TEXTILES, TESTING

1. Textile Fibers

There are many types of textile fibers that can be used in numerous products and applications (5–11). The fibers are broadly classified as *natural fibers*, such as cotton, jute, flax/linen, kenaf, milk weed, (commonly known as the *vegetable fibers*) and wool, silk, hair, etc, (commonly known as the *protein fibers*) and *man-made, synthetic or regenerated fibers*, such as nylon, polyester, acrylic, polyethylene, polypropylene, Aramid, Lycra spandex, carbon, P.B.I., rayon, Tencel, lyocell, etc. Ultrafine, high-performance nano fibers are the latest new developments of a rather old technology of electrospinning. Textile fibers are also classified according to their length. They can be either staple (in case of most natural fibers), or cut-staple (mostly in case of synthetic fibers), or filament (mostly synthetics). Textile Institute defines textile fibers as units of matter characterized by flexibility, fineness, and a high ratio of length to thickness (11). The fiber length depends on the fiber type and the source of production. Staple fibers generally vary from 2 cm to 18 cm ($\sim$1" to 6"), but they all must have a high length to thickness ratio ($>$1000). Staple fibers mostly are used in staple-spinning systems, such as ring spinning, open-end/rotor spinning, air-jet/vortex spinning, etc, to produce yarns for knitting, weaving and sewing threads. Short and hence less expensive staple fibers are used in producing nonwoven fabrics without the process of yarn spinning. Filament fibers/yarns on the other hand generally are continuous and infinitely long. The length is actually determined by the total length of the fiber/yarn on the supply package. A filament yarn may be a monofilament or a multifilament (of several fine, individual filament strands). Filament yarns include natural silk and synthetic fibers such as nylon, polyester, acetate, polypropylene, and the like. Beside the length, textile fibers should also have adequate temperature stability, strength, and extensibility. Other important fiber qualities include cohesiveness or spinability and uniformity. There are also several secondary characteristics that improve product quality and consequently customer satisfaction. These include cross-sectional shape, specific gravity or density, moisture regain, absorbency, resiliency, luster, elastic recovery, and affinity for dyes and pigments. However, the fibers should be resistant to environment-sensitive chemicals, to environmental and weathering conditions of sunlight and temperature, and to biological organisms. Thus, the knowledge of fiber properties, including physical, mechanical and chemical behaviors, is fundamental to understanding the fiber's suitability for a particular textile structure, whether it is a singles, plied or folded yarn, a woven, knitted or nonwoven fabric, or just a fibrous congregate for a certain end-use application.

1.1. Properties. Fiber properties can vary considerably depending on the fiber type and production source. For example, cotton, being a natural product, has properties that significantly vary from fiber to fiber within a boll on a cotton plant, from bale to bale, from crop to crop, from region to region, from variety to variety, and from cultivar to cultivar. Some of the representative physical properties of textile fibers are shown in Table 1.

In addition to the kind of fiber, the fiber quality plays a significant role in determining the price of the fiber in the market place. For example, price of cotton in the United States is largely determined by the fiber quality as determined by standard fiber measurements conducted (on fee basis) by the Agricultural Marketing Service (AMS) of the U.S. Department of Agriculture (USDA) (12). Fiber tests are conducted from each cotton bale produced in the States, in accordance with the official American cotton grading system that now mostly utilizes the state-of-the art High Volume Instruments (HVI) (13,14).

1.2. Testing Physical Properties. *Fiber Length.* The average or mean fiber length (L) and the distribution of fiber lengths, ie, the fiber length distribution (FLD) of a population of staple fibers, are very important quality parameters, because these parameters considerably influence processing of the fibers into yarns and consequently fabrics. The L and FLD are particularly critical in case of natural fibers, especially cotton. Fiber length and the fiber length distribution influence spinning performance as well as the yarn strength, uniformity, evenness, surface imperfections, hand and appearance. It may be mentioned that FLD, ie, the Fiber Length Uniformity Index (UI), in the case of cotton is more influential than L in the fiber processing and fabric quality. The fiber length or staple of cotton is generally determined by the Upper Half Mean Length (UHML) or Upper Quartile Length (UQL) of the FLD. A High Volume Instrument (HVI) is currently used to obtain information on the cotton fiber length. However, presently, there is no standard high-volume instrument or method to determine a truly representative average or mean length of staple fibers. Advanced Fiber Information System (AFIS-Pro), a trademark of the Uster Corporation (15), is currently involved in further investigating the FLD data, in order to fully understand the impact of fiber length distribution of cotton on the fiber quality, processing efficiency, and product quality. Accurate testing for fiber length is essential as the fiber length-to-diameter ratio is utilized to facilitate efficient conversion of the fiber into yarn. The standard test methods used to measure fiber length and its distribution are listed in Table 2.

In these methods, both the average or mean staple length and the distribution of fiber lengths are recorded. ASTM D3661 gives the procedures for measuring average staple length and distribution of staple length for synthetic fibers ranging in length from 25 to 250 mm. Because synthetic filaments are cut or broken into staple fibers, the possibility of multiple lengths of fiber exists. ASTM D3513 gives the procedures for determining the percentage of multiple-lengths (over length) fibers using visual inspection of a combed sample of fibers. The test instruments in these methods use either photoelectric, capacitance, or pneumatic scanning devices to determine fiber length. The results from these methods, however, do not agree with those obtained from ASTM D1440 (Manual Array) because of the differences both in the treatment of fiber crimp and in the definition of the length being measured. Other automatic and semiautomatic systems exist for determining length and length distribution for wool, which can be found in the literature (11, 16–18).

Fiber Density, Fineness and Cross-Sectional Shape. *Fiber density* is defined by the mass per unit volume of the fibers and its measurement is useful when comparing substances having different volumes. For fibers, the relative mass per unit volume, called the specific density, is often given. The specific densities of most common textile fibers as well methods of determining fiber densities by traditional means such as by the displacement of liquids and by precise microscopic measurements of the fiber length, cross-sectional area, and weight are available in literature (11, 19–23).

Fiber fineness, linear density, or transverse dimension is usually described by fiber diameter (for cylindrical fibers), fiber linear density, or fiber weight per unit length (for fibers that have irregular cross-sections or that taper along their lengths). All of these terms basically represent the fiber fineness, which is a measure of the fiber size. In the English system, the fiber size is expressed as micrograms/inch length of fiber. In the universal metric system, it is termed as denier, tex, or decitex (dtex).

tex	=	weight in grams of 1000 meters (1 kilometer) of fiber or yarn
decitex (dtex)	=	weight in grams of 10000 meters (10 kilometer) of fiber or yarn
kilotex	=	weight in kilograms of 1000 meters (1 kilometer) of fiber or yarn
denier (den)	=	weight in grams of 9000 meters (9 kilometer) of fiber or yarn

An airflow type of instrument, called *micronaire*, is widely used in the HVI system to determine fiber fineness. Fiber fineness determines the yarn size potential and affects the yarn strength, uniformity, and appearance. An overview of the fiber fineness testing procedure is available in (24). Information on measurement of fiber diameter using optics is available in Ref. 25. ASTM D629, Sections 23 through 28, describes procedures for determining fiber diameter using microscopic analysis. Characterization of cotton fibers by cross-section, fineness, and maturity has been discussed in Refs. 11,26,27. These references show one simple method for determining the fiber cross-sectional area and length (27) and describe general methods for measuring and calculating fiber transverse dimensions (11) (See also Table 3).

Fiber cross-sectional shape varies both naturally and by design (1,2,28). For example, wool fibers are essentially round, ignoring the scales; cotton fibers are elliptical or kidney-shaped; and synthetic fibers can have any desired cross-sectional shape depending upon the method of spinning and the shape of the spinneret hole through which the fiber is extruded (11). Cross-sectional shape influences the stiffness (flexural rigidity) of fibers (11,29), the tendency of fibers to pack together in yarns, as well as the luster of fiber, yarn and hence fabric. In addition, fibers of specific cross-sectional shapes are often engineered to provide particular fiber properties for a particular application. For example, circular hollow fibers can be used to improve fluid transport and insulation properties. DuPont manufactures a fiber that has a square cross-section containing four longitudinal, continuous holes or channels (Antron III) to hide soil. Eastman manufactured an irregular cross-sectioned, deep-groove fiber (4DG) used for fluid movement and absorbency. The cross-sectional shapes of synthetic fibers, unlike those of natural fibers, can be easily verified by using microscopic analysis.

$$\text{Cross-sectional area of fiber}\,(\mathrm{cm}^2) = \frac{\text{denier (gm)}}{900000(\mathrm{cm}) \times \text{density of the fiber}\,(\mathrm{gm/cm}^3)}$$

Crimp. Practically all staple fibers have crimp, which is defined as "waviness" of the fiber. Fibers such as cotton and wool have a natural spiraling or helical crimp (convolutions). In synthetic fibers crimp is imposed by mechanically deforming the fiber. The elasticity of crimp may vary, especially in synthetic fibers where the method of deformation and heat setting are important factors. Essential in the conversion of fiber to yarn, crimp determines the capacity of fibers to entangle during processing and thus determines the cohesiveness of card webs as well as the hairiness of the resultant yarn (30). Crimp is the principal feature governing bulking power of textile materials and, generally, the specific volume of yarns and fabrics (11). Physical properties of fibers may be used to determine their amount of crimp (See Table 4).

Moisture Absorption. Absorption of moisture by a fiber usually changes the latter's properties (11). It may cause swelling, which alters dimensions of the fiber and, in turn, changes the fiber size, shape and stiffness. The mechanical and frictional properties may also be altered, thus affecting behavior of the fibers during processing. Wetting and drying may lead to permanent set or creasing. Moisture condition or content of fibers is also an important factor in determining electrical properties (11). The amount of moisture present in a mass of fibers, a yarn, or a fabric is calculated as moisture regain or moisture content. Moisture regain is the difference in wet and dry fiber weight relative to the dry fiber weight, whereas moisture content is water weight loss as a percentage of the combined fiber and water weight.

$$\begin{cases} \text{Moisture regain value}\,(\%) = \dfrac{\text{Original weight} - \text{Dry weight}}{\text{Dry weight}} \\ \text{Moisture content value}\,(\%) = \dfrac{\text{Original weight} - \text{Dry weight}}{\text{Original weight}} \end{cases}$$

The normal methods for determining these values involve weighing, bone-drying, and reweighing the test materials. Moisture regain values of common hydrophilic as well as hydrostatic and hydrophobic fibers at standard testing conditions of 65% relative humidity and 21°C and at higher relative humidity can be found in the literature (2,11,28,31–33).

Color. The reflection of light falling on an object determines visual appearance or color of the fibers. These optical properties of fibers are measured by light microscopy methods and by a colorimeter. The meter measures grayness (Rd), which indicates how light or dark the sample is, and also yellowness (+b), which indicates how much yellow color is in the sample. This fiber attribute gives an indication of the fiber's quality and its ability to accept dyes in subsequent textile finishing processes (11, 34–39).

Shrinkage. Shrinkage of a bundle of crimped or non crimped fibers that contract at least 10% in boiling water or hot air can be determined by ASTM D2102 and ASTM D5104 methods. More information about the fiber shrinking mechanisms is available in the literature (40, 41–43).

1.3. Testing of Mechanical Properties. The most important properties of textile fibers probably are their mechanical properties, such as tensile or breaking strength, stress–strain behavior, modulus of elasticity, etc. Knowledge of fiber's mechanical properties is essential in understanding the fiber behavior during processing as well as in the end product. Fiber strength is closely related to the spinning efficiency and to the yarn and fabric strengths. The properties of yarns and fabrics generally are dependent on the fiber properties, the fiber orientation within the yarn, and the arrangement of the yarns in the ultimate fabric. Breaking strength of single fiber is determined by using an instrument such as Instron. However, the testing of single fibers really is tedious and time-consuming. Therefore, the *fiber tensile or breaking strength* most commonly is measured by breaking a clamped beard of parallel fibers on a Stelometer with 1/8" (or, zero) gage spacing between the clamp jaws. The strength is reported as the force in grams required to break a bundle of fibers one tex in size. The bundle strength of fibers may also be determined by using an incline-plane (for constant rate of loading), or a pendulum-type (for a constant rate of strain) instrument (11). An overview of test procedures for evaluating the tensile properties of fibers and their significance is available in Refs. 11,44 (See also Table 5).

The stress-strain behavior of textile fibers can be obtained by several methods (21,44–46). The *loop and knot strengths* of textile fibers are essential. Their relationship with fiber strength and rupture is available in literature (11,21,47–49). The *elastic property* of the fiber is defined by its ability to deform under below-rupture loads and to return to its original configuration or dimension upon load removal. The elastic recovery, delayed recovery, and permanent set of fibers are also measured and their effects on the strain rate, temperature, length of time strained, etc, have been discussed in the literature (11,30,50–52). Other fiber deformations such as bending, torsion, shear, and compression also are of practical importance in textile applications. Several test methods are available in literature to measure the fiber properties related to such deformations. For example, the measurement of *flexural rigidity* of fibers is in Refs. 53–59, of *torsional rigidity* of a fiber, or resistance to twisting is in Refs. 60–66, of *shear properties* of fibers is in Refs. 60,67, and of the *effect of compressive stresses* on a mass of fibers is in Refs. 11,68.

1.4. Testing of Friction. It is mostly interfiber cohesiveness or friction that holds fibers together in a spun yarn or in a nonwoven fabric. In woven and knitted fabrics, it is again the interyarn friction that keeps the interlacing yarns together. High fiber friction can be both an advantage and a disadvantage. If the fiber-to-fiber friction is too low, the yarn strength will also be low. If the yarn-to-yarn friction is too low in a woven or a knitted fabric, the fabric dimensional stability will diminish. Friction also plays an important role in the processing of fibers, yarns and even fabrics. To avoid excessive fiber breakage, the friction-induced tension buildup in the fiber during processing must be less than the average fiber strength. Fabric properties that are influenced by frictional effects are fabric hand, strength, elongation, abrasion resistance, dimensional stability, and seam slippage. Fiber friction can be determined by physical methods. For rapid evaluation of fiber or yarn friction, the capstan method, where a fiber or a yarn is pulled over a cylindrical surface (usually a highly polished steel rod), is most commonly used. However, several methods for determining fiber-to-fiber friction have been developed in the past (69–76) and the frictional properties of fibers and its measurement scheme are compiled in the manuscript (77). Because fiber frictional properties are so important in the conversion of staple fibers to spun yarns, the measurement of fiber cohesive/frictional force is essential. The frictional properties of fibers are affected by the latter's surface lubrication, linear density, surface configuration, staple length, and crimp.

1.5. Testing of Electrostatic Properties. In the past it was believed that static electricity was generated when two different materials were rubbed together. Though the separation of two unlike surfaces does produce a static charge, it now has been shown that the asymmetric rubbing of two identical surfaces also results in generation of charge (78). If the resulting charge is retained and accumulated (ie, not conducted away), a measurable electric potential is generated. If the material under consideration is an electrical conductor that is grounded, the charge is removed as fast as it is deposited and there is no static electricity. However, if a material is a dielectric (11), the charge builds up to the point where it may interfere with textile processing, such as carding and spinning, fabric spreading, and ply separation in the cut-and-sew (garment) industry. Buildup of static charge may also be objectionable to a person wearing the material because of its clinging and sparking. Four criteria, viz., surface resistivity, volume resistivity, rate of charge buildup and release, and maximum charge capable of being retained, are used to study static electricity in a textile material (See Table 6).

1.6. Testing of Thermal Properties. Depending on their reaction with heat or temperature, textile fibers may be classified as *thermoplastic*, such as polyamides, polyesters, acrylics, olefins, acetates, etc, and *nonthermoplastic* such as wool, silk, cotton, linen, jute, regenerated rayon, and synthetic protein and aramid fibers. A group of fibers that are highly resistant to high temperature has been produced from highly aromatic compounds. The well-known fibers in this group are Kevlar (DuPont), Nomex (DuPont), and PBI (Hoechst-Celanese) (3). These fibers exhibit no clear melting point, degrade only at very high temperatures, and maintain a high percentage of their original strength even at elevated temperatures. These fibers are primarily used in body armor (Kevlar) and protective clothing for firefighters, race-car drivers, and astronauts. Their great thermal stability obviously is responsible for their resistance to burning, as well. The effect of heat on fibers has been described in Refs. 11,28,79. Contraction temperatures and melting points of thermoplastic fibers are available in Refs. 11,80. It should be noted that most fibers have similar thermal conductivities and heat capacities. The heat insulating characteristics of textiles are more related to fabric structure or geometry than they are dependent on constituent fibers' thermal characteristics.

It is appropriate to mention here that most of textile testing worldwide involves cotton and cotton textiles. In fact, cotton is the only natural, agricultural commodity that undergoes intensive testing for stringent quality measurements to assist in its marketing and processing. Accordingly, high volume instruments (HVI) have been developed to efficiently and cost effectively measure the fiber's essential properties, in order to establish uniform cotton quality standards globally. Although many countries today have quite a few HVI systems and/or some derivatives thereof, the United States is probably the only country where cotton lint testing for classification and grading of the country's entire cotton production each year is now done on HVI. Australia and China reportedly are also in the process of completely switching to HVI for classification and marketing of their cotton productions.

1.7. Testing of Chemical Properties. Textile fibers widely vary in their chemical reactivity, and testing for the chemical properties of textile fibers is of paramount interest (81). Furthermore, concentration of chemicals, processing temperature and pressure, condition of substrate, and time or exposure of reaction also greatly influence their chemical reactivity. Both acids and alkalis, although they are extensively used in many textile processes, can attack and damage most textile processes and products, if the reaction conditions are imprecise and not optimally controlled. For example, even a dilute (4–10%) sulfuric acid at a high temperature may damage (carbonize) a cotton fabric instantly, whereas it may not affect a wool fabric. Caustic or ammonia of optimum concentration at a certain temperature may not adversely affect a cotton fabric in wet condition, but it may instantly damage the treated fabric if it is dried without a thorough rinsing. Fiber absorbency also plays a critical role in wet finishing of specially those textiles that are made of two or more different types of fibers with different absorbencies. For example, cotton, wool, polyester have all different absorbencies (ie, affinities for water and other chemicals). When a fabric made with a blend of these fibers is union dyed or otherwise specially finished, it is imperative to ensure that the finished product has uniform appearance and other aesthetics and evenly meets all the required performance attributes. Frankly, textile wet finishing, although it seems an easy chore, is as complex as textile manufacturing itself. Knowledge of chemical properties of the various fibers and chemicals and their conditions involved in textile wet processing is vital. Chemical reactivity of a few typical fibers with some commonly used chemicals is briefed below.

Cotton. cotton is a hydrophilic fiber, it has high absorbency compared to many noncellulosic fibers. Consequently, it is an excellent substrate for many dyes and special chemical finishes, such as flame-retardant, antimicrobial, durable-press finishes, etc. However, it can be badly damaged, if not totally destroyed, by oxidation in improper reactions with both acids and alkalis. However, caustic of certain concentration and conditions is extensively used in wet finishing of cotton materials, such as scouring and bleaching.

Wool. Wool is a protein fiber, it can accept without damage dilute acids (sulfuric) even at moderate temperatures, if other conditions of reaction are properly maintained. To get rid of foreign matter, such as grass, cotton, or any other organic contaminant, from a woolen/worsted fabric, it is customary to treat a woolen fabric with a dilute acid in a chemical finishing process called carbonization. However, extreme care must be exercised in controlling the reaction conditions. Otherwise, a fabric of nonuniform appearance and properties will result.

Polyester and Nylon. Although polyester and nylon are hydrocarbons, they, unlike cotton, are relatively quite stable in low concentrations of both acids and alkalis, because they are relatively much less absorbent than cotton or wool. However, they can fuse, melt, and even decompose at high temperatures, which sometimes limit their chemical reactivity. In general, when compared to natural fibers, they are inert to many chemicals, most of which are hydrocarbons, anyway.

2. Textile Yarns

A yarn is a structure of long continuous length of interlocked fibers, which is suitable for use in production of fabrics, sewing threads, sweaters, hosiery, ropes, or reinforced industrial products, such as engine belts, sandpaper, and other composites. Yarn can be made from any number of natural and/or synthetic fibers and their blends, using one of several spinning systems. Yarn can be a *staple-spun*, a *mono-filament*, or a *multi-filament*. Yarns can be *singles, plied, folded, or cable*. Two or more singles yarns, when twisted together, form a plied (2-ply, 3-ply, etc) yarn. Two or more singles yarns, when assembled parallel to each other, ie, without twisting, form a folded yarn. A sewing thread generally is a 2-ply or 3-ply yarn. Industrial sewing threads may be produced by further plying two or more ply yarns. Two or more plied yarns, when assembled/twisted together, can also form a cable yarn, depending on the number and linear density of constituent components. In some cases, a thread may be a monofilament, in which case it is a single (synthetic) fiber. The only natural fiber that is considered as a monofilament is silk.

Yarn is manufactured by a spinning process. Yarn production was one of the very first industrialized processes. Yarns for fabric manufacture are generally made by spinning staple fibers (of relatively short lengths) of various natural and synthetic materials, although substantial quantities of yarns today are also extruded (melt- or solution- spun) from synthetic or natural polymers. Synthetic fibers that have high strength, artificial luster, and/or fire-retardant qualities are blended in different proportions with natural fibers that have good water absorbency and skin-comforting qualities, in order to produce yarns for manufacturing fabrics of desired characteristics for apparel and other end-uses. The most widely used fiber blends for apparel today are cotton–polyester and perhaps wool–acrylic. A yarn is usually "sized," i.e., measured according to its linear (mass) density. In the United States, staple-spun yarns are generally sized/measured in the old English system (Ne), which indicates the number of 840-yard hanks in one pound of yarn. In Europe and in most of the rest world, the unit of yarn measurement often is Tex (g/km), which is the weight in grams of 1000 meters of yarn. Many other yarn sizing methods and units exist for different types of yarns.

Although there are many kinds and types of yarns, the cotton yarns, and for that matter any other staple-spun yarns, can be broadly classified as *carded* or *combed*. Carded yarns generally are coarser and fuzzier than combed yarns, which are smooth, lustrous, and uniform. Combing is a process which removes about 15% short fibers from the fiber population, while extracting minute trash and parallelizing the remaining long fibers. Combed yarns generally are superior to carded yarns and thus command a premium price. Similarly, sheep's wool is divided into the following two categories when referring to the resulting yarn or fabric, depending on the length and fineness of the fibers and the way they are processed before spinning: *Worsted* and *Woolen*. Worsteds are spun from longer, combed fibers, and the resulting yarn is smooth and firm. Woolen yarn is spun from only carded (not combed) wool and is fuzzier and weaker than an equivalent worsted yarn. However, the different characteristics of both of these yarns definitely produce certain desirable effects in the finished garments.

2.1. Properties of Textile Yarns. Evaluations and QC of staple and filament yarns are normally conducted by monitoring some or all of the following yarn properties:

Appearance: It is generally evaluated with the standard Yarn Standards maintained by ASTM, AATCC, or individual mills or labs.

Yarn size or Count: Contrary to the linear density method (Direct System)-for measuring fibers in which weight for a specified length is recorded, yarns in the United States are usually characterized by count (Indirect System) or the units (hanks) of certain length for a specific weight. For cotton yarns, the unit or hank consists of 840 yards of yarn. For worsted yarns, the unit or hank is comprised of 560 yards. The unit of weight in both cases is English pound. Table 7 gives yarns size and conversion factors.

Linear density: It is the direct system of sizing yarns. The popular units of measurements in this system are: tex; dtex; denier, metric (10 km), etc.

Unevenness: It is usually determined as a coefficient of variation (CV %) of the mass per unit length of a certain length (generally, 1000 m) of the yarn. The yarn unevenness indirectly is a measure of the yarn "uniformity or evenness."

Imperfections: They are very minor defects especially in cotton and other staple-spun yarns. Imperfections can be thin places (typically −50% of average yarn thickness); thick places (+50 % of the average yarn thickness); and neps (+200% spot density).

Tensile Properties: They include the breaking strength and/or tenacity and the breaking elongation as a % age of the original test specimen length.

Frictional Properties: They mainly include the coefficient of friction of a yarn against a highly polished steel cantilever rod (capstan).

Twist Torque / Liveliness: Excessive twist torque in a yarn is very detrimental to the yarn processing. A well-balanced yarn is preferred.

Abrasion Resistance: This indirectly determines the yarn's processing performance and ultimately the durability of the end product.

Hairiness: It is a critical characteristic of staple-spun yarns and considerably influences the yarn processing performance and the "hand and feel" of the end textile.

2.2. Testing of Physical Properties. *Size, Number, or Linear Density.* The count of a yarn of a given cross-sectional diameter varies according to the particular spinning process used. The yarn size conversion Table 7 lists the most common forms of yarn count, which apply for any fiber or blend of fibers processed by a particular system. The yarn size can be determined by weighing a specific length of yarn. Like fibers, continuous-filament yarns are normally sized using the direct system of determining the linear density of yarns. See also Tables 8 and 9.

Yarn Evenness and Grade. Unevenness of diameter/mass along the yarn length, which is more prevalent in spun yarns than in filament yarns, gives rise to poor strength and a non-uniform appearance in fabric form, ie, thick and thin spots. Yarn evenness is usually measured by passing a length of yarn through an instrument that continuously measures capacitance. Fluctuations in capacitance readings are proportional to yarn unevenness. Yarn grade is assessed using a subjective test and also quantitatively (82).

2.3. Testing of Mechanical Properties. *Yarn Strength.* Yarn strength is important not only in governing the strength of the resultant textile structure, but also in terms of the ease of conversion of the yarns into the structure. Weaving and knitting processes impart significant stresses on the component yarns. Weak yarns cause difficulties and breakages in the fabrication process, resulting in fabric defects and loss of manufacturing efficiency. The translation of fiber strength to yarn strength is complex even in the case of rather uniform filament yarns. Although the yarn strength may be expected to be equal to the fiber strength multiplied by the number of individual fibers in the yarn cross-section, it, in reality, however, is usually significantly lower than the sum of the individual fiber strengths. This is explained by the weak-link theory, which argues that there is a distribution of individual fiber strengths in a yarn bundle. If all fibers/individual filaments in a yarn are stressed uniformly, the weakest fiber will break at a combined stress level less than $1/n$ of the average yarn strength, where n is the number of fibers/filaments in the yarn (bundle). The total stress in the yarn then must be shared by the remaining n-1 fibers, which causes a stress surge in the remaining filaments. This increase in stress exposure thus causes the filaments to fail at some combined stress level below that calculated from the average fiber strength multiplied by the number of fibers/filaments in the yarn bundle. Consequently, the larger the bundle size, the lower the yarn strength is relative to the predicted value obtained from the average fiber strength, because the probability or opportunity for the presence of a weak fiber/filament is increased by the larger number of fibers present. In staple spun yarns, the yarn strength is only a fraction of that predicted by the individual fiber strengths and the number of fibers in the yarn cross-section. In addition to fiber strength, the twist, fiber migration, and frictional forces all influence yarn strength. If a yarn contains two or more fibers of differing stress–strain behavior, it would fail at a stress governed by a combination of the breaking stress of the low-elongation fiber and the stress development in the high-elongation fiber, at the breaking extension of the low-elongation fiber. This phenomenon has encouraged the synthetic fiber industry to develop special fiber variants for blending with cotton and wool to ensure compatibility of the stress–strain curves for both blended fibers.

Yarn Twist Torque/Liveliness. Excessive twist torque is very detrimental in yarn processing. A well-balanced yarn is preferred. In staple yarns, twist is required to force the fibers into contact with one another, thus increasing cohesion and thereby developing yarn strength. Without twist, constituent fibers in a staple yarn would slip past one another easily. In filament yarns, each individual filament is as long as the yarn itself, thus, eliminating the concern of yarn breakage resulting from fiber slippage. Thus, for continuous-filament yarns, twist has a secondary effect on yarn properties. Without twist in a continuous-filament yarn, the individual filaments would spread out, separate from one another, and cause the bundle to lack unit integrity. Twist in continuous-filament yarns is also useful to help prevent snagging by tucking any loose fiber filaments into the yarn bundle or structure. Twist results have been discussed (83). Measurement of twist in a yarn spun on an open-end spinning system, which is a kind of modern, relatively newer and faster method of yarn spinning as compared to conventional ring spinning, is difficult. The difficulty arises because of wrapper fibers on the yarn surface. Because these fibers in part lay loosely on the yarn surface, during the untwisting of the yarn they tend to become twisted and lead to an erroneous measurement of yarn twist. Optical observation of the surface fibers has been suggested as the most reliable method for measuring twist in open-end spun yarns (84). The selection of twist level is important not only in establishing the surface characteristics of the yarn (eg, low twist for a soft, fuzzy yarn and high twist for a compact, smooth yarn), but also in determining the yarn strength. Yarn strength as a function of yarn twist level is shown in Fig. 1.

As seen from Figure 1, there is an optimum twist level in terms of strength development in spun yarns. As the twist increases, the frictional forces holding the fibers together increases, thus reducing the chances of yarn breakage as a result of fiber slippage. However, twist in excess of the optimal development of frictional forces can cause a decrease in fiber orientation with respect to the yarn axis. This decrease in orientation causes a decrease in strength because only in the most oriented position do fibers bear the maximum stress in a tensile test. Therefore, optimization of twist level for desired strength for a given application and for desired yarn surface characteristics must occur. Because a given number of turns per unit length produce a greater helix angle in a thicker, ie, a low-count, yarn than in a thinner one, it is customary to express twist in the form of twist multiplier or twist factor. These terms take into account the turns per unit length required to give a constant helix angle in yarns of differing counts. If this unit of twist measurement is substituted for the horizontal axis in Fig. 1, then it is possible to determine the optimum twist level for maximum yarn strength for any size yarn of a given fiber composition. Filament yarns require much lower twist factors for optimum strength than spun yarns. These yarns are often used as supplied by the manufacturer and contain producer twist only, which can be as low as 0.25 turns per centimeter. *Singles yarns* may be twisted together to form a *plied yarn*. Several plied yarns may be twisted together to form *a cable yarn*, or *a rope yarn*. Several cable or rope yarns may also be combined and twisted together to produce an even bigger and stronger *cord*. A method for analyzing yarn construction and the nomenclature used to define yarn construction is found in ASTM D1244 (See Table 10.)

2.4. Testing of Friction Properties. Frictional properties of yarns are important in considering the performance life of some machine components, eg, yarn guides, heddles, reed dents, and knitting and sewing needles. Frictional properties also affect the quality and performance attributes of yarns. In high-speed sewing, yarn friction plays an important part in the fabric-to-thread interaction. Sewing threads must be highly lubricated to ensure good stitch quality. In sewing, high yarn friction may result in needle heating, which in turn may cause yarn fusing and even the needle breakage. Also, high yarn-to-yarn friction may hinder the needling from passing between yarns during stitching, thus causing poor stitch quality. In determining frictional properties, it must be remembered that no coefficient of friction exists for a single body. The coefficient of friction measures the frictional interaction between two bodies or elements in dynamic contact (See Table 11).

Testing of Abrasion Resistance, Hairiness, and Fiber Migration. Abrasion resistance indirectly determines the yarn's processing performance and ultimately the durability of the end product and it is the ability to withstand rubbing or frictional forces on its surface (9). ASTM D 6611-00 has test method for estimating yarn-on-yarn abrasion resistance of wet and dry yarn. Hairiness is a critical characteristic of only staple-spun yarns. It considerably influences the yarn processing performance and the "hand and feel" of the end textile product. A guide for estimating yarn hairiness by photo-electric apparatus is given in ASTM D 5647-01. Fiber migration, which influences yarn properties, is the "ability or desirability" of individual staple fibers (in a dynamic fibrous bundle) to alter their radial positions along the length of the bundle in a yarn formation/ spinning process. It enhances the interlocking of the fibers in the yarn structure and increases the number of contact points among the fibers. An in-depth discussion of fiber migration in yarn is available in Refs. 86–88. A comprehensive discussion of the effects of fiber migration, or lack thereof on fabric drape, hand, pill resistance, and abrasion resistance, along with various methods for determining fiber migration, is also available in (89) (See Table 11).

Testing of Textured Yarns. Synthetic filament yarns are often textured to impart stretch, comfort, and bulk properties, which are desirable for certain clothing. Texturing also alters hand and luster and improves insulating properties of the filament and its ultimate product. In evaluating textured yarns, along with typical yarn properties such as linear density, strength, and elongation, the yarn shrinkage and bulk are of special importance. Properties of textured yarns are mostly determined by using the standard test methods for regular continuous-filament yarns by using a Dynamic Textured Yarn Tester described in ASTM D 6774-02 (90–93) (See Table 11).

3. Textile Fabrics

A textile fabric can be broadly defined as an integrated, flexible structure of textile fibrous material. A fabric is constructed in many ways, such as weaving, knitting, nonwoven, composites, and any derivative thereof. However, the weaving is by far the most common method of producing fabrics, worldwide. Knitting comes next, followed by nonwovens and others. In weaving, two sets of yarns, viz., warp and filling, are required to construct a fabric by interlacing the two sets of yarns, while only one set of yarn, or even just one yarn package, may be used to knit a fabric. A nonwoven fabric from staple fibers is produced by simply preparing a card web or an air-laid mass of fibers, interlocking the fibers by mechanical action or fusing them by heat, chemical or adhesive, and finally finishing the fabric as required. Spunbonding and melt-blown technologies are most often used in the production of non-woven fabrics directly from polymer chips. Within each of these broad classifications of fabrics, there are numerous types of fabrics for even more numerous applications in the apparel, household, furnishing, medical, military, industrial, geo, transportation industries, and huge retail markets. Examples of fabrics used in apparel are woven poplins and single-knits for shirting; woven twills and double-knits for trousers; leno, voiles and lawns for blouses; and plain broadcloth for pajamas. Examples of household fabrics are sheeting, blankets, and terry towels. Similarly, the upholstery, drapes and table cloths are examples of home/office furnishings. Diaper and wipes perhaps are the largest end-use application of consumer nonwoven fabrics. Basically, fabrics are designed and produced according to their end-use applications. Fabric metrics, viz., fiber content, yarn structure, and fabric construction and finishing, largely determine the end-use performance of a particular fabric (See also Table 12 and 13).

The main types of fabrics are: Woven (conventional, tri-axial, multi-axial), plain, twill, stain and sateen weaves and their derivatives; knitted [weft knitted (single-knits, double-knits), warp knitted]; and nonwoven (needle-punched felts; spun-laid for synthetics; hydro/air−entangled).

3.1. Properties of Textile Fabrics. Depending on the end-use application of a fabric, the following properties may be important in evaluation of the fabric:

Physical Properties: Aesthetic appearance, hand, luster, width, uniformity construction/thread count, shrinkage, and weight per unit length or area.

Mechanical Properties: Tensile strength, tearing strength, abrasion resistance, and pilling resistance.

Chemical Characteristics: Flame resistance or retardancy, antimicro bacterial character, substrate value, and effect of acids and alkalis.

Performance Characteristics: Absorbency and comfort, dimensional stability, easy-care/durable-press, conductivity (static charge), effects of light and environment on color fastness, and the ultimate core performance and durability. Table 14 gives representative properties of some typical fabrics.

3.2. Testing of Textile Fabrics, General. Textile testing is the use of engineering principles in the measurement of properties of textile fibers, yarns and fabrics. Tests performed on textile structures relate to, but do not necessarily define, textile's use performance. These tests can be categorized as either objective or subjective. Objective testing is done on standard equipment with established test procedures. Subjective testing or evaluation is based on human perception and generally follows after fabric finishing and especially after certain number of laundering and/or dry cleaning cycles, in order to evaluate the fabric's performance in use.

Properties of finished textile fabrics are an accumulation of properties of constituent fiber(s), yarn configuration, fabric construction, and selected finish. Fiber properties, beside their very important uniformity and consistency, include length, crimp, transverse dimensions, density, cross-sectional shape, shrinkage, friction, moisture absorption, electrostatic and thermal properties, as well as optical, tensile, and elastic properties. Yarn properties, again, beside their uniformity and consistency, include size or number, twist, strength, evenness, friction, and texture. Fabric properties include construction (number of yarn strands per unit area and type of weave or stitch); thickness; air permeability; breaking strength and elongation; snag, pilling and abrasion resistance; shrinkage; thermal and moisture transmission; color fastness after certain number of laundering/dry-cleaning cycles; flammability; hand; drape; wrinkle resistance; luster; and comfort, among others. Properties of textile structures are dictated by interactions of the properties and parameters of the constituent materials and the processing treatments thereof. Table 15–18 show the standard fabric test methods recommended by ASTM and AATCC.

Objective Tests. Fabric properties are dependent on the geometry and form of the fabric structure, as well as the properties of the yarns or fibers from which the fabric is constructed. The three principal types of fabric structures are woven, knitted, and nonwoven. In many cases, the types of tests required to characterize fabric properties are defined by the fabric structure itself. Those properties that are measurable in quantitative terms using instrumentation are referred to as objective properties, eg, tensile strength or color measurement. Other fabric characteristics must be evaluated, at least in part, by human observation and judgment. These are referred to as subjective properties. Fabric hand, drape, luster, and comfort are of this second category (28), although in more recent years, instrumentation has been developed to allow quantification of some of these properties. Many of the test methods for determining physical properties of fabrics are ASTM standards (1). Test methods requiring chemical procedures are primarily based on AATCC standards (2). Because of the moisture sensitivity of most textile materials, particularly hydrophilic fibers such as cotton, and the dependence of physical properties on the moisture content of the material, most test procedures should be carried out at standard conditions of temperature and humidity. For a textile testing laboratory, these conditions generally are $21 \pm 1^{\circ}$C and $65 \pm 2\%$ relative humidity, as specified in ASTM D1776.

3.3. Testing of Physical Properties. *Fabric Construction.* Woven fabrics are characterized in terms of length, width, yarn count, and yarn crimp. Fabric analysis may also include raveling warp and filling yarns to determine type of yarn and its twist level. In addition, the weave of the fabric is usually specified, eg, plain, twill, or satin weave. Knitted fabric constructions are characterized by yield (area per weight), width, length, and yarn count (number of courses and wales per unit length). The type of knit is also specified, eg, warp knit or weft knit. Yarn analysis may be difficult on account of problems in raveling individual yarns from the knitted structure, particularly warp knits. Regardless of whether the fabric structure is woven or knitted, accurate characterization of construction parameters is necessary to evaluate test results for other properties and to explain differences noted when comparing test data from fabrics of different constructions. Nonwoven fabrics are generally described by the method of production, eg, needle-punched or spun-bonded (95) (See also Table 15).

Thickness. Because two fabrics that have identical weight per unit area values may have widely varying bulks; so the specification of thickness is essential for properly characterizing a fabric. Fabric thickness has been shown to be directly proportional to thermal insulation, or warmth. Fabric warmth is the result of the entrapment of air between fibers and yarns. A thicker fabric in general allows an increased amount of entrapped air and thus is warmer. The proper methods for measuring fabric thickness are described in ASTM D1777. Because fabric thickness is dependent on the applied pressure, any measurement of thickness should also report the pressure at which the measurement was made. Thus, an apparatus capable of applying variable pressure to the sample while determining thickness would be desirable. Many instruments, however, allow only incremental increases in pressure, depending on the weight used. Regardless of the instrument used, it is always necessary to state the pressure under which the thickness was determined.

Air Permeability. Air permeability is an important parameter for certain fabric end uses, eg, parachute fabrics, boat sails, warm clothing, rainwear, and industrial air filters. Air permeability of a fabric is related to its cover, or opacity.

Both of these properties are related to the amount of space between yarns (or fibers in the case of nonwovens). The most common method for specifying air permeability of a fabric involves measuring the air flow per unit area at a constant pressure differential between the two surfaces of the fabric. Units for air permeability measured by this method are generally abbreviated as CFM, or cubic feet per square foot per minute. An alternative method for measuring air permeability is based on measuring differential pressure when a constant rate of air flow passes through the fabric. In this case, air resistance is reported in typical units of kPa·s/m.

3.4. Testing of Mechanical Properties. *Breaking Strength and Elongation.* The breaking strength and elongation (extensibility) of woven fabrics are often used as quality-control parameters. These properties are especially important for industrial uses where tensile strength is a principal consideration. For many apparel uses, however, breaking strength is of little consequence, although minimum standards are generally reported in most ASTM performance specifications. Most fabrics far exceed the reported minimum tensile strength standards. Nonetheless, tensile strength tests, generally easy to conduct, are relied upon as popular quality-control tests. In some cases, the maximum or minimum elongation produced at a selected stress level below rupture is specified as a criterion, eg, percent stretch in stretch fabrics. Two types of fabric tensile strength tests are commonly used: the grab test (ASTM D5034) and the raveled strip method (D5035). These tests are designed to be carried out on either constant rate of extension (CRE), constant rate of load (CRL), or constant rate of traverse (CRT) testing machines, although CRE testers are becoming the most commonly used. Empirical attempts have been made to relate strip and grab test results, particularly for cotton fabrics, so that if one strength is known, the other can be calculated. The relationship is complex, depending on fiber strength and modulus, yarn size and crimp, yarn-to-yarn friction, fabric cover factor, weave, weight, and other factors (28) (See also Table 16.)

Bursting Strength. The tensile tests discussed above are not suitable for knitted fabrics because of the distribution of applied forces in all directions in a knitted structure. The strengths of knitted fabrics are measured by determining bursting strength. ASTM D3786 describes the measurement of bursting strength of knits of low-to-intermediate extensibility using a hydraulic burst tester. The fabric is held over an expanding diaphragm, and the hydraulic pressure in the diaphragm at the instant of fabric rupture is reported. For knitted fabrics exhibiting high extensibility to failure, the ball burst test is recommended. A polished steel ball is pressed onto a rigidly held circle of knitted fabric. The force on the ball required to rupture the fabric is reported as breaking strength.

Tear Strength and Energy. For flat, sheet-like materials such as woven fabric, films, paper, and leather, the breaking strength of a material in a tensile test is generally stronger than its tear resistance. Although it may be difficult to initiate a tear in any of these materials, once started the tear can usually be propagated using relatively low force. Three basic methods for determining tear strength have historically been used for testing textile fabrics: the tongue tear (ASTM D2261 and D2262), the Elmendorf tear (D1424), and the trapezoid tear (D1117). The tongue and Elmendorf (falling pendulum) methods are generally used for woven fabrics, and the trapezoid method is recommended for nonwoven fabrics. The tongue tear test can be performed on either a CRE-type tester (ASTM D2261) or a CRT-type tester (D2262), although the former is preferred. The trapezoid test method (ASTM D1117) is recommended for determining the tear resistance of nonwoven fabrics.

Snag Resistance. Although knits do not tear easily, they are prone to snagging on sharp, pointed objects. The tendency of a woven and knitted fabric to snag can be measured. Fabric specimens in tubular form are placed on a rotating cylindrical drum, and a mace is allowed to bounce randomly against the rotating specimen. The degree of snagging is evaluated by comparison of the tested specimen with visual standards of fabrics or photographs of fabrics. Resistance to snagging is reported on a scale from 5 (no snagging) to 1 (very severe snagging). A second snag test method is the bean bag snag test. Each fabric specimen is made into a cover for a bean bag, which is randomly tumbled for 100 revolutions in a cylindrical test chamber fitted on its inner surface with rows of pins. Evaluation is similar to that for the mace snag test. For tests performed in simulated situations such as the snag tests, the results are meaningful only if an established correlation exists between performance in the tests and in wear situations. Thus, the acceptable level of performance in the test should not be selected arbitrarily but should be established in actual wear studies (96).

Stretch and Compressional Resilience. The growth and stretch properties of knitted fabrics can be determined according to ASTM D2594. This test is for fabrics intended for applications requiring low power stretch properties. To determine growth (or stretch recovery), the specimen is extended to a specified percentage stretch and held for a prescribed length of time. The specimen is then allowed to recover under zero load. During the recovery period, the specimen length is measured at various time intervals. Fabric stretch is measured by applying a load to a fabric specimen of known length and determining the length of the fabric before and after loading. A similar method, ASTM D3107, has been developed for measuring stretch and stretch recovery of woven fabrics made in whole or in part from stretch yarns. The term stretch yarns refers to thermoplastic filament or spun yarns having a high degree of potential elastic stretch and rapid recovery. These yarns are characterized by a high degree of yarn curl. Resilience of textile fabrics when compressed in the bent state is related to wrinkle resistance and retention of shape, drape, and hand. Resilience is an important parameter for evaluating blankets, wearing apparel in which warmth is a factor, pile fabrics including carpets, and bulk fiber utilization in mattresses, cushions, etc. The general method for determining compressional resilience is to compress and unload the material cyclically, creating a plot of compressive force versus fabric thickness.

3.5. Testing of Pilling, Abrasion and Wear. *Pilling Resistance.* Fabrics containing high strength synthetic fibers, especially in blends with weaker natural fibers, exhibit a tendency for pill formation in varying degrees. The mechanism of pill formation involves breaking of the weaker fibers and entangling of the stronger fibers with some retention of the broken fibers, resulting in small balls of fiber adhering to the fabric surface. Pilling resistance testing involves rubbing the sample against a mildly abrasive surface, followed by visual comparison of the fabric sample to a series of photographic standards representing no pilling (No. 5) to very severe pilling (No. 1). The most common method of testing for pilling resistance is the random tumble method (ASTM D3512), the brush pilling test (ASTM D3511) and elastomeric pad method (ASTM D3514) calls for laundering of the sample, followed by rubbing against an elastomeric pad. Synthetic fiber producers have attempted to minimize the tendency for pilling by several methods, one of which is to reduce polymer molecular weight. The resulting lower strength fiber would break away from the fabric surface more readily. Another method for reducing pilling is to notch or etch the fiber surface either before or after incorporation in fabric form (See also Table 17).

Abrasion and Wear Resistance. Abrasion resistance is generally measured by subjecting the fabric to some type of rubbing action under known conditions of pressure, tension, and abrasive action. The term wear is broader in scope and includes the combined effects of additional factors such as laundering, dry cleaning, ironing, and wearing of apparel. Correlation of laboratory abrasion resistance with general wear resistance is very difficult. More often than not, laboratory testing is useful for predicting the relative abrasion resistance of a series of samples that vary greatly in resistance properties. Resistance to abrasion is affected by such factors as fiber properties, yarn structure, fabric construction, dyes and finishes, as well as test factors such as the nature of the abradant, tension of the specimen, pressure between specimen and abradant, and dimensional changes in the specimen. Depending on the test method, the abradant itself may change over the course of the test. Seven common abrasion test methods are as follows:

Rotary Platform, Double-Head Method (ASTM D3884). Abrasion resistance can be evaluated either by determining the loss in breaking load of the abraded area after a specified number of cycles or by determining the number of cycles required to give specified destruction, eg, color change as based on the AATCC Gray Scale.

Flexing and Abrasion Method (ASTM D3885). This method tests the resistance of woven fabrics to flexing and abrasion. The specimen is subjected to unidirectional reciprocal folding and rubbing over a bar under known conditions of pressure and tension. Resistance to flexing and abrasion is evaluated by determining the number of cycles to rupture the specimen, by comparing the breaking load of the abraded fabric to the breaking load for nonabraded fabric, or by examining the abraded specimen for visual changes to luster, color, napping, pilling, etc.

Inflated Diaphragm Method (ASTM D3886). This method is applicable both to woven and knitted fabrics. The specimen is abraded by rubbing either unidirectionally or multidirectionally against an abradant having specified surface characteristics. The specimen is supported by an inflated rubber diaphragm under a constant pressure. Evaluation of abrasion resistance can be either by determination of the number of cycles required to wear through the center of the fabric completely or by visual examination of the specimens after a specified number of cycles.

Oscillatory Cylinder Method (ASTM D4157). This test is applicable to woven fabrics and measures abrasion resistance by subjecting the specimen to unidirectional rubbing action under known conditions of pressure, tension, and abrasive action. Abrasion resistance may be evaluated either by determining the number of cycles required to rupture the specimen, by comparing the breaking load of the abraded fabric to the breaking load for nonabraded fabric, or by examining the abraded specimen for visual changes to luster, color, napping, pilling, etc.

Uniform Abrasion Method (ASTM D4158). This test is applicable to a wide range of textile fabrics and materials, including floor coverings. Abrasive action is applied uniformly in all directions in the plane of the specimen surface. The test may be run dry or wet. Evaluation is made by comparing initial and final value for various properties, which may be thickness, weight, electrical capacitance, or absorption of beta emission from a radioactive surface. An abrasion curve may be constructed by plotting values for the measured quantity against the number of rotations of the tester.

Martindale Abrasion Tester Method (ASTM D4966). The Martindale tester is used to determine the abrasion resistance of woven or knitted textile fabrics by subjecting the specimen to straight-line rubbing motion, which becomes a gradually widening ellipse, until it forms another straight line in the opposite direction under known conditions of pressure and abrasive action. Evaluation of abrasion resistance is either by determining the number of cycles to break two or more threads on a woven fabric or by causing a hole in a knitted fabric. Change in shade, as evaluated using the AATCC Gray Scale for Color Change, can also be used to determine the end point.

Impeller Tumble or Accelerotor Method (AATCC 93). A fabric specimen is driven by a rotor in a random path so that it repeatedly impinges the walls and abradant liner of the test chamber. The specimen is subjected to flexing, rubbing, shock, compression, stretching, and other mechanical forces during the test. Evaluation of abrasion resistance is based on weight loss of the specimen, loss in breaking load, or changes in various other properties, such as air permeability, light transmission appearance, or hand. The variety of evaluation methods for abrasion resistance testing requires the tester to choose a method to align most closely with the desired performance of the fabric under end-use conditions. Although abrasion to rupture is an easy parameter to measure, unsightliness of a textile garment or other consumer product would precede this stage. Alternative techniques are the measurement of weight loss or the measure of remaining fabric strength after abrasion. However, even these results generally exceed the degree of fabric surface damage objectionable to the consumer. For example, in blended fabrics containing two fibers of slightly varying color shades, preferential wear of one fiber can cause a shade change in the abraded area known as frosting. Therefore, visual observations should be made frequently over the course of testing, and the first detectable appearance changes should be noted. The determination of the point where unacceptable damage to the fabric resulting from abrasion begins to occur is subjective and depends on the judgment of the observer. Thus, abrasion-testing results often show a great deal of variability. Acceptance standards and controls for evaluation of abrasion results have, in many cases, not been estalished. Therefore, acceptability criteria must be determined based on requirements for the specific material and end use. Fiber requirements for high abrasion resistance are low modulus of elasticity, large immediate elastic deflection, high ratio of primary to secondary creep, high magnitude of primary creep, and high rate of creep recovery. Three methods of fiber abrasion are frictional wear, surface cutting, and fiber rupture or slippage. Surface cutting occurs when a fiber is subjected to metal-cutting or grinding, as when a fine abrasive or emery surface is rubbed across a fabric, and is applicable where surface projections of the abrading surface are small relative to fiber diameter (See also Table 17).

3.6. Performance and Chemical Characteristics

Flammability. The terminology relating to the testing of flammability of textile fabrics and the resulting classifications of materials may be somewhat confusing. ASTM D4391 defines standard terminology relating to the burning behavior of textiles. A material may be classified as combustible, flame-resistant, flammable, noncombustible, or nonflammable. Various organizations and government agencies have established test methods for determining flammability and these methods are indexed and described in ASTM D4723. The Consumer Product Safety Commission (CPSC) has defined specifications and test methods for clothing and textiles, including 16 CFR 1610 for general wearing apparel; 16 CFR 1615 for children's sleepwear, sizes 0 through 6X; 16 CFR 1616 for children's sleepwear, sizes 7 through 14; and 16 CFR 1630 for carpets and rugs. In addition to the conventional methods for determining flammability of the fabric itself, some laboratories are using techniques for studying the thermal protection afforded by a garment. A few research laboratories are equipped with mannequins containing heat sensors to provide a temperature profile when the garment covering the mannequin is exposed directly to flames representing flash fire conditions. Garments tested in this manner are generally made of high performance fibers such as Nomex (DuPont) and are designed for use by the military, race car drivers, or firefighters. (See also able 18).

Laundering Shrinkage (Dimensional Instability). Shrinkage, often a result of laundering textile fabrics, can be of three types: relaxation, swelling, or felting. Relaxation shrinkage occurs when a fabric that has been finished in a stretched state is exposed to heat and/or moisture and allowed to relax. Swelling shrinkage may occur when a fabric that is composed of hydrophilic fibers is soaked in water, resulting in the increase of fiber diameter relative to the fiber length. Because hydrophobic fibers do not swell in water, they do not shrink by this mechanism when laundered. Hydrophobic fibers are much more susceptible to relaxation shrinkage. Felting shrinkage is associated exclusively with wool and other animal hair fibers and is characterized by a continued reduction in fabric area and increase in fabric density. Felting is caused by a combination of heat, moisture, and mechanical motion during aqueous washing. Five AATCC methods are described for determining the dimensional stability of fabrics and garments (AATCC 135, 150, 96, 158, 99) (See also Table 18).

Thermal Transmission. Thermal transmission of a fabric is an important property affecting the comfort of a garment made from that fabric. Dry heat transfer can be by conduction, convection, or radiation. As related to comfort, heat transfer can also occur by evaporative heat loss from sweating skin. Thermal transmittance is defined as the overall heat transfer through a fabric resulting from a combination of the three mechanisms for dry heat transfer (97). Because the convection mechanism is based on the transport of heat by moving air or liquids, the insulating properties of a textile fabric are therefore improved by creating dead air spaces between and within fabric layers to reduce heat transfer by convection (98). Increasing fabric thickness can also reduce heat transfer. Although fabric thickness correlates well with thermal insulation, fabric weight per unit area shows almost no correlation to this property. Thus, the fabric's ability to maintain its thickness under conditions of compression, tension, bending, laundering, dry cleaning, and wear can affect its insulative properties under conditions of use. One additional factor is fabric density. Two fabrics may have the same thickness and, hence, the same thermal conductivity, but to obtain such equal thickness, different weights of fiber may be needed. Thus, aggregates of different fibers may have different bulk densities, and on this weight basis one fiber may exhibit a thermal insulating advantage over another. Thermal conductivity of a fabric is related to its air permeability, or movement of air between the interstices of the yarn and fabric. For fabrics of a given thickness, the one that has greater air permeability allows greater heat dissipation by convection. Thus thermal insulation falls as air velocity rises. A guarded hot-plate method, ASTM D1518, is used to measure the rate of heat transfer over time from a warm metal plate.

Water Repellency and Water Resistance. Water repellency is defined as the ability of a textile fiber, yarn, or fabric to resist wetting, whereas water resistance is a general term applied to a fabric's ability to resist wetting and penetration by water (2). A third term, waterproof, is applied to those fabrics that do not allow any water penetration at all. Waterproof fabrics are generally coated with an impermeable surface layer that does not allow air permeability. Water-repellent finishes are hydrophobic compounds that are applied to fabrics to inhibit water penetration while still allowing air permeability. AATCC methods for determining water repellency are AATCC 22 (spray test) and AATCC 70 (tumble jar dynamic absorption test). In the spray test, water is sprayed against the taut surface of the test specimen to produce a wetted pattern the size of which depends on the repellency of the fabric. Evaluation is by comparing the pattern with a series of patterns on a standard chart. The latter method evaluates the percentage by weight of water absorbed by a sample after dynamic exposure to water for a specified period of time. Water resistance test methods include AATCC 127 (hydrostatic pressure test), AATCC 42 (impact penetration test), and AATCC 35 (rain test). In the hydrostatic pressure test, a sample is subjected to a column of increasing water pressure until leakage occurs. The impact penetration test requires water to be sprayed on the taut surface of a fabric sample from a height of two feet. The fabric is backed by a blotter of predetermined weight, which is reweighed after water penetration. The rain test is similar in principle to the impact penetration test.

Color, Colorfastness, and Lightfastness. Spectrophotometers are commonly used to quantify color shade and intensity. White light impinged on the surface of a dyed fabric causes light of a specific wavelength to be absorbed or reflected, depending on the properties of the chromopores in the dye. The reflected light passes through a prism and is measured by a photoelectric cell. A plot of reflectance (or absorbance) versus wavelength results. Although this curve is adequate to define quantitatively any color, the transmission of these plots from customer to dye house is difficult. However, it is possible to define a color by comparing the intensities of the three reflected primary colors, ie, red, green, and blue. Thus, a system of tristimulus values allows the storage and transmission of color data. Dyestuff manufacturers list these tristimulus values for each of their dyes as measured for fabrics of specific fiber content, allowing the dyer to approximate closely the desired color. Final adjustment should still be made by a human eye skilled in shade matching. The science of color measurement has been explored by various authors (99,100). AATCC evaluation procedure no. 6 describes a method for instrumental measurement of color of a textile fabric. AATCC evaluation procedure no. 7 may be used to determine the color difference between two fabrics of a similar shade. Instrumentation may be either a spectrophotometer for measuring reflectance versus wavelength, or a colorimeter for measuring tristimulus values under specified illumination. If a spectrophotometer is used, however, the instrument must be equipped with tristimulus integrators capable of producing data in terms of CIE X, Y, and Z tristimulus values. Another test method applicable to textiles is ASTM E313, Indexes of Whiteness and Yellowness of Near-White, Opaque Materials. The method is based on obtaining G, ie, green reflectance, and B, ie, blue reflectance, from X, Y, and Z tristimulus values. Whiteness and yellowness indices are then calculated from the G and B values. This method has particular applicability to measurement of whiteness of bleached textiles. AATCC test method 110 also addresses measurement of the whiteness of textiles.

A variety of test methods exist for determining the fastness, or color retention, properties of dyed fabric exposed to various conditions of weathering, laundering, or general exposure associated with the end use of the product. The AATCC Technical Manual should be consulted for the applicable test method for the expected exposure of the sample. Fastness to acids and alkalies, bleaching, gas fumes, crocking, dry cleaning, heat, light, perspiration, washing (laundering), seawater, and numerous other conditions can be determined according to AATCC methods. Four of the most common types of colorfastness tests are described below. Evaluation of the results is generally performed by visual comparison of the exposed samples to the unexposed against the AATCC Gray Scale for Color Change.

AATCC test method no. 16 describes various techniques for measuring lightfastness of textiles. Exposure can be directly to the sun through glass or by an accelerated method using a carbon-arc or xenon light source. The xenon light source is the most commonly used accelerated exposure type, has a spectral distribution similar to sunlight, and gives better correlation with direct sunlight than the carbon-arc lamp (See also Table 18).

Laundering Fastness: Colorfastness to laundering (washing) under various conditions of temperature, bleaching, and abrasive action is determined according to AATCC test method no. 61. A Launder-Ometer or other apparatus for rotating closed containers in a thermostatically controlled water bath is required.

Abrasive action: It is accomplished by the use of a low liquor ratio and an appropriate number of steel balls enclosed with the sample in a cylindrical container. Samples are sewn to a multifiber test fabric, and the color change of both fabrics after laundering is evaluated using an appropriate color change scale.

Gas Fading: Many dyes used in textiles, particularly disperse dyes on acetate, triacetate, and polyester, will fade on exposure to oxides of nitrogen derived from the combustion of illuminating or heating gas. Gas fading can also occur in some sensitive resin-bonded pigments applied to cotton fabrics. AATCC test method no. 23 describes a method for exposure of test specimens and a control fabric to oxides of nitrogen until the control shows a change in color corresponding to that of the standard of fading. The test specimen is then examined for fading. If none is observed, the cycle is repeated until fading is obvious. The specimen is then ranked according to the number of exposures required to produce a shade change and the change in color according to the AATCC gray scale.

Fastness to Crocking: Crocking is defined as the transfer of color from the surface of a dyed fabric to another surface by rubbing. AATCC test method no. 8 is a method by which a colored test fabric swatch is fastened to the base of a Crockmeter and rubbed against a white crock test cloth under controlled conditions. Color transfer to the white cloth is evaluated by comparison with the AATCC Chromatic Transference Scale. A similar method, AATCC 116, uses a Rotary Vertical Crockmeter, which requires a smaller area of test fabric than the Crockmeter.

Soil Redeposition and Soil Release. Hydrophobic synthetic fibers have affinity for oily materials and therefore attract oily soils to a greater extent than natural fibers and hydrophilic synthetic fibers. To promote release during laundering of oily stains, a number of soil-release and whiteness-retention finishes have been developed. Two factors are involved in evaluating the soiling characteristics of fabrics: the amount of soil that can be deposited on a fabric during laundering, and the ease with which soil can be removed during laundering. Several AATCC methods exist to evaluate soil release of fabrics. AATCC test method no. 130 measures a fabric's ability to release oily stains during laundering by using a weight to force a stain into a fabric and then rating the residual stain after laundering by comparison with a standard replica. AATCC test methods no. 151 measure a fabric's resistance to soil re-deposition during laundering using a launder-ometer and a terg-o-tometer, respectively; the latter is a more accelerated test. This method evaluates soil edeposition by measuring the change in reflectance of the samples. Carpet soiling can be evaluated by AATCC 121, 122, and 123. Method no. 121 describes a procedure for visually rating degrees of cleanness in floor coverings; 122 involves subjecting carpets to foot traffic; and 123 is an accelerated laboratory procedure for tumbling carpet samples and a prepared synthetic soil in a ball mill, followed by evaluation by the visual rating method. The cross-sections of many carpet fibers, eg, trilobal or internal voids, are designed to hide soil, so carpet appearance does not always correlate with the amount of dirt present in the carpet (See also Table 18).

3.7. Subjective Tests. *Fabric Hand or Handle.* Fabric handle is somewhat difficult to define, although the term generally refers to properties such as draping quality, fullness, or stiffness (95). ASTM D123 defines a list of eight terms relating to fabric properties that make up the components of the general term, hand. These properties are flexibility, compressibility, extensibility, resilience, density, surface contour, surface friction, and thermal character (98). AATCC Evaluation Procedure no. 5 also provides guidelines for subjective evaluation of hand properties. Although the description of fabric handle may rely on subjective terms, several methods exist to quantify the stiffness of a fabric. ASTM D1388 is used to measure the flexural rigidity and bending length of a woven fabric by calculating its resistance to bending under its own weight.

The cantilever test is the preferred method for this ASTM procedure, in which a strip of fabric is slid in a direction parallel to its long dimension so that the fabric end projects from the end of a horizontal surface. The length of overhang is measured when the tip of the specimen is depressed under its own weight to the point where the line joining the tip to the edge of the platform makes an angle of 41.5°. with the horizontal. The bending length is defined as one-half the length of overhang. Bending length is related to the drape stiffness of the fabric. Flexural rigidity is defined as the cube of the bending length multiplied by the fabric weight per unit area. A fabric having a higher flexural rigidity is stiffer. A second method, ASTM D4032, is a circular bend stiffness test, in which a fabric specimen is forced through a circular opening 1.5 in. in diameter by a plunger that is 1 in. in diameter. The maximum force to push the fabric through the opening is determined. This method is a good indicator of the three-dimensional bending stiffness of a woven, knitted, or nonwoven fabric (98). Years of development have led to a standardized system for objective evaluation of fabric hand (98). This, the Kawabata evaluation system (KES), consists of four basic testing machines: a tensile and shear tester, a bending tester, a compression tester, and a surface tester for measuring friction and surface roughness. To complete the evaluation, fabric weight and thickness are determined. The measurements result in 16 different hand parameters or characteristic values, which have been correlated to appraisals of fabric hand by panels of experts (98). Translation formulae, have also been developed based on required levels of each hand property for specific end uses (101). The properties include stiffness, smoothness, and fullness levels as well as the total hand value. In more recent years, abundant research has been documented concerning hand assessment (102–105).

Drape. Drape is closely related to fabric hand. Whereas hand is based on tactile criteria, drape refers more to a fabric's appearance by its tendency to fall into graceful, three-dimensional folds. Fabric drape depends to a large degree on the same properties that influence hand, ie, flexural rigidity, thickness, and compressibility. Although stiffness is normally measured in a single direction, drape implies bending in all directions. Drape can be measured by placing a circular fabric specimen over a round table or pedestal and viewing from directly overhead. A drape coefficient is defined as the ratio of the area of the fabric's actual shadow to the area of the shadow if the fabric were rigid. Drape is closely related to stiffness: the drape coefficient for a stiff fabric approaches a value of 1; a limp fabric has a drape coefficient near 0. The Cusick drape tester is an example of this type of measurement. For this method, the relative weights of paper rings representing tracings of the fabric's shadows are used to calculate drape coefficient.

Crease Retention, Wrinkle Resistance, and Durable Press. On bending or creasing of a textile material, the external portion of each filament in the yarn is placed under tension, and the internal portion is placed in compression. Thus, the wrinkle-recovery properties must be governed in part by the inherent, tensional elastic deformation and recovery properties of the fibers. In addition to the inherent fiber properties, the yarn and fabric geometry must be considered. AATCC Test Method no. 66 describes measurement of recovery angle after placing a crease in a specimen. The specimen is creased by subjecting is to a prescribed load for a length of time. The recovery angle is then measured after a controlled recovery period. Recovery angles of an angle of 120° are considered to indicate good wrinkle resistance (98). Because wrinkle resistance is particularly important for summer clothing, the AATCC stipulates that recovery angles be measured at 90% as well as 65% relative humidity. The former is considered to represent the most humid condition to which apparel textiles may be subjected in summer.

Fabrics that have been given durable-press or permanent-press finishes are generally treated with an uncured resin. In the post-cure process, curing is done by the garment maker to set the garment in the desired configuration. In the pre-cure process, the fabric is cured prior to garment manufacture. Although the latter process does not result in permanent pleats, the smoothness of the cured fabric is retained during wear and laundering. Thus, durable-press goods are tested for recovery angle under both wet and dry conditions. A second wrinkle-recovery test, AATCC test method no. 128, describes the determination of the appearance of textile fabrics after intentional wrinkling followed by evaluation of appearance in comparison to standard replicas. A visual rating from 1 (wrinkled) to 5 (smooth) is assigned. This method may be used for both woven and knitted fabrics, whereas the recovery angle method is applicable only to woven fabrics.

Appearance After Laundering. The extent to which permanent-press fabrics retain smoothness after laundering is determined by conducting a series of tests devised by AATCC: 143 for appearance of apparel and other textile end products after repeated home laundering; 124 for appearance of durable press fabrics after repeated home laundering; as well as 88C and 88B for appearance of wash-and-wear items, including creases after home laundering and seams after home laundering. In each of these tests, the specimens are subjected to standard procedures simulating home-laundering conditions. A choice is provided for alternative washing temperatures and drying procedures to conform with care instructions recommended for the fabric or final garment. Evaluation is performed by visual comparison with standards prepared by AATCC under prescribed lighting; five grades from very poor to excellent can be assigned.

Luster. Luster is defined as the amount of light reflected from a fabric at different angles. It depends on fiber, yarn, and fabric geometries which control the regularity of the fabric surface. The greater the degree of parallelization of fibers in yarns and yarns in fabrics is, the greater the luster. Luster is also affected by fiber cross-sectional shape and, in synthetic fibers, the addition of delustrants, eg, titanium dioxide. Luster can be evaluated quantitatively by measuring light reflectance and the angle of the reflected light, but visual observation is necessary for a complete appraisal of luster. In general, a fabric having a smooth flat surface shows higher luster than a fabric having a rough surface and loose fibers. The more irregular the surface of the fabric is, the greater the degree of scatter of reflected light.

Comfort. In the past, the evaluation of fabric or garment comfort has been a subjective process influenced by such variables as temperature, insulating efficiency, moisture absorption, drying speed, softness, bulk, fabric construction, and air permeability. Human factors must also be considered. To predict the comfort of a material, a combination of hand evaluation, eg, using the (Late) Kawabata system, as well as determination of the heat and moisture transport properties, is necessary. Often, these values are correlated with a sensory evaluation of the tactile qualities of the material by a human subject panel. A thorough discussion of the many physical and psychological factors affecting comfort is available (106,107).

4. Fiber-to-Fabric Production, Processing and Testing of Cotton

Cotton is one of the oldest natural fibers and continues to be the one of the most commonly used fibers today. About 85 countries grow cotton and produce about 115 million bales (480 pounds net each) of lint cotton annually, which is used by almost all the countries of the world to produce various textiles. Although cotton has recently been losing its market share to other textile fibers, it still represents approximately 35% of the world consumption of all fibers. Cotton grows on a seed pod boll that grows on a gossypium plant in a warm climate. Cotton bolls are harvested (picked) mechanically in the U.S., although manual picking is most common in other countries. Cotton fibers (lint) are separated from the seed pods in a ginning process at a gin, which generally is located away from the cotton fields. The byproducts of a ginning process are linters (very short cotton fibers) and cotton seeds. The worldwide cotton production in 2005 crop year was about 115 million bales of approximately 480 pounds each. China, the U.S., Russia, India, Pakistan, Brazil and Turkey, in that order, are the major cotton producing countries, producing about 80% of the world production. The United States is the second largest producer of cotton (23.3 millions of 480-lb bales almost 20% of the world cotton production) and the largest exporter (14 millions of 480 lb bales) of high quality cotton in the world (108). Texas, California, Mississippi and Arizona are the major cotton producing states. Cotton is a versatile fiber which is used in many textile products for apparel, household, furnishing, industrial, military and medical applications. Perhaps, it is the only fiber that easily absorbs moisture, transports the moisture through its capillary action, and quickly dissipates it to the outside atmosphere. It is this peculiar characteristic of cotton, which makes it so-called "*breathable*" and, thus, provides comfort to the wearer. It is an excellent substrate in dyeing and finishing and thus ideally suitable for apparel and household textiles. However, the fiber is often blended with manufactured fibers to produce fabrics that are stronger and more resilient and crease-resistant than equivalent 100% cotton fabrics.

In this section the most popular terminology used in cotton production and processing is described, highlighting the relevant textile testing practices used. A flow chart of manufacturing cotton-based fabrics is shown in Figure 3. The related terminologies and relevant testing practices are summarized below.

4.1. Harvesting/Picking. Cotton is harvested and picked in cotton fields. In the U.S., almost all cotton now is machine picked, while it is mostly hand picked in the rest of the world.

Testing. Productivity is measured by the yield (typically 2 bales per acre) of picked cotton per acre of land. Quality of picked cotton is subjectively assessed by the visual inspection of foreign matter content, such as the plant leaves, stems, branches, bark, trash, etc.

4.2. Ginning. It is a mechanical process of separating cotton fibers (lint) from the seeds and simultaneously cleaning the fibers to a certain degree by removing the foreign matter. Ginned cotton, or the so-called lint, is hard compressed into a bale of 480 lb net.

Testing. Every ginning mill in the U.S. must send a test sample of cotton, from each bale produced, to a USDA facility for conducting fiber quality measurements, in order to determine the cotton grade, which subsequently determines the marketing price (and any subsidy) for the cotton. Major fiber properties tested are the length, strength, maturity, trash, and color. Today, the average price of cotton is about \$ 0.65 per pound. For decades, it has been fluctuating between \$ 0.45 to a dollar per pound.

4.3. Lay-down, Mixing, Opening and Cleaning. Physical attributes of cotton fibers vary considerably from boll to boll, from crop to crop, from bale to bale, and even within a bale. Appropriate lay-down of bales and subsequent mixing of fibers enhance uniformity of the input material and consequently of the end product. Opening and cleaning of a cotton mix with different types and numbers of machines (beating/cleaning points) loosen fiber tufts and removes large particles of foreign matter as well as very short fibers (linters).

Testing. There are no specific quality tests in this particular processing area, although the trash removed is monitored to assess effectiveness of the process.

4.4. Carding. The somewhat opened and cleaned cotton from the opening/cleaning line is chute fed to a card. Carding is a process for further fine opening and cleaning of cotton and for parallelizing the fibers and converting them into a consolidated sliver of continuous length.

Testing. Number of neps in the card web (web NEP count) and the various wastes removed from the card determine effectiveness of the carding process. Linear density and uniformity (unevenness) of the output sliver generally are quality controls.

4.5. Drawing. Drawing is a process to further enhance uniformity of the card sliver by combining 6 to 12 card slivers and drawing them with a draft (stretch) of 6 to 12, in order to “average out” any irregularities in the input card slivers.

Testing. Measurements of linear density and uniformity of the output sliver are typical quality controls.

4.6. Combing. Combing is a process of removing (15–20%) short fibers from carded cotton stock (lap) to produce a sliver of long and parallel fibers, which ultimately produces a smooth, lustrous cotton fabric of premier quality and, of course, price.

Testing. A combed sliver is also tested for its linear density and uniformity.

4.7. Spinning. Spinning (rotor, ring, air-jet/vortex, friction, and tandem) is a process of converting cotton fibers (in a sliver or a roving form) into a strong, continuous strand (yarn) of much lesser diameter and linear density, compared to the input material. Basically, a yarn is an integrated structure of fibrous material that has been twisted to impart intrafiber cohesion and hence strength. Today, there are many spinning systems available. The selection or deployment of a spinning system for a particular fiber largely depends on the type of fiber and the type of end product. For ring spinning, an extra process for making a roving (much lighter than a sliver) is necessary. The yarn properties vary with the fiber and the spinning system used. Almost all modern spinning systems utilize a sliver and produce yarns at much greater production rates than ring spinning. However, unique all-staple core-wrap bicomponent yarns of truly co-axial configuration and significantly improved properties can be produced on modified ring spinning systems (109–111). Tandem Spinning is a new high-speed system, which produces integrated bicomponent (core-wrap) yarns of unique physical and mechanical properties (112). Efficiency of a spinning system is mainly influenced by the frequency of ends down (yarn breakage or any other failure) per unit time or production.

Testing. Yarn quality inspection and testing include: Appearance (with the standards); defects (major and minor slubs, snarls, bad splice/knot etc); imperfections (thin and thick places and neps, per unit length, usually 1000 m); tensile breaking strength and elongation (%); linear density, count or size, and their statistical variations.

4.8. Winding, Warping, and Sizing. Winding is a preparatory process for preparing yarn for weaving or knitting. In this process, small packages of the yarn as spun are wound onto a relatively much larger package, while simultaneously 'clearing' the yarn by removing its major defects and also lubricating it with a lubricant/wax, if necessary especially for knitting. The warping and sizing are two independent processes for preparing warp yarns for weaving. Depending on construction of the desired fabric, a number of warp beams are prepared on a warping machine (warper). Each warp beam may have several hundred individual warp yarns/strands. These beams, generally 10 to 20 in number, are placed in a creel of a slasher (sizing machine). The yarns from all of these beams are assembled and sized, ie, coated with a thin film of chemical formulation of an adhesive (starch, CMC, PVA, acrylics, etc), dried and wound onto a loom beam that is ready for looming and weaving. Packing Density (Rockwell) and Build of the packages are normal quality controls in the winding process. *Warping machine stoppages due to broken or failed yarn strands provide the major quality and/or production assessments.*

Testing. Warp sizing is a costly, complex, and environmentally sensitive process and requires quite a few indigenous/local tests and precautions to ensure preparation of a good loom beam with uniform size-add-on, drying, winding tension/stretch and moisture regain throughout the entire loom beam; parallel yarn strands with no crossed ends, etc.

A Recent Important Development. It may be worthwhile to mention here that the size formulation added to the warp in the sizing operation must be completely removed from the greige woven fabric at the first instance. The process of removing size is termed desizing. Although warp sizing and subsequent fabric desizing are the centuries-old, traditional processes, they (no both) really are costly, complex and environmentally sensitive. The textile industry certainly likes to eliminate warp sizing, if at all possible. Recent research conducted at USDA-ARS on weaving cotton fabrics with reduced or preferably without warp sizing has demonstrated that the so-called *size-free weaving* is at least mechanically feasible. For the first time ever, hundreds of meters of 100% cotton, 2/1-twill fabrics of relatively low weight and construction have been woven with no yarn breakage or failure on a conventional fly-shuttle loom as well as on a modern high-speed weaving machine - both operating under almost mill-like conditions. Although this indeed is a pioneering development and a significant milestone in textile manufacturing, the fabric quality still is not satisfactory. The fabric has numerous tiny soft-ball-like fibrous defects on its surface. Efforts to eliminate fabric defects in size-free weaving are underway (113–114).

4.9. Weaving. (Weaving is Done by the Factoring: flexible-rapier, air-jet, water-jet, and missile weaving machines and the traditional fly-shuttle loom). Weaving is a process of converting yarns into a woven fabric. It may be done on a modern high-speed rapier (flexible or rigid), air-jet, water-jet, or missile weaving machine, or on a conventional fly-shuttle loom. Weaving involves two sets of yarns, namely warp and filling or weft. Woven fabrics are made of different width, fiber content, construction, weave, weight and appearance. Although there are many types of weaves and their derivatives, only three are the basic ones, which account for the bulk (probably 80%) of weaving, worldwide. Those basic weaves are:

1 *Plain weave* (1 up and 1 down) is the most commonly used weave. However, it has quite a few derivatives, such as Warp Rib (Oxford), Weft Rib, and Basket Weave Hopsacking.
2 *Twill weaves* are formed when each warp or filling yarn floats over two or more filling or warp yarns with a progression of interlacing by one to the right or left to form a pronounced, wale-like diagonal line. Twill weave also has a number of derivatives, such as 1/2 - 2/2 - 1/3- 4/5 regular twills, several irregular twills, and some elaborate diamond weaves.
3 *Satin and sateen weaves* have long floats and hence are relatively easier to weave. In these weaves, each warp or filling yarn floats across generally four filling or warp yarns with a progression of interlacing by two to the right or left. Regular warp satin and weft sateen complete a repeat on odd number of ends, ie, 4/1 and 1/4, while irregular satins and sateens repeat on even number of ends, ie, 4, 6, 8,. . ..

Today, there are many types of weaving machines that give much higher production rates, compared to convention fly-shuttle looms. However, they do require high quality of warp and filling yarns, in order to minimize yarn breakages or failures that cause relatively more expensive machine stoppages and hence production interruptions.

Testing. The production efficiency, defects, width and construction of greige fabrics are typical process controls.

4.10. Knitting. Knitting is an alternative process of producing a fabric from a yarn. Unlike weaving, a fabric can be (weft) knitted from a single set of yarn and even from a single yarn package. However, warp knitting may require a separate warp beam, as well. Knitting productivity generally is about 5 times greater than that of weaving. However, the knit structures are not as stable as woven structures. They generally are loose and thus shrink on laundering. Hosiery (ie, socks, undergarments, etc) is a big knitting industry.

Testing. Generally, the fabric productivity and quality controls in knitting are similar to those in weaving industry.

4.11. Wet Processing and Finishing of Fabrics. Since the warp sizing agents in a fabric can adversely affect the latter's finishing processes and quality, it is imperative that the sizing ingredients are completely removed at the first opportunity available. Thus, the boil-off, desizing and scouring are the initial wet processes for removing the size and foreign matter/contaminants, (i.e., waxes, oil stains, sugars, etc.) from a greige woven fabric.

Testing. A finished fabric is tested for fabric construction (in order, to comply with the customer's requirements), tensile strength, tear strength (durability), dimensional stability, color fastness, defects, appearance, hand, etc, before and after a certain number of laundering cycles, usually 5 to 10. Chemical finishing of fabric generally consists of: Bleaching; dyeing/printing; and any special finishing (ie, flame-retardancy, crease-resistance/Durable-Press (DP), antimicrobial, mildew resistance, and the like). The bleached fabric usually is examined for its whiteness and any strength loss.

4.12. Cotton Nonwovens. Utilization of cotton in nonwovens is still very limited. Cotton's market share in nonwovens presently is approximately 4% of the world market, which mostly consumes manufactured fibers. However, because of cotton's high absorbency and biodegradability features, its utilization is growing in certain applications, such as medical textiles, pads, wipes and diapers.

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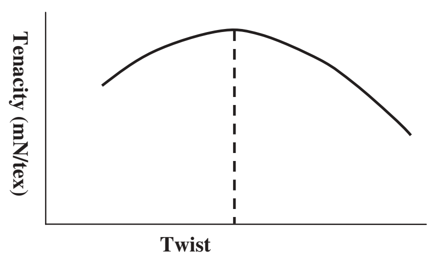

Fig. 1. Effect of twist on the yarn strength (85).

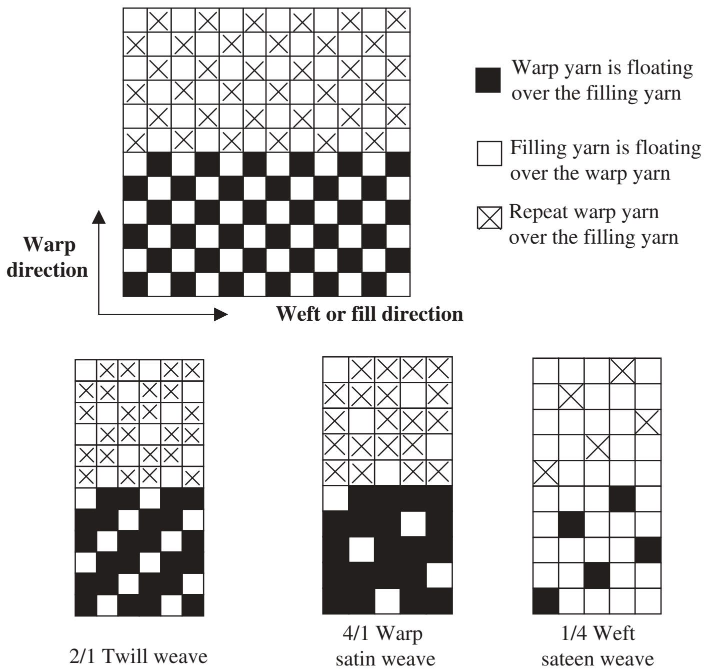

Fig. 2. Basic weaves or structures of woven fabrics.

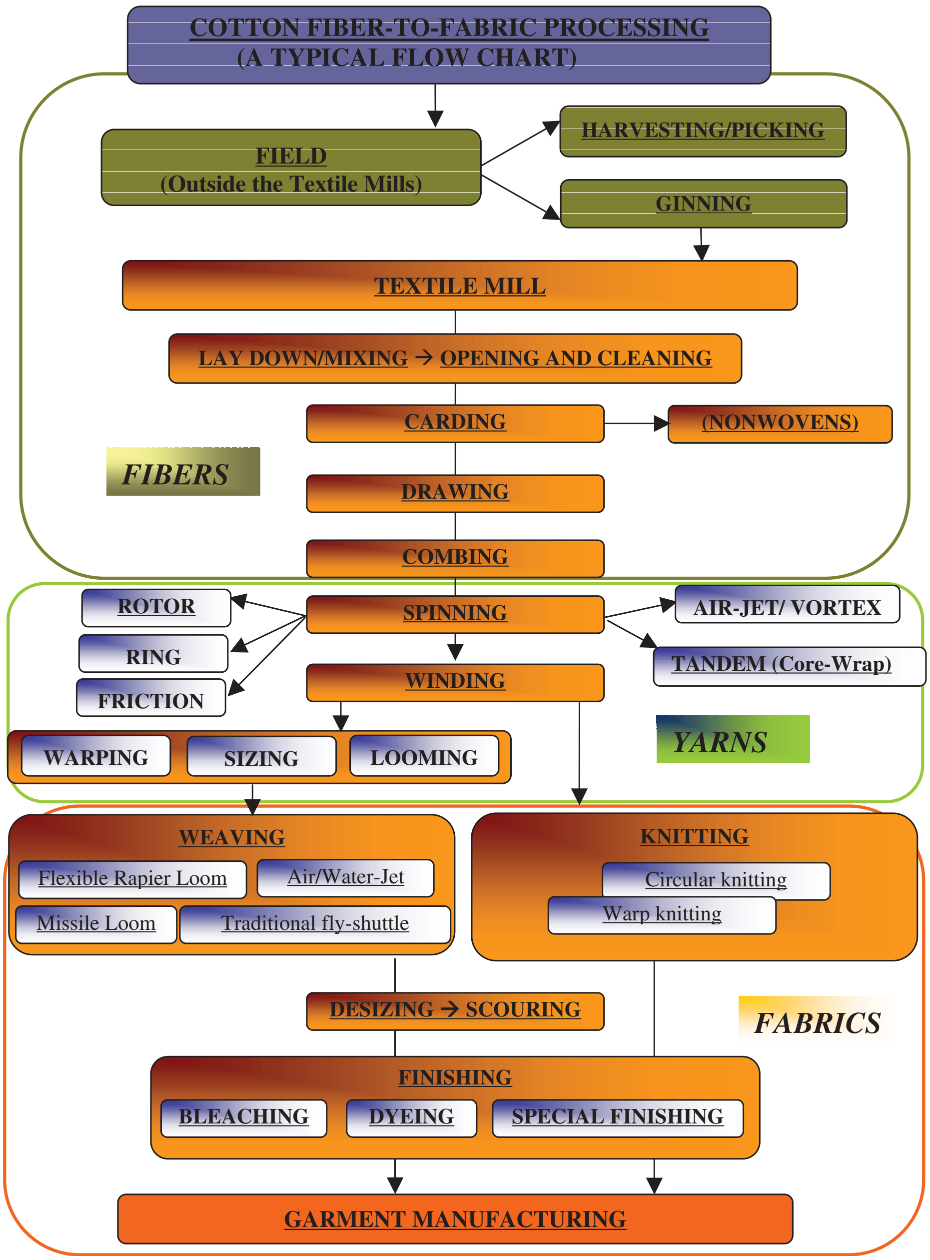

Fig. 3. Flow chart of a representative cotton textile production process.

Table 1. **Representative Physical Properties of Some Commonly Used Textile Fibers**[a,b]

Properties → Fiber types ↓	Diameter	Fiber length (inches)	Density (g/cm3)	Breaking tenacity (g/denier)		Moisture regain (%)	Elastic recovery (%)	Fiber stiffness (g/denier)
				Dry	Wet			
cotton	12–20 μm	0.75–1.75	1.54	3.0–5.0	3.3–6.4	7–11	74	57–60
wool	17–40 μm	1.0–15	1.30–1.32	1.0–1.7	0.8–1.6	~15	99	3.9
silk		900–1200 m	1.25	2.4–5.1	1.8–4.2	10–11	92	
nylon	1.5– 6 den (as desired)	1.5–3.0 (as desired)	1.14	2.5–9.5	2.0–8.2	4.0–4.5	100	5–60
polyester	0.5 den (as desired)	1.5–3.0 (as desired)	1.22, 1.38	2.2–9.5	2.2–9.5	0.4–0.6		6–80
polyethylene	(as desired)	1.5–3.0 (as desired)	0.92–96	1.0–8.0	1.0–8.0	0	100	18–60
Kevlar (aramid fiber)	(as desired)	(as desired)	1.38	18–26.5	17–25.0	1.2–4.3	100	
glass	2–10 μm	(as desired)	2.45–2.55	9–15.3	9–15.3	0		310–380
acetate	(as desired)	(as desired)	1.32	1.1–1.5	0.8–1.0	3–6	~65	3.5–5.5
rayon	2–3 den (as desired)	1.5–3.0 (as desired)	1.51	1.0–6.5	0.5–4.3	11–14	~75	6–50
spandex	(as desired)	(as desired)	1.20–1.41	0.5–1.5	–	0–1.3	100	0.11–0.16

[a] Refs. 6–12 TFN.

[b] Note: Besides the constituent fiber's properties, the yarn and fabric structures and the applications of special chemical, thermal, or mechanical finishes that the fabrics generally undergo also influence performance of the end-products.

Table 2. **Standard Test Methods for Evaluating Fiber Length and its Distribution**

Test number	Test method
ASTM D 1234	for length (greased wool and other animal hair fibers)
ASTM D 1440	for length and length distribution (cotton fibers: Array Method)
ASTM D 1445	for breaking strength and elongation of cotton fibers
ASTM D 1447	for length and length distribution (natural fibers: fibrograph)
ASTM D 1575	for length and length distribution (wool)
ASTM D 3660	for length and length distribution (synthetic staple)
ASTM D 5103	for length and length distribution (natural and synthetic fibers)
ASTM D 5332	for length and length distribution (natural fibers: AL-101)
ASTM D 4604	for length and length distribution (HVIFIS)
ASTM D 4605	for length and length distribution (spinlab system HVI).

Table 3. **Standard Test Methods for Evaluating Fineness, Linear Density, Shape of Fibers**[a]

Test number	Test method
ASTM D 276	for determining fiber density
ASTM D 861-01A	practice to designate linear density of fibers, yarn intermediates, and yarns
ASTM D 1448	for linear density and fineness (micronaire for cotton)
ASTM D 3818	for linear density and fineness (IIC-Shirley maturity tester for cotton)
ASTM D 4604,5	for linear density and fineness, using High Volume Instruments (HVI)
ASTM D 1282	for linear density and fineness (Port-Arwira fiber fineness meter:wool)
ASTM D 1577	for determining linear density of textile fibers using a vibroscope
ASTM D 2130	for average fiber diameter, using microprojection (wool, hairs)
ASTM D 629	for determining fiber diameter and shapes, using microscopic analysis.

[a]Ref. 28.

Table 4. **Standard Test Methods for Evaluating Crimp, Moisture, Color and Shrinkage in Fibers**

Test number	Test method
ASTM D 3937-01	for crimp frequency of manufactured staple fibers
ASTM D 1774	to determine amount of crimp in textile fibers
ASTM D 2612	to measure the cohesive/frictional force in the drafting of sliver
ASTM D 2654-89	for measuring moisture in textiles
ASTM D 2462	for determining moisture specifically in wool
ASTM D 4920−98R03	terminology relating to moisture in textiles
ASTM D 1576−90R01	for moisture in wool by oven-drying
ASTM D 1909-04	table of commercial moisture regains for textile fibers
ASTM D 2118-05	practice for assigning a standard commercial moisture content for wool test
ASTM D 2495-01	method for moisture in cotton by oven-drying
ASTM D 2525-90R01	practice for sampling wool for moisture
ASTM D 6961-03	for color measurement of flax fiber
ASTM D 2102	for measuring shrinkage of a bundle of crimped or noncrimped fibers
ASTM D 5104	for measuring the shrinkage of crimped and noncrimped single fibers

Table 5. **Standard Test Methods for Evaluating the Mechanical Properties of Fibers**

Test number	Test method
ASTM D 76	for fiber tensile testing
ASTM D 1445	for fiber bundle strength (incline-plane and pendulum-type machines)
ASTM D 1294-05	for tensile strength and breaking tenacity of wool fiber bundles
ASTM D 3822	for measuring stress-strain parameters
ASTM D 2101	for measuring stress-strain parameters
ASTM D 1774	for measuring elastic recovery, and permanent set of fibers
ASTM D 4604	for measuring fiber bundle strength
ASTM D 3217	for measuring the loop and knot strengths

Table 6. **Standard Test Methods for Important Fiber Properties**

Test number	Test method
ASTM D 2612	to measure the cohesive/frictional force in the drafting of fibers
ASTM D 276	to measure the optical properties of fibers by light microscopy
ASTM D 276	the fiber melting point
ASTM D 4238	to measure electrostatic propensity of textiles
AATCC 84-1960	to measure the electrical resistivity of yarns
ASTM G 23-25	general practice to evaluate sunlight aging of textile materials
ASTM D 7024-04	for steady state and dynamic thermal performance of textile materials
ASTM D 1518	for thermal transmittance of textile materials
ASTM D 7140-05	to measure heat transfer through textile thermal barrier materials
ASTM D 5866-05	for Neps in Cotton Fibers (AFIS-N Instrument)
ASTM D 5867-05	for measurement of physical properties of cotton fibers by HVI
ASTM D 7139-05	terminology for cotton fibers
AATCC 20, 20 (A)	for qualitative and quantitative identification of textile fibers

Table 7. **Yarn Size and Conversion Table**

	Cotton count (CC)	Worsted count (WdC)	Wood count (Wc)	denier (den)	tex
cotton count (CC)	—	$1.5 \times CC$	$52.5 \times CC$	$\frac{5315}{CC}$	$\frac{590.5}{CC}$
worseted count (WdC)	$\frac{WdC}{1.5}$	—	$35 \times WdC$	$\frac{7972}{WdC}$	$\frac{885.8}{WdC}$
wool count (WC)	$\frac{WC}{52.5}$	$\frac{WC}{35}$	—	$\frac{279030}{WC}$	$\frac{3100}{WC}$
denier (den)	$\frac{5315}{den}$	$\frac{7972}{den}$	$\frac{279030}{den}$	—	$\frac{den}{9}$
tex	$\frac{590.5}{tex}$	$\frac{885.8}{tex}$	$\frac{31000}{tex}$	$9 \times tex$	—

Table 8. **Representative Properties of Some Yarns**[a]

Yarn type ↓	Typical yarn properties →							
	Linear density/ size	Tensile breaking strength (~ gm)	Breaking tenacity (~ g/tex)	Breaking elongation (%)	Hand or feel	Twist torque (liveliness)	Uniformity (CV %)	Defects (major per 1 km)
cotton carded yarn	30-tex	400	13.3	7–8	soft	lively	12–14	1–2
cotton combed yarn	30-tex	450	15.0	8–10	very soft	slightly lively	8–10	0.5–1
woolen yarn	9 woolen	200	6.6(min)	20–30	slightly harsh	lively	15–18	2–5
worsted yarn	27 worsted	250	8.3(min)	20–30	typically 2-plied med. soft	balanced	10–12	1–3
polyester filament yarn (high-tenacity)	300-den	1200	40.0(max)	10–14	soft and smooth	Balanced	1–1.5	0–0.25
low-tenacity polyester staple yarn	30-tex	550	18.6	15–20	slightly harsh	lively	8–10	0.5- 1.5
nylon filament yarn(high tenacity)	300-den	1100	36.6	12–18	soft and smooth	balanced	1–1.5	0–0.25
low-tenacity nylon staple-spun yarn	30-tex	500	16.6	20–30	moderately soft	slightly lively	8–10	0.5–1.0
gel-spun polyethylene and cotton blend yarn (20:80)	30-tex	650	18.6	7–10	harsh	lively	12–14	2–4

[a]Approximately similar linear density/size.

Table 9. **Standard Test Methods for Evaluating the Physical Properties of Yarns**

Test number	Test method
ASTM D 1907	for measuring skein lengths
ASTM D 1059	for measuring short lengths
ASTM D 861	for linear density of yarns
ASTM D 2260	for linear density of yarns (conversion table, yarn numbering systems)
ASTM D 1425	for yarn evenness by measuring the equivalent capacitance
ASTM D 2255	to assess yarn grade relative to preserved yarn standards
ASTM D 2591-01	for linear density of elastomeric yarns
ASTM D 6587	for yarn number, using an automatic tester
ASTM D6612	for yarn number and yarn number variability, using an automated tester

Table 10. **Standard Test Methods for Evaluating the Mechanical Properties of the Yarn**

Test number	Test method
ASTM D 2256	for determining yarn strength (single strand)
ASTM D 1578	for determining yarn strength (yarn skeins)
ASTM D 885	for testing tire cords and industrial filament yarns
ASTM D 1422	for determining the twist in conventional ring spun yarns
ASTM D 1423	for determining the twist in conventional ring spun yarns
ASTM D 1244	for analyzing yarn construction and defining yarn nomenclature
ASTM D 2653,2731	for tensile properties of elastomeric yarns
ASTM D 7269-06	for tensile testing of aramid yarns

Table 11. **Standard Test Methods for Evaluating Special Properties of Yarns**

Test number	Test method
ASTM D 3108	for determining yarn-to-solid friction
ASTM D 3412	for determining yarn-to-yarn friction
ASTM D 6611-00	for wet and dry yarn-on-yarn abrasion resistance
ASTM D 5647-01	for measuring hairiness of yarns by the photo-electric apparatus
ASTM D 2259	for determining shrinkage in yarns
ASTM D 4031	for determining bulk properties
AATCC 84-1960	for electrical resistivity of yarns
ASTM D 6774-02	for crimp and shrinkage properties of textured yarns
ASTM D 4031-01	for bulk properties of textured yarns
ASTM D 5591-04	for thermal shrinkage force of yarn and cord

Table 12. **Typical Fabric Styles and Constructions Made with Basic Weaves**

Fabric	Typical fiber content	Approximate fabric construction: Warp yarn (tex)	Weft Yarn (tex)	Ends × picks (per cm)	Weave	End use
print cloth						shirting, blouses
carded	cotton and cotton blends	20	15	23.62 × 21.26	plain	
combed		15	12	36.22 × 29.92	plain	
chambery						apparel, furnishing,
carded	cotton and cotton blends	20	15	25.20 × 18.90	plain	drapes
combed		15	12	34.65 × 31.50	plain	
poplin						shirting
carded	cotton and	21	25	39.37 × 18.90	plain, warp, rib	
combed	cotton blends	16 (2-piled)	20	120.0× 68.0		
coarse drills						work trousers
carded	cotton	37	42	22.05 × 12.60	2/1 twill	
coarse denim						work trousers, jeans
(warp dyed)	cotton	54	45	24.41 × 14.96	2/1 twill	
satin/sateen	nylon, acetate, rayon, silk				satin	blouses, neck ties, scarf
		8	30	118.11 × 35.43	sateen	

Table 13. **Typical Woven Fabrics and Weaving Systems/Machines**

Typical woven fabrics	Typical weaving systems
Apparel and Household: sheeting, shirting, poplins, lawn, towels, bottom-weight (trousers), light-weight (blouses), medium-weight (misc), draperies sheens, furnishing	*Conventional Looms*: fly-shuttle looms. *Modern Weaving Machines*: missile or projectile, flexible rapier, rigid rapier, air jet, water jet, multiphase or progressive-shed
Industrial: tire cord, carpet backing, awnings, roofs, belts and hoses, sandpaper foundation cloth, geo-textiles, technical fabrics	*Conventional Looms*: fly-shuttle looms. *Modern Weaving Machines*: rigid rapier, missile or projectile, water jet, multiphase- or progressive-shed (these mostly are wide weaving machines that weave either a single wide fabric or multiple fabrics of standard (narrow) width).
Others: medical- and bio- end-use fabrics, specialty fabrics	all of the above weaving systems may be used, in addition to air-jet weaving machines that are becoming increasingly popular.

Table 14. **Representative Properties of Some Typical Fabrics**[a]

Fabric	Bending stiffness, (dyne-cm)	Weights (g/m^2)	Shear stiffness gf/(cm)	Tensile properties		
				LT	WT ($gf\text{-}cm/cm^2$)	RT (%)
plain1	35	110	1.110	0.570	11.7	49.27
plain 2	82	194	2.297	0.631	13.12	47.43
plain 4	129	168	2.634	0.696	11.308	44.174
interlock 6	38	202	0.552	0.779	3.394	45.573
rib	38	211	0.9489	1.7127	12.7014	47.4833
lawn	68	95	1.8117	0.6532	13.1004	52.6073
challis	91	153	0.7412	0.6198	14.8874	50.8424
twill 1	122	190	2.060	0.660	6.710	58.540
oxford 5	129	211	2.093	0.658	6.561	52.122
sheeting	138	189	2.3055	0.6184	26.5521	36.9171
sateen	180	248	4.4332	0.6881	11.6228	49.4988
poly twill	213	254	0.7929	0.6194	37.3918	66.7362
corduroy	251	217	2.4607	0.5916	19.094	50.6522
momie	470	180	3.0817	0.7043	12.0568	58.0024

[a] Ref. 94.

Table 15. **Standard Test Methods for Evaluating Physical Properties of Fabrics**

Test number	Test method
ASTM D 3773	for determining the length of woven fabric
ASTM D 3774	for determining the width of woven fabric
ASTM D 3776	for determining the weight per unit area of the woven fabric
ASTM D 3775	for determining the yarn count, number of warp and filling yarns/unit length
ASTM D 3883	for determining the yarn crimp in the woven fabric
ASTM D 1059	for determining the twist and yarn number in the woven fabric
ASTM D 3887	for characterizing knitted fabric (yield, width, length, and yarn count)
ASTM D 1117	for evaluating nonwoven fabrics
ASTM D 1777	for measuring fabric thickness
ASTM D 737	for measuring permeability of woven, knitted, and nonwoven fabrics

Table 16. **Standard Test Methods for Evaluating Mechanical Properties of Fabrics**

Test number	Test method
ASTM D 5034	for fabric tensile strength tests (the grab test)
ASTM D 5035	for fabric tensile strength tests (the raveled-strip method)
ASTM D 3786	for bursting strength (knitted fabric)
ASTM D 3787	for bursting strength (ball burst test: knitted fabric)
ASTM D 1424	for determining tear strength of textile woven fabrics (Elmendorf tear)
ASTM D 1117	for determining tear strength of textile non-woven fabrics (trapezoid tear)
ASTM D 2261	for fabric tear strength (the tongue tear: CRE type)
ASTM D 2262	for fabric tear strength (the tongue tear: CRE type)
ASTM D 1424	for fabric tear strength (Elmendorf tear)
ASTM D 3939	for quantifying the fabric snag resistance
ASTM D 5362	for quantifying the fabric snag resistance (bean bag snag test)
ASTM D 2594	for quantifying the growth and stretch properties of knitted fabrics
ASTM D 3107	for measuring stretch and stretch recovery of woven fabrics

Table 17. **Standard Test Methods for Evaluating the Pilling, Abrasion and Wear Properties of Fabrics**

Test number	Test method
ASTM D 3512	for pilling resistance (the random tumble method)
ASTM D 3511	for pilling resistance (the brush pilling test)
ASTM D 3884	for abrasion resistance (rotary platform, double-head method)
ASTM D 3885	for flexing and abrasion resistance (flexing and abrasion method)
ASTM D 3886	for abrasion resistance (inflated diaphragm method: woven and knitted)
ASTM D 4157	for abrasion resistance (oscillatory cylinder method)
ASTM D 4158	for abrasion resistance (uniform abrasion method: wide range of fabric)
ASTM D 4966	for abrasion resistance (Martindale Tester: woven and knitted)
AATCC 93	for abrasion resistance (impeller tumble or accelerotor method)

Table 18. **Standard Test Methods for Evaluating Performance and Chemical Characteristics of Fabrics**

Test number	Test method
ASTM D 1230	for evaluating flammability for apparel textiles
ASTM D 2859	for evaluating flammability for finished textile floor-covering materials
ASTM D 3411	for evaluating flammability for textile materials
ASTM D 4151	for evaluating flammability for blankets
ASTM D 4372	for evaluating flammability for camping tentage
AATCC 135,150	for laundry shrinkage (home laundering conditions)
AATCC 158	for laundry shrinkage (dry cleaning)
AATCC 96	for measuring stability of all fabrics except wool (laundering conditions)
AATCC 99	for determining the shrinkage specifically for wool fabrics
ASTM D 1518	for thermal transmission (heat transfer in fabric)
AATCC 22,70	for water repellency in fabrics
AATCC 127,35	for water resistance of the fabric
AATCC 130	for soil redeposition and soil release in fabric (oil stain)
ASTM D 4391	for testing of flammability of textile fabrics
AATCC 76	for electrical resistivity of fabrics
AATCC 115	for electrostatic clinging of fabrics
ASTM D 4238	for determining electrostatic propensity of textiles
AATCC 101	for colorfastness to bleaching with hydrogen peroxide
AATCC 172	for colorfastness to nonchlorine bleach in home laundering
ASTM D 123	for fabric hand or handle