of spandex, and heat causes slow deterioration at elevated temperatures.

End-Use Properties

Spandex is widely used and sold as an elastomeric fiber under that designation or under such trade names as Cleerspan, Glospan, Lycra, or Numa. Spandex possesses excellent elastomeric properties and acceptable aesthetics for use in constructions requiring such a fiber. Spandex is dull, but luster may be improved with brighteners. Although it has low water absorbency, spandex has good resistance to abrasion and wrinkling and may be heat set if desired. It has good resistance to household chemicals other than bleach and is resistant to sunlight or heat-induced oxidation. It can be dyed relatively easily to reasonable degrees of colorfastness. It stands up well to repeated laundering and dry-cleaning, and it dries readily without damage at moderate temperatures (less than 120°C). Spandex burns readily but melts and shrinks away from the flame. Spandex can be used effectively in all elastomeric fiber applications.

OTHER ELASTOMERIC FIBERS

Anidex

In 1970, anidex fibers were introduced as an elastomeric fiber by Rohm and Haas with the trade name Anim. Anidex fibers are defined as fibers containing polymers that are at least 50% of one or more polymerized acrylate esters. Anidex fibers are formed through emulsion copolymerization of acrylate esters with reactive crosslinkable comonomers such as N-methylolacrylamide. The resulting copolymer emulsion is mixed with a filler and wet spun to form a fiber which is heated to crosslink the polymer chains and provide the necessary elastomeric properties. The morphology and elastomeric action of the fiber resemble spandex and rubber, but anidex generally has a lower elongation at break than these fibers. It has a round cross section. The fiber has a specific gravity of 1.22 and a moisture regain of 0.5% under standard conditions. Anidex is reported to be more resistant to heat, light, and chemicals than either spandex or rubber. Otherwise, the fiber possesses end-use properties very much like those of spandex. Anidex fibers apparently did not have sufficient differences in properties to become an economic success and are no longer being produced.

Nylon-Spandex Biconstituent Fiber

An inherent problem with elastomeric fibers is their low strength and limited abrasion resistance. A new biconstituent elastomeric fiber--Monvelle--has been introduced to answer these problems. The fiber is a side-by-side bicomponent fiber containing nylon and spandex. The fiber is melt spun by special spinnerets to form the fiber. On drawing, the nylon portion of the fiber stretches and becomes more molecularly oriented, whereas the spandex simply elongates as would be expected for an elastomeric fiber. On relaxation, the spandex portion contracts, whereas the nylon portion does not, and the fiber coils into a tight coil which will have excellent elastomeric properties and high strength even as the spandex approaches its elastic limit. Sheer fibers may be formed from this bicomponent fiber, and the fiber is readily dyeable due to its nylon content. The fiber is particularly useful in support hose and in pantyhose and other constructions where elasticity and strength are important.

12. Mineral and Metallic Fibers

A number of fibers exist that are derived from natural mineral sources or are manufactured from inorganic and mineral salts. These fibers are predominantly derivatives of silica (SiO_2) or other metal oxides. In addition, metal fibers (either alone or encapsulated in a suitable organic polymer) are produced. The common feature of these fibers is their inorganic or metallic composition and tendency to be heat resistant and nonflammable, with the exception of polymer-coated metallic fibers.

GLASS

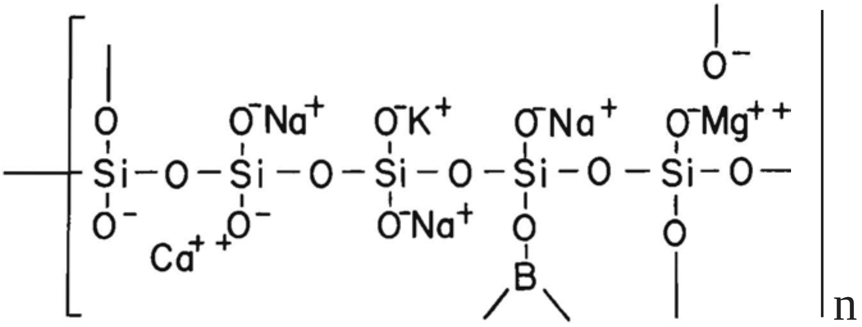
Fibers spun from glass are completely inorganic in nature and possess unique properties that cannot be found in organic textile fibers. Glass fibers have some deficiencies in properties that severely limit their use in apparel. Glass fibers are used in a number of industrial and aerospace applications and in selected home furnishing uses where heat and environmental stability are of prime importance.

Structural Properties

Glass fibers are formed from complex mixtures of silicates and borosilicates in the form of mixed sodium, potassium, calcium, magnesium, aluminum, and other salts. The silicate-borosilicate prepolymer is prepared through mixing and fusing the following inorganic salts in the range of concentrations indicated:

Silica	50%-65%
Calcium oxide	15%-25%
Alumina	2%-18%
Boron oxide	2%-15%
Other oxides	1%-10%

The exact composition of the manufactured glass polymer will affect the ultimate properties of the glass fiber formed. The glass thus formed as small marbles is melted in an electric furnace at high temperatures (>800℃) and melt spun to form fine smooth glass fiber filaments (Figure 12-1). The resultant silicate-borosilicate chains within the fiber are not ordered, and the glass structure is totally amorphous. Glass is actually a supercooled liquid that exhibits extremely slow but observable flow characteristics with time. The polymer chains within a glass fiber can be represented as follows:



GLASS

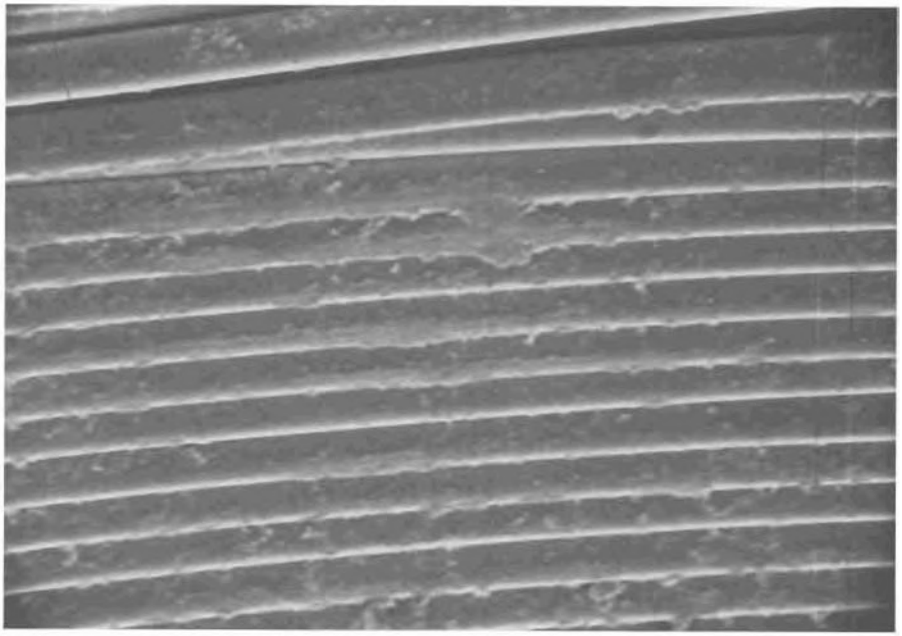


Figure 12-1. Glass. x1100.

Physical Properties

Glass fibers are extremely strong, with tenacities of 6-10 g/d (54-90 g/tex) dry and 5-8 g/d (36-72 g/tex) wet. They possess elongations at break of only 3% or 4% but are perfectly elastic within this narrow deformation range up to their breaking point. Glass fibers are quite stiff and brittle and break readily on bending. As a result, they exhibit poor resistance to abrasion, although appropriate organic sizings can alleviate this problem to some extent. Glass fibers are extremely dense, having a specific gravity of about 2.5.

The surface of glass fibers can be wetted by water, but otherwise the fibers have essentially no affinity for water. As a result the moisture regain of these fibers is 0.5% or less. Glass fibers are not soluble in common organic solvents but can be slowly dissolved by concentrated aqueous base and more rapidly by hydrofluoric acid. Glass fibers exhibit excellent heat and electrical insulation properties and are not affected by heat up to their melting point of 750°C or above.

Chemical Properties

Glass fibers are chemically inert under all but the most extreme conditions. Glass fibers are attacked and etched by dilute hydrofluoric acid and by concentrated alkalies over long periods of exposure. Oxidizing and reducing agents and biological agents have no effect on glass fibers under normal conditions, and glass fibers are unaffected by sunlight or heat.

End-Use Properties

Glass fibers are manufactured for industrial and consumer use under a number of names including fiberglas, Beta glass, J-M fiberglass, PPG fiberglass, and Vitron. Glass fibers are strong, but they exhibit poor abrasion resistance, which limits their use in textile structures for consumer goods. Heat setting of glass fabrics imparts good wrinkle resistance to fabrics made from these fibers. Glass fabrics have low moisture absorbency and good hand and luster when used in home furnishing applications. The high density of glass provides reasonable draping properties for most applications, although glass fabric constructions are extremely heavy in weight. Its sunlight and heat resistance make glass fibers useful in window coverings. Glass fibers are extremely difficult to dye, and pigment-binder or pigment-melt coloration must be used. Glass substrate must be laundered or dry-cleaned using minimum mechanical action and drip drying. Glass substrates do not need ironing, although careful ironing up to 400°C is possible. Glass and related inorganic fibers are the only truly nonflammable man-made fibers. They are used extensively in curtains and draperies, electrical and thermal insulation, tire cord, reinforced plastics, industrial filters, and protective clothing and accessories. Apparel applications are limited to very fine Beta glass fibers.

INORGANIC FIBERS

A series of man-made inorganic fibers other than glass exist that are nonflammable, heat stable amorphous materials useful in industrial fabric constructions, including refractory materials. These inorganic fibers include pure silica, potassium titanates, aluminum borosilicates, and aluminum oxide-zirconium oxide polymers, Most of these fibers have high strength, are less susceptible to chemical attack than glass, and melt above 1000°C. They may be used in higher-temperature applications than possible with most glass fibers.

ASBESTOS

Asbestos is the name given to several natural minerals (anthophyllite, amphibole, serpentine) which occur in a fibrous crystalline form. The asbestos is initially crushed to open up the fiber mass, followed by carding and spinning to yield fibers of circular cross section 1-30 cm in length. Asbestos is very resistant to heat and burning, to acids and alkalies, and to other chemicals. Although it has low strength, asbestos fiber does not deteriorate in normal usage, and it is not attacked by insects or microorganisms. Asbestos is used in fireproof clothing, conveyor belts, brake linings, gaskets, industrial packings, electrical windings, insulations, and soundproofing materials. Inhaled asbestos fibers have been shown to be a serious health hazard, and it has been removed from the textiles market.

METALLIC FIBERS

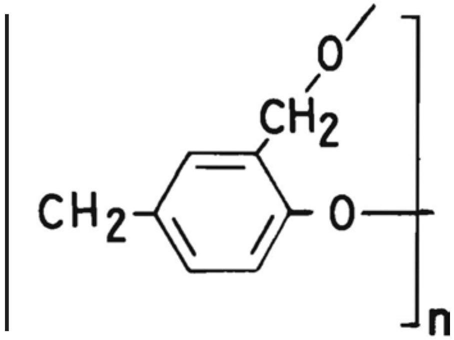
Metallic fibers are defined as fibers composed of metal, plastic-coated metal, or metal-coated plastic. Single-component metallic fibers for textile usage are fine drawn filaments of metal which can be spun and woven on normal textile machinery. These metallic fibers possess the properties of the metal from which they are formed. Multicomponent metallic fibers are more commonly used in textiles and are usually made from flat aluminum filaments surrounded with or bonded between clear layers of polyester, cellophane, or cellulose ester or from polyester film which has been metallized through vacuum deposition of aluminum and then encapsulated in polyester. In general, the properties of these fibers resemble the properties of the plastic film used to form the multicomponent fiber. The fibers are generally weak and easily stretched but can be used for decorative purposes and for applications where electrical conductivity and heat resistance are important. Trade names for metallic fibers include Brunsmet and Lurex.

13. Miscellaneous Fibers

In this chapter fibers which do not logically "fit" under other classifications are listed--novaloid, carbon, poly-*m*-phenylenedibenzimidazole and polyimide fibers. These fibers were developed for specific industrial applications and do not find wide use in consumer goods. For the present, it appears unlikely that new generic fiber types will be introduced in the marketplace unless they have distinguishing characteristics that make them uniquely suited to particular applications. All of these fibers possess such properties.

NOVALOID

Novaloid is the designation assigned by the FTC for a class of flame retardant fibers made from crosslinked phenol-formaldehyde polymer. The fibers of this class in U.S. production are called Kynol and are manufactured by American Kynol, Inc. The fiber is golden yellow in color and possesses good physical and chemical properties. The fiber is thought to be formed through spinning phenol-formaldehyde prepolymer, followed by heating the fiber in formaldehyde vapor to crosslink the structure. The fiber has low crystallinity with a tenacity of 1.5-2.5 g/d (14-23 g/tex) and an elongation at break of about 35%. The fiber has a specific gravity of 1.25 and a moisture regain of 4%-8%. It is inert to acids and organic solvents but is more susceptible to attack by bases. The fiber is totally heat resistant up to 150°C. It is inherently flame retardant and chars without melting on exposure to a flame. LOI of the fiber is very high (36). This characteristic yellow fiber is dyeable with disperse and cationic dyes. Novaloids are characteristically used in flame retardant protective clothing and in apparel and home furnishings applications where low fiber flammability is desired.



NOVALOID

CARBON

Carbon or graphite fibers have been developed recently for use in industrial and aerospace applications. The carbon fibers are prepared from rayon, acrylic, or pitch fibers by controlled oxidation under tension in limited oxygen atmosphere at 300°-400°C. At this stage of oxidation, carbon fibers have sufficient flexibility to be used in apparel applications such as flame retardant clothing. Further oxidation at temperatures near or exceeding 1000°C under tension results in a high strength fiber consisting of a continuous condensed aromatic network similar to graphite. Fully oxidized carbon fibers have tenacities from 10 to 23 g/d (90 to 207 g/tex) dry or wet and elongations at break of just 0.4% to 1.5%. They have specific gravities from 1.77 to 1.96 and are mildly electrically conducting. Although the fibers are of high strength, they exhibit poor abrasion characteristics and must be sized with epoxy or other resins before formulation into textile substrates. Carbon fibers are inert to all known organic solvents and to attack by acids and bases under normal conditions. These black fibers have excellent resistance to sunlight and biological agents, are inherently flame retardant and are resistant to oxidation at high temperatures. Carbon fibers are extensively used in reinforcing fibers for resins and plastics in high performance fiber-polymer composites and are marketed as Celion, Hi-Tex, and Thornel.

POLY-m-PHENYLENEDIBENZIMIDAZOLE (PBI)

PBI was developed by the U.S. Air Force and Celanese as a flame retardant fiber for use in aerospace applications. The fiber is spun from N,N-dimethylacetamide followed by derivatization with sulfuric acid to form a golden fiber. It has moderate strength (3 g/d or 27 g/tex) and good elongation at break (30%), a moderate density (1.4 g/cm^3), and a high moisture regain (15%). Fabrics from the fiber possess good hand and drape and are stable to attack by ultraviolet light. PBI does suffer from poor dyeability, however. In addition to its low flammability, the fiber has a high degree of chemical and oxidation resistance, does not show appreciable heat shrinkage up to 600°C and generates only small quantities of smoke and toxic gases on ignition. In recent years, it has shown potential as a replacement for asbestos, as a flue gas filter material, and as an apparel fabric in specialized applications.

POLYIMIDE

An aromatic polyimide has been introduced by Upjohn Company for use in flame retardant, high-temperature applications. The fiber is spun from the polymer by wet or dry processing techniques using a polar organic solvent such as N,N-dimethylformamide to give a fiber with a round or dog-bone cross section. The highly colored fiber may be crimped at 325°C using fiber relaxation. The fiber has a tenacity of 2-3 g/d (18-27 g/tex) and a 28%-35% elongation at break. The fiber has a moisture regain of 2.0%-3.0% and melts at about 600°C.