Textile processes have experienced radical change due to new inventions and the stringent demands of high-quality products. The past three decades have seen the development of new fibers, new spinning methods and new weaving techniques as well as the value addition of existing products and increased productivity of current processes. Modern looms are operating at very high speeds, thus imposing stringent requirements on the warp that can be woven efficiently. In the sequence of textile processes, sizing has continued to retain its importance in the value chain and has proved necessary even with today’s demanding requirements. Using innovative techniques, the sizing machine and chemical manufacturers have tried to keep pace with the increased speed of looms. Despite the rapidly changing scenario in textile processing and attendant research in sizing, little of this progress has been documented in a single volume. The motivation to write this book arose from this gap, and the material developed from continued research at Clemson University provided the foundation.

The subject of sizing is complicated because of the important roles played by interactions among fiber type, yarn type, sizing chemicals, preparatory weaving processes, characterization of the performance of sized yarns that can help in predicting the behavior of warp during weaving, easy size removability after weaving, and environmental pollution. Prediction of the efficiency of sizing—type of size, amount of size, penetration of size in different yarn structures, and the mode of different deformations of the sized yarns—in terms of weaving efficiency has confounded textile scientists and
technologists for a long time. The subject matter in this volume is arranged with this in mind. The introductory chapter summarizes the importance of fiber properties, yarn quality, sizing process, sizing materials and their evaluation, performance evaluation of sized yarn and the sizing process, and modern instrumentation and control of the sizing machines. Chapter 2 is devoted to different fibers and yarns and their properties. Most recently developed fibers are covered, and then principles of different spinning systems are described to enable the reader to understand the structural differences in various yarns. Recently developed yarn spinning systems are described to acquaint the reader with modern developments and their effects on sizing. Chapter 3 is devoted to the chemistry of sizing ingredients and their properties that determine suitability for applications. The importance of desizing and its effect on size recovery and environment pollution are also discussed.

Good preparatory processes, such as winding and warping, and their effect on the sizing operation are discussed in Chapter 4. Besides the basic principles of winding, warping and sizing operations, this chapter also covers the principles of process controls and modern instrumentation techniques. Effect of sizing machine parameters and practical aspects are briefly described. Single-end sizing systems for filament sizing have become popular in the past two decades, along with developments in draw-warping and sizing to improve the economics of processes. Chapter 4 also deals with the principles of sizing of different types of yarns such as ring, rotor, and filament. The efficiency of sizes on yarns in terms of the types of loom used for weaving is also examined. Prewetting of spun yarns, with its impact on the economy of sizing, is presented. Chapter 5 deals with performance evaluation of sized yarns. The major portion of this chapter is drawn from the research material developed through exhaustive studies conducted at Clemson University over the past fifteen years. A comprehensive bibliography on sizing is appended for the benefit of researchers and interested readers who would like to delve into the subject matter in more detail. References in the bibliography include material that is scattered in various publications in several languages besides English.

This text has been developed with a view to providing systematic information for textile students, engaged in both undergraduate and research studies. The information presented will help textile practitioners comprehend the prevailing practices in the industry and understand the changing processes and practices.

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THE SIZING PROCESS

1.1 INTRODUCTION

The old adage that sizing is the heart of weaving still holds good today. This statement is all the more important in today’s environment when loom speeds have increased tenfold from those used in shuttle looms. The weaving process depends upon a complexity of factors which include the material characteristics, the sizing ingredients, the sizing operation, and the yarn parameters. Table 1.1 shows all the important factors that come into play in deciding the performance of warp yarns during weaving. On the whole, the aim of the textile technologist is to produce “quality” fabric economically and efficiently. Here these terms refer to the production of fabrics up to the loom stage.

The selection, evaluation, and performance of the warp (yarn/size system) for any specific fabric sett and the loom must be determined in the context of the developments and changes that have occurred in the spinning/winding/warping and the slashing processes. The following is a brief discussion of a number of considerations that a textile technologist must be conversant with when making a decision regarding the appropriate yarn/sizing system.

In the past four decades, the weaving industry has been subject to inordinate competition which has primarily come from the fashion (short runs), knitting, and nonwoven segments. The weaving machinery manufacturers answered the pressure of competition by concentrating on the design of looms that offered relatively very high speeds. Table 1.2 shows the relative speeds of various processes of manufacturing fabrics. Obviously, to meet the demands...
Table 1.1  Parameters Affecting Performance of Warp Yarns During Weaving

Material characteristics
- Fiber type, e.g., cotton, polyester, acetate
- Yarn type and structure including blend composition, e.g. staple
- Ring, open end, air-jet, combed, carded, core spun, continuous filament
- Yarn hairiness.

Yarn preparation
- Winding
- Warping

Slashing
- Tension on yarn during sizing
- Moisture content
- Drying temperature

Slashing machine parameters
- Slashing speed
- Size box characteristics
- High pressure squeeze rolls, including hardness of rolls
- Type of sizing method, e.g., single end, Cutt method, foam method
- Amount of size
- Yarn tension
- Closeness of yarns

Loom parameters
- Type of loom, e.g., shuttle, rapier, projectile, air-jet
- Weave
- Loom speed
- Warp tension

of the higher productivity on the loom, the material characteristics and the quality and efficiency of the preceding processes also needed to be improved. This volume deals with the material characteristics, yarn structure and properties, yarn preparation, chemistry of sizing ingredients, and the performance analysis of sized yarns subjected to simulated loom parameters and its correlation with actual performance on the loom. The attempt to put this material in the present form comes at a time when the emphasis in the weaving industry is shifting away from simply higher production speeds toward optimization of the weaving process, dependability, and fabric quality.

The difficulty in predicting the performance of warp during actual weaving is compounded by the fact that there have been a number of developments in materials and preparation and processing techniques that have taken place.


Table 1.2  Relative Production Rates for Textile Processes

<table>
<thead>
<tr>
<th>Fabric/fiber sheet making process</th>
<th>Machine</th>
<th>Relative production rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weaving</td>
<td>Automatic loom with shuttle(^a)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Shuttleless looms</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rapier</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Projectile</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Air-jet</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Multiphase</td>
<td>30</td>
</tr>
<tr>
<td>Knitting and hosiery</td>
<td>Circular knitting machine (wide)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Warp knitting loom</td>
<td>16</td>
</tr>
<tr>
<td>Nonwoven bonded fabrics</td>
<td>Stitch bonding machine</td>
<td>38</td>
</tr>
<tr>
<td>Dry method</td>
<td>Short fiber carding, nonwoven card</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Long fiber carding, garnetting</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>Tufting machine</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Aerodynamic web-making machine</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>spun-bonding machine</td>
<td>200–2,000</td>
</tr>
<tr>
<td>Wet method</td>
<td>Rotoformer</td>
<td>2,300</td>
</tr>
<tr>
<td>Paper manufacture</td>
<td>Paper-making machine (high powered type)</td>
<td>40,000–100,000</td>
</tr>
</tbody>
</table>

\(^a\)Average output 5 m\(^2\)/h, 150 picks/min.

over the past three decades. The following is the discussion of some of the factors that needed to be considered when evaluating and predicting the performance of warp during weaving. With almost a constant demand for improving the quality and productivity in weaving there has been an equal emphasis on the development of better quality yarns with improved tenacity, elongation, elastic recovery, in both the dry and wet state, and above all in reduction in hairiness of staple yarns.

1.2 MATERIAL PROPERTIES

There have been a number of developments in the quality of cotton fibers produced around the world. Although there has been a constant and gradual improvement in strength and elongation of the upland variety, one noticeable development that is worth mentioning here is the significant improvement that has occurred in the area of the strength and elongation of extra long cotton

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fibers. The strength of most of these extra long staple cottons is in the range of 35–37 cN/tex, and elongation varies anywhere from 6 to 8%. These properties translate very well into improvement in yarn characteristics.

In practical mill operation, the strength property of the yarn has always been considered the prime factor that influences the performance of warp yarn during weaving. However, in recent years the mill supervisors and textile scientists have realized that other mechanical characteristics—such as elongation, elastic recovery in both wet and dry states, and physical characteristics such as abrasion resistance and moisture sorption—are equally influential in performance in the loom shed. On the other hand, as far as synthetic fibers are concerned, the trend has been more toward using finer fibers, especially when considering polyester fibers for blends with cotton. Polyester fibers of denier as low as 0.7 have been developed, but most commonly used fibers are in the range of 1 to 1.2 denier in current mill practice. This increases the number of fibers in the yarn cross section, which eventually enhances the strength, elastic recovery, and abrasion resistance of the resultant yarns. There has not been much change in the strength and elongation properties of synthetic fibers.

However, it is not the new material (fiber) properties alone that account for the continuous improvement in yarn quality; optimization of the processes, despite the increase in speed, has made the process of sizing and weaving much more efficient. This is true for most spun and filament yarns. The improvement in the quality of yarn over the last three decades can be best demonstrated by the data published by Zellweger Uster [1] for staple yarns. It is fairly safe to assume that there has not been much change in fiber length distribution, fineness, strength distribution and trash content in the raw stock of natural fibers; the properties of the yarns then are a function of the vagaries of the spinning processing technologies. The variations in a yarn that have an important influence on the efficiency of the weaving process are yarn mass variations, thin places, and strength variation. Numerous studies have demonstrated some correlation between thread breaks and thin places and variation in yarn strength. Figures 1.1 and 1.2 show the reduction in the coefficient of variation of strength and thin places of the 50% line of the Uster statistics of ring-spun combed 10 tex yarn, respectively. Even such a small reduction in the variation in yarn strength can significantly influence the yarn failure rate on the loom. There have been significant improvements in the quality of both ring- and open-end rotor-spun yarns.

Online monitoring of yarn quality during spinning and splicing during winding, clearing devices, and yarn tension control on modern machines have improved the final yarn quality that is delivered to the warping department.

Fiber and yarn characteristics are discussed in detail in subsequent chapters.
**Fig. 1.1** Strength variation; percent CVF\textsubscript{max}.

**Fig. 1.2** Variation of thin places (imperfections).
1.3 SIZING MATERIALS

Natural starch and its derivatives still constitute nearly 75% of the sizing agents used in the textile industry throughout the world. It will remain the predominant ingredient, in the near future, for use in the industry because it is relatively inexpensive. The need for the development of different sizing agents other than starch and its derivatives was prompted by the introduction of new spinning and weaving technologies; these include, as previously described, spinning technologies that produce types of yarn structures that are different from the ring spun yarns and the various types of high speed shuttleless looms. The use of either starch or its derivatives proved inadequate for the achievement of quality and efficiency in the weave room. In addition, the environmental concerns regarding the discharge of effluent in local streams and wastewater treatment plants have also been influential in the search for new sizing materials. Generally, the amount of starch applied to staple yarn varies anywhere up to 15% of the weight of the yarn. The introduction of the new types of polymer synthetic sizing materials such as polyacrylates, polyesters, and polyvinyl alcohols (PVAs) has helped to reduce the amount of coating required to achieve similar if not significantly better quality warps and weave room efficiencies. However, there is still a lack of enough experience and data to allow prediction with certainty how a particular size material will behave during sizing, weaving, and desizing or in recycling of the materials. Carboxymethyl cellulose (CMC) sizing has very good adhesion to cellulose fibers, but due to the high viscosity, the concentrations used in the industry are limited to low levels. CMC sizes are combined with PVA or acrylic sizing agents to improve their performance and desizing characteristics. However, the sizes containing CMC are very difficult to recycle. PVA is sometimes combined with acrylics and acrylate type sizes.

1.4 PERFORMANCE EVALUATION

The performance of warp yarns on the loom is influenced by a number of factors as it is subjected to complex deformation including abrasion, cyclic bending and tension, and impact loading. Until recently, various constituents, such as size liquor, size film, yarn characteristics, and size/yarn behavior, have been characterized by a single measurement. For example, the size film and sized yarns have been characterized by the tenacity and elongation. Abrasion resistance is another criterion that has been used for establishing the protection provided by the size film to the yarn during weaving. None of the parameters on its own provided a reliable method for establishing a definitive correlation
between the measurements made in the laboratory and actual performance of the yarn during weaving, especially during high speed weaving (over 400 picks/min). This is understandable because the process of yarn deformation during weaving is very complex. In the past two decades some progress has been made in devising a test method, empirical in nature, that incorporates the various modes of deformation that the warp yarns experience during weaving. Nevertheless, the method of data analysis to extract the information obtained from such a test method needs careful study so that the performance of warp may be predicted reliably.

In the current state of affairs, it is also important to mention that besides fulfilling the need for improving weaving performance the sizing material should not interfere adversely in the subsequent processes (e.g., dyeing and finishing) or obviously the environment.

1.5 SELECTION AND EVALUATION OF SIZE MATERIALS

At the outset it may be stated that there is no single size material that meets all the requirements as far as compatibility with every yarn being processed on any specific slasher for every fabric sett and weave room conditions. Obviously the objectives to keep in mind are that the sizing material should be easy to handle and apply to the yarn (and easy to remove) and the size–yarn system offers the best performance during weaving (improved abrasion resistance of size and yarn, yarn strength and resiliency, low shedding, and no size cracking).

In recent years several advances in improving the quality of sizing materials have been made. The properties that are important and that can be easily determined are (1) the viscosity or fluidity and (2) the mechanical and moisture sorption characteristics of the size film and the adhesion of the size to various types of fibers. For example, the polyvinyl alcohol film has an adhesive strength that is more than three times that of starch to polyester fibers. Starches have been chemically modified to improve their adhesion to fibers, strength, stability, and solubility of the size material.

The size formulations used for spun yarns (including blends) also contain other ingredients such as lubricants and binders. The lubricants help to reduce the friction and abrasion between the adjacent yarns and between yarns and heddles, dropwires, shuttles, rapiers, or projectiles. The lubricants also enhance the flexibility of the size film. The lubricants are generally fats, oils, or waxes.

In addition, another ingredient, usually a binder, is used either to enhance or suppress certain interactions between the size film and the fiber. The binder
materials usually tend to reduce “skinning” in the size box and help reduce the force required to separate the yarns at the bust rods located at the front of a slasher. Acrylics and polyesters are generally used as binders. Some of these binder materials, especially acryliics, increase the viscosity of the size bath allowing better encapsulation of the yarn, which prevents hairiness of yarns from interfering in the weaving operation. Other ingredients, such as humectants, wetting agents, and defoamers, are added to the size formulation to ease the process of size application to the yarn.

The techniques to measure the size and the processing characteristics are well established, and it is important to establish standards that will help select the proper size or size blend that will give the best results. Some of the factors that need to be considered are the fiber type, yarn structure (ring spun, open end, air jet, or continuous filament), fabric sett, the slashing equipment, and such finished fabric requirements as fabric hand, brightness of color, and texture.

1.6 EVALUATION OF THE SIZING PROCESS

Weavers have been placing very stringent requirements on the quality of warp due to higher loom speeds and the need to produce first quality fabrics with an absolute minimum in defects. If the sizing is defective, the quality of the warp will be poor, which will affect the weaving operation and consequently the quality of the fabric.

In recent years a number of developments in process controls and sensing devices have made the process of applying the size and controlling the machine factors and yarn parameters much easier. The factors that need to be monitored and controlled on the slasher are as follows:

- Size add-on control
- Viscosity of size formulation
- Yarn speed
- Size encapsulation, which may be influenced by
  - Size temperature/viscosity
  - Size level
  - Amount of solids in the formulation and between different formulations
- Tension in size box
- Moisture in yarns
- Tension in the leasing section
- Tension in the creel section
1.6.1 Size Add-On

The amount and the uniformity of size add-on are extremely important in influencing the performance of warp during weaving. Size add-on is affected by the viscosity of the size bath and combination of warp speed and squeeze roll pressure. Modern machines are equipped with controls that regulate the squeeze roll pressure with respect to the warp speed. In other words if the warp is running slower, the squeeze roll pressure is increased to empirically regulate the amount of add-on. These controls are designed to monitor the size add-on as a percentage of the dry warp weight as a function of the warp speed with liquid size flow. Although with modern technology both measurements can be accurately made, the time element is such (requiring approximately 30 to 45 s to compute) that with each event a large length (approximately 50 to 75 m) of the warp passes through the machine before any adjustment is made. There are other factors, for example, the amount of solids in the size formulations, that have to be entered in the controls manually, and the controls do not compensate for evaporation and the errors due to incorrect formulation. In recent years very precise gauges, e.g., low energy source nuclear gauges, have been used for maintaining web density. This type of device, as shown in Fig. 1.3, is used for online measurements of the density of the incoming warp and the sized warp. The sensors are calibrated to take the amount of moisture (both in the incoming warp and the sized warp) and the stretch (extension) in the warp into account in the sensing process. Even though the nuclear gauges provide high accuracy in the measurement of web densities, they are not as effective over the whole range of slasher speeds (including deceleration and acceleration of the slasher) in adjusting the size add-on by regulating the squeeze roll pressure. Consequently, additional sensors in the form of microwave sensing and conductive kiss rolls are placed at various locations along the squeeze rolls. Both these methods sense wet pick-up, but they require calibration to compensate for the web density and the electrical conductivity of different size formulations. These can be used in conjunction with high accuracy nuclear gauge to obtain a fast response and thus control the add-on at all speeds during deceleration and acceleration of the slasher.

1.6.2 Yarn Encapsulation

In addition to the optimized and uniform size add-on, another factor that influences loom efficiency and warp breaks is the degree of encapsulation of the staple fiber yarn. This is necessary to suppress the deleterious effect of yarn hairiness, which has been formed due to abrasion in the weaving process to have a very strong influence on warp breaks during weaving. In recent years
sensors have been introduced which monitor the hairiness of yarns in the sizing operation. The developments in machine vision technology have enabled the monitoring and efficient acquisition of data (images), such as on web density, of randomly arriving objects. This is accomplished by triggered cameras that take snapshots on demand. On higher speed continuous web, such as warp sheet in a slasher, cameras that can scan in time delay and integration (TDI)
mode are mounted for efficient acquisition of material influence. One such sensor is the Strandberg Size Encapsulation Monitor shown in Fig. 1.4. The sensor for encapsulation is based on the principle of monitoring the hairiness of a yarn before and after sizing. Yarn size encapsulation here is defined in terms of the protruding hairs 360 degrees around the yarn diameter integrated over a set length (e.g., 1 m or 1 yard). The empirical relationship is given as follows:

\[
\text{size encapsulation} = 360 \left( 1 - \frac{H_d}{H_c} \right) \text{ degrees}
\]

where \(H_d\) is hairiness of yarns at delivery and \(H_c\) is hairiness of yarns at entry. There is evidence that the optimal amount of encapsulation is achieved at an optimal size add-on. The encapsulation efficiency deteriorates when the size add-on is either increased or decreased from this optimal value of add-on. The optimal add-on for optimal encapsulation is highly dependent on the yarn type and the other yarn physical parameters. Studies have also shown that warp breaks on the loom are strongly influenced by the degree of encapsulation. Specifically, the optimal size encapsulation is dependent on four primary factors: (1) moisture in the yarn when it contacts the first drying cylinder of the final dryer, (2) temperature of the first drying cylinder of the final dryer, (3) yarn tension in the leasing section, and (4) the size add-on. The qualitative relationship between these four factors is shown in Fig. 1.5. There is an optimum for each factor where the optimal size encapsulation is achieved. A process controller being used in the textile industry to monitor and control size encapsulation as a function of all the four factors is shown in Fig. 1.6.

The amount of moisture in the sized yarn is also an extremely important parameter that affects the quality of a warp. The constancy of the amount of moisture throughout the length of the warp will depend on the efficiency of drying. Consequently, new controls have been developed and are currently being used on the machines to regulate and control temperature of drying cans to arrive at the desired moisture content in the entire warp at all speeds. The final moisture content in the warp can be closely controlled by automatically controlling the wet pick up, which is affected by constant regulation of squeeze roll pressure. Obviously, the instrumentation used in these highly automated operations is designed to control the moisture in different types of fibers, fiber blends, and warp densities. The sensors are highly sophisticated and have the capability of regulating moisture within very narrow tolerances (±0.1%). A moisture-sensing transducer assembly mounted on a slasher is shown in Fig. 1.7.
Fig. 1.4 Encapsulation monitor. (Courtesy of Standberg Laboratories, Inc.)
Another area of extreme sensitivity is the yarn strength in the wet stage which occurs between the size box and the first drying cylinder. Machinery manufacturers are using highly sensitive sensors, some of which are surface-driven sensors that can also sense stretch down to near zero running speed and thus help in automatically controlling motors that control the speed of Positive Infinitely Variable (PIV) Variators or variable speed transmission systems. There are a number of different types of sensors available in the market that allow the control of temperature and consequently the viscosity of the size formulation in the size box.
Strain gauges are being used in controlling warp tension through the entire length of the slasher all the way from creel, between drying sections, to the lease rods and winding. Torque motors are used for controlling the tension between the drying sections and the leasing sections, while pneumatic brakes help control tension in the creeling sections.

The use of cameras located at strategic points also helps in the timely detection of faults and in instantly stopping the machine for repairs. The camera devices are sensitive enough that even a single thread passing within its focal point will actuate the device. The actual controllers along with their recording devices have become very useful in enhancing the quality of the sized beams. Some of these controls and data collection devices include the history of the processing of a sized beam. The following data may be generated, as one of the manufacturers of controls has suggested [2]:

Date and time at start of each beam
Time to make a beam

Fig. 1.6 Process controller to monitor and control size encapsulation as a function of moisture, stretch, add-on, and tension.
Fig. 1.7 Typical moisture-sensing transducer installation consisting of transmitter, receiver, junction box amplifier, hardware, and cables.

Time during stop of slasher
Time during slow movement
Warp length in meters delivered
Warp length delivered in slow motion
Average slasher speed
Average moisture content in beam
Average stretch in yarn from each size box to delivery
Average stretch in creel
Chapter 1

1.7 EVALUATION OF WARP PERFORMANCE

For efficient operation of the weave room, it is important to know how the warp yarn will perform during weaving. Until recently weaving technologists believed that by determining (1) the adhesion of size to the yarn, (2) the ease with which the size wears or rubs off (abrasion), and (3) the improvement in the tenacity of the yarns, the performance of warp during weaving could be predicted. Obviously, various test methods have been devised to determine these factors both qualitatively and quantitatively. However, a closer examination of the weaving process indicates that yarn failure during weaving is controlled by a very complex mechanism. Yarn failure does not occur due to abrasion of the size or in simple tensile mode. The warp yarn on the loom is subjected to very complex deformation modes which include abrasion, cyclic bending, cyclic tension, pseudotwisting/untwisting (torsion), and cyclic impact loading in addition to the base tension applied to the yarn. The literature is full of studies where researchers have tried to establish simple one-to-one correlation with the abrasion characteristics, tensile strength, and hairiness of warp yarn with performance on the loom. Studies have also been reported in the literature that try to show that the behavior of yarns during weaving and the number of breaks during spinning (all these on yarns before they are sized) can also be correlated with loom performance. However, the complex fatigue mechanism that controls the failure of yarns on the loom has been the subject
of recent studies in which this mode has been simulated in the laboratory. The Sulzer-Ruti Webtester is one such experimental method. Nevertheless, because of the nature of the fatigue results of yarns, it has been difficult to establish one-to-one correlation with the yarn performance in the laboratory with that observed in the weave room. Our studies have attempted to establish such a correspondence. This is the subject of discussion in Chapter 5.

1.8 CLOSING NOTES

In this volume we give readers an idea of the complexity of the problem of the sizing of yarns for weaving. The chemistry of sizing material, the additives, the types of fibers and yarn structures, the method of application of size, and the control of the material and machine factors compound the task of establishing simple relationships between various parameters. Nevertheless, we hope this compendium will prove to be of great help to both mill practitioners and the students of textiles and especially weaving.

This volume is primarily concerned with familiarizing the reader with the current status of sizing machines, chemistry of different sizing materials, and above all the laboratory methods of evaluation of sized yarns. In addition, the correlation between the fatigue behavior of sized yarns determined in the laboratory and in actual loom trials will be presented.

REFERENCES

2
PROPERTIES OF FIBERS AND YARNS

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

The process of woven fabric manufacturing is neither simple nor accomplished in one step. The conversion of raw materials (fibers) into finished products (fabrics) involves many different steps, broadly categorized as spinning of a yarn, weaving of a fabric, and finishing. Each of these steps in turn involves many intermediate processes to perform well-defined specific functions. The process of spinning staple yarns involves preparatory steps such
as opening and cleaning of cotton fiber stock, or only opening for synthetic fibers, optimal blending of different fibers, carding, combing, drawing, and twist insertion. The process of weaving is preceded by preparatory steps of winding, warping, and slashing (more commonly known as sizing).

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

### 2.2 FIBERS

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

Besides slenderness ratio, the other most important property of textile fibers is elasticity. The breaking extension of an ideal textile fiber should be between 5 to 50% depending upon the actual end-use application [5]. The extensibilities of glass and crystalline solids are below 5%, and those of rubbers are above 50%, which makes them very difficult to process during subsequent spinning and weaving operations. These fibrous materials having suitable extensibility for successful textile processing are all partially oriented, partially
Table 2.1 Length-to-Diameter Ratios of Natural Textile Fibers

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

Source: Refs. 4 and 5.

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

2.2.1 Classification of Textile Fibers

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

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

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

A. Natural polymer fibers in which the fiber-forming polymer is of natural origin, referred to as regenerated fibers.
Table 2.2A Classification of Fibers

| Source: Refs. 4–9. |

- **Natural (See Table 2.2B)**
  - Animal Origin
    - Silk
    - Wool
    - Hair
  - Seed Origin
    - Cotton Kapok
  - Bast Origin
    - Flax, Jute, Hemp Kenaf, Ramie etc.
  - Leaf Origin
    - Sisal, Manila, Henequen Abaca, Pineapple
  - Fruit Origin
    - Coir

- **Manmade**
  - Vegetable Origin
  - Mineral Origin (Asbestos)

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### Table 2.2B Classification of Manmade Fibers

<table>
<thead>
<tr>
<th>Natural Polymers</th>
<th>Synthetic Polymers (from natural origin)</th>
<th>Synthetic Rubber</th>
<th>Miscellaneous (carbon, metallic, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regenerated Protein (casein, vegetable protein, etc.)</td>
<td>Polylactic Acid (PLA fiber)</td>
<td>Polysulfide (polypropylene)</td>
<td>Polybenzimidazoles (PBI)</td>
</tr>
<tr>
<td>Regenerated Cellulose (viscose, cuprammonium)</td>
<td>Polyester (PET, PBT, PCDT, etc.)</td>
<td>Polyvinyl Alcohol</td>
<td>Miscellaneous (vinylation, acrylics)</td>
</tr>
<tr>
<td>Cellulose Esters (cellulose acetate)</td>
<td>Polyamides (nylon 6, 6.6,aramids, etc.)</td>
<td>Monosubstitution (vinyl chloride &amp; derivatives)</td>
<td>Monosubstitution (vinylidene chloride)</td>
</tr>
<tr>
<td>Miscellaneous (alginate, natural rubber)</td>
<td>Polyanhydrides (quinique, polyhydroylene)</td>
<td>Disubstitution (vinylidene chloride)</td>
<td>Disubstitution (vinylidene chloride)</td>
</tr>
</tbody>
</table>

**Source:** Refs. 7–9.
B. Synthetic fibers in which the fiber-forming material(s) is from basic chemicals. There is now also a new class of synthetic fibers, those produced from material derived from a natural renewable origin, such as corn, known as polylactic acid or polylactide (PLA).

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

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

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

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

2.2.2 Essential Properties of Textile Fibers

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

Table 2.3 lists various essential properties of textile fibers.

Dimensional Properties

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

<table>
<thead>
<tr>
<th>A. Dimensional</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Length</td>
</tr>
<tr>
<td>2. Diameter</td>
</tr>
<tr>
<td>3. Cross-sectional shape</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Physical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Density</td>
</tr>
<tr>
<td>2. Crimp</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C. Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Strength</td>
</tr>
<tr>
<td>2. Elongation</td>
</tr>
<tr>
<td>3. Elasticity</td>
</tr>
<tr>
<td>4. Recovery</td>
</tr>
<tr>
<td>5. Bending stiffness</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D. General Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Frictional</td>
</tr>
<tr>
<td>2. Softness</td>
</tr>
<tr>
<td>3. Light fastness</td>
</tr>
<tr>
<td>4. Thermal stability</td>
</tr>
<tr>
<td>5. Resistance to chemicals, organic solvents</td>
</tr>
<tr>
<td>6. Pliability</td>
</tr>
<tr>
<td>7. Durability</td>
</tr>
<tr>
<td>8. Abrasion resistance</td>
</tr>
<tr>
<td>9. Dimensional stability</td>
</tr>
<tr>
<td>10. Wearing comfort</td>
</tr>
</tbody>
</table>

Source: Refs. 5 and 6.
Properties of Fibers and Yarns

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

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

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

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

The task of measuring fiber fineness is not made any easier by the fact that variations in cross-sectional shape and size exist not only between different fiber types, but also within the same fiber type. The classical method of measuring the fiber fineness of wool known to have a reasonably circular cross section,
Table 2.4  Minimal Number of Fibers Required to Spin a Yarn

<table>
<thead>
<tr>
<th>Spinning system</th>
<th>Number of fibersa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring spinning</td>
<td>60</td>
</tr>
<tr>
<td>Rotor spinning</td>
<td>120</td>
</tr>
<tr>
<td>Open-end friction spinning</td>
<td>100</td>
</tr>
<tr>
<td>Air-jet spinning</td>
<td>70</td>
</tr>
<tr>
<td>Filament wrap spinning</td>
<td>40</td>
</tr>
</tbody>
</table>

aFor 100% polyester yarn from 1.5 denier, 38 mm polyester fiber.

Source: Refs. 90 and 110.

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

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

The density of textile materials plays an important role in processing behavior and the ultimate fabric properties. Crimp is another important property of...
textile fibers, especially those of natural origin, but is not that common in the case of other solid materials. The manmade fibers are usually crimped before processing on the textile equipment.

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

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

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

The crimp in textile fibers is usually considered to have two dimensions, namely, wavelength along the fiber axis and the amplitude along the transverse dimension (i.e., diameter) of the fiber as shown in Fig. 2.2a. If the length of
Table 2.5  Fiber Densities

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Density (g/cm³, Mg/m³)</th>
<th>Specific volume (cm³/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>65% RH</td>
</tr>
<tr>
<td>Cotton (lumen filled)</td>
<td>1.55</td>
<td>1.52</td>
</tr>
<tr>
<td>Viscose rayon</td>
<td>1.52</td>
<td>1.49</td>
</tr>
<tr>
<td>Secondary acetate, triacetate</td>
<td>1.31</td>
<td>1.32</td>
</tr>
<tr>
<td>Wool</td>
<td>1.30</td>
<td>1.31</td>
</tr>
<tr>
<td>Silk</td>
<td>1.34</td>
<td>1.34</td>
</tr>
<tr>
<td>Casein</td>
<td>1.30</td>
<td>1.30</td>
</tr>
<tr>
<td>Nylon 6.6, nylon 6</td>
<td>1.14</td>
<td>1.14</td>
</tr>
<tr>
<td>Terylene (and other polyester fibres)</td>
<td>1.39</td>
<td>1.39</td>
</tr>
<tr>
<td>Orlon (and other acrylic fibres)</td>
<td>1.19</td>
<td>1.19</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Polyethylene, low density</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>Polyethylene, high density</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>Dynel (modacrylic)</td>
<td>1.29</td>
<td>1.29</td>
</tr>
<tr>
<td>Teklan (modacrylic)</td>
<td>1.34</td>
<td></td>
</tr>
<tr>
<td>Polivinyl chloride</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Polytetrafluorethylene</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Source: Refs. 5 and 6.

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

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

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

Mechanical Properties

The mechanical properties of textile materials are measured in terms of their resistance to deformation under applied stresses or loads. The nature of loads applied may be tensile, shear, bending, compressive, etc. The tensile behavior
of a textile fiber has a very profound influence on subsequent processing behavior and the ultimate fabric behavior. The tensile properties under forces applied along the fiber axis are therefore most widely studied.

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

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

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

\[
\text{tenacity} = \frac{\text{force at break (N)}}{\text{linear density (tex)}}
\]
For comparing strengths of different engineering materials on the basis of area of cross section, the stress at break, termed ultimate stress, is used. However, textile fibers generally do not have well-defined geometric cross sections. Therefore, expressing the strength of fibers in terms of ultimate tensile stress is susceptible to error.

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

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

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

\[
\text{breaking extension (\%) } = \frac{L_b - L_g}{L_g} \times 100
\]
Initial Modulus. A close analysis of the stress–strain curve of a fiber reveals that the relationship is fairly linear, at least in the initial region, until a point is reached where the yielding begins. The slope of the stress–strain curve of an initially straight fiber at the origin is defined as initial modulus, as shown in Figure 2.3. However, the natural crimp in textile fibers will tend to change the initial part of the load–elongation curve. When a crimped fiber is subjected to axial tension, an extremely small load is registered until all the crimp present in the fiber is removed [20–22], as shown in Fig. 2.4. To calculate the initial modulus in such a case, the origin of the curve is shifted to a point O, where the fiber is assumed to be straight. The point O, an artificial origin, is located by extrapolating the initial slope of the curve. The slope of the initial part of the curve (before the straight line) determines the crimp rigidity of the fiber.

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

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

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

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

The study of fiber elasticity and recovery under applied stresses has great technical importance because the knowledge of the extent to which a fiber is permanently deformed is essential for subsequent processing and for designing fabrics for special end uses to attain the desired properties. The perfect elasticity as discussed in the previous paragraph is a special case of the general hysteresis effect, as shown in Figure 2.6, commonly observed in viscoelastic materials, which form the basis of most textile fibers [23].
Elastic and plastic recovery. (From Refs. 5 and 23.)

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

General Properties

In addition to the dimensional, physical, and mechanical properties of fiber discussed in the foregoing sections, several other general fiber properties are
of significant importance. A list of all the important general properties discussed in the following sections is presented in Table 2.3.

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

Moisture. The ability of fibers to absorb moisture from the atmosphere is usually expressed in terms of either the moisture regain ($R$) or the moisture content ($M$), expressed as follows:
Fig. 2.8  Creep behavior under cyclic loading and unloading. (From Ref. 5.)

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

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

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

\[ M = \frac{R}{1 + \frac{R}{100}} \]

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

**Thermal Properties.** The thermal properties of textile fibers are of great practical importance because they determine the usefulness of fibers in view of the end-use application in the textile field. The maximal processing temperature that the fibers can withstand without deterioration, decomposition, and softening often dictates the end-use application. Heating of fibers at elevated temperatures causes a weakening of the fiber structure due to molecular changes.
The thermal response and the characteristics of different fibers are diverse. For example, when subjected to heat, wool begins to decompose without melting; polypropylene and regenerated acetate soften and subsequently melt before decomposition; and cotton becomes yellowish brown and subsequently diffuses before decomposition. Many of the newer synthetic fibers are thermoplastic in nature and soften when heated and eventually melt. The decomposition characteristics of textile fibers are important in view of their flammability behavior. Natural fibers, such as cotton, wool, and linen, do not cause severe burn injuries since they do not soften and melt at high temperatures. The softening and melting tendency of some synthetic and regenerated acetate fibers may cause severe burn injuries if they stick to the skin.

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

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

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

**Electrical Properties.** The electrical properties of textile fibers are important when they are used for insulation purposes in electrical components. The generation of static electric charges during processing and in use of most of the synthetic fibers has led to many investigations of the electrical properties of textile fibers [36–38]. The static electricity is produced by the friction
Table 2.6  Relative Loss in Strength Due to Exposure to Sunlight

<table>
<thead>
<tr>
<th>Exposed behind glass</th>
<th>Exposed outdoors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bright Orlon</td>
<td>Bright Orlon</td>
</tr>
<tr>
<td>Semidull Orlon</td>
<td>Semidull Orlon</td>
</tr>
<tr>
<td>Bright Dacron</td>
<td>Bright acetate, bright Dacron, bright nylon, type 680 dull nylon, bright rayon, cotton</td>
</tr>
<tr>
<td>Semidull Dacron</td>
<td>Semidull Dacron</td>
</tr>
<tr>
<td>Bright acetate, bright nylon, type 680 dull nylon, bright rayon, cotton</td>
<td></td>
</tr>
<tr>
<td>Silk and most other semidull fibers</td>
<td>Silk and most other semidull fibers</td>
</tr>
<tr>
<td>Most dull fibers excluding dull Dacron or those with a light-degradation inhibitor, such as type 680 nylon</td>
<td>Most dull fibers excluding dull Dacron or those with a light-degradation inhibitor, such as type 680 nylon</td>
</tr>
</tbody>
</table>

Source: Ref. 5.

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

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

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

Resistance to Microorganisms. Natural cellulosic fibers, such as cotton are susceptible to attack by microorganisms such as certain molds and bacteria. Such microorganisms cause the decomposition of the cellulose fibers, leading to a degraded product. Cotton fiber is susceptible to attack by bacteria and microorganisms when stored in warm and damp conditions. Synthetic fibers are resistant to attack by bacteria and mildew.
Resistance to Chemicals, Acids, Alkalies, and Organic Solvents. The processing and use of textile materials usually involves a variety of chemical materials. For example, peroxide-based bleaching agents, dyestuffs, and other dyeing auxiliaries; detergents for washing; alkaline scouring agents; and finishing chemicals. The fibers, therefore, need to be resistant to a variety of chemicals without decomposition and deterioration. Most textile fibers are affected by very strong acids and alkalies; however, many are resistant to moderate concentrations of a variety of chemicals used in processing. During dry cleaning of garments, some organic solvents, such as carbon tetrachloride and trichloroethylene, are used; most natural fibers are insoluble in such organic solvents, but some synthetic fibers do suffer some damage.

2.2.3 Natural Fibers

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

Cotton

Cotton is a natural fiber of vegetable origin which grows on the seed of a plant belonging to the Gossypium family. The cotton fibers are formed on the plant itself as long thin hairs attached to the seeds inside the boll. As the plant grows, the cotton fiber matures and eventually the boll opens up and the cotton appears as a soft fluffy wad of fine fibers, as shown in Fig. 2.10. The cotton boll itself is a fruit, which is formed when the flowers wither and drop from the cotton plant. The full length of a cotton fiber, about two to three thousand times its diameter, is developed inside the boll. During the initial period the cotton fibers grow into a thin-walled hollow tube of cellulose with one end attached to the seed and the other end closed. The fiber at this stage is filled with protoplasm and liquid nutrients drawn from the plant. Once its lengthwise growth ceases the development of the internal structure begins. Figure 2.11 shows a schematic of the gross internal structure of a cotton fiber. The growth of this internal structure is attributed to the deposition of cellulose layers one after the other as a thin cellulose membrane from the inside of the cell. Each growth ring so deposited day by day during the development of the internal structure has two layers, one is compactly packed solid and the other is porous. Figure 2.12 shows a daily development of growth rings in a single fiber swollen and stained for clear visibility. The deposition of cellulose chains is in the form of spiral fibrils. A mature cotton fiber therefore consists of several thousands of fibrils of bundles of cellulose chains arranged in a spiral configuration. Until the cotton boll opens, the fibers remain in their tube-like shape with a circular cross section. The opening of the cotton boll occurs at the completion of the ripening process, when the fibers come in contact with air; consequently, they
lose moisture and the drying causes the collapse of the cell wall. The fiber collapses into a convoluted ribbon form and attains the kidney bean shaped cross section, as shown in Fig. 2.13.

The growth and basic characteristics of numerous varieties of cotton fibers grown all over the world vary inherently due to the genetics (cultivars), environmental conditions, and methods of cultivation. Fiber properties such as length, fineness, and maturity are affected by these factors. Therefore, cotton fibers grown in different parts of the world generally have different properties.
Fig. 2.11  Schematic diagram showing the gross internal structure of a cotton fiber. (From Ref. 57.)

Fig. 2.12  Photomicrograph of a cross section of a single cotton fiber showing the development of growth rings. (From Ref. 40.)
The proportions of short and immature fibers in a cotton variety are two of the many criteria used in determining its quality. Both these properties are important in view of the subsequent processing behavior of cotton fibers. The incidence of an excessive amount of short fibers indicates a poor growth in the early phase of development of the cotton fiber boll. Many fibers with thin walls (immature) indicate interrupted or retarded development of the cell wall during the second phase. The immature fibers, due to lack of cellulose deposition, exhibit poor dyeing affinity, lower strength, and higher flexibility than the mature fibers. Relatively easy bending of the immature fibers gives rise to nep formation. The measurement of the maturity of a cotton fiber is usually made in terms of the degree of cell wall thickening. The maturity ratio is a measure of the degree of development of the cell wall and is expressed as \( \theta \), the ratio of the actual cross-sectional area of the cell wall, \( A \), to the area of the circle with the same perimeter, \( A' \) [43], as shown in Figure 2.1b.

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

where

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

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

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

where \( p \) is the perimeter of the circle.
Therefore,

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

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

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

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

The effective length is the upper quartile of the fiber length distribution obtained by ignoring short fibers whose length is below half the effective length [47]. However, the elimination of short fibers for deriving the effective
length is a reasonable practice since classers also tend to ignore them while estimating staple length manually. Lord and Underwood [47] have reported that a simple relationship can be established between effective length and staple length for American upland cottons of 19 to 32 mm (0.75 to 1.25 in.) lengths. This is given by

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

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

The theoretical analysis of fiber length distribution in terms of frequency, survivor, and beard diagrams is reported by Morton and Hearle [5]. Eventually several methods were developed for the reliable estimation of fiber length [48–52], described fully in standard texts [5,6,11]. The photoelectric scanning principle as used in the Fibrograph instrument is most distinctive [52]. In Fibrograph, fiber samples are presented in the form of a pair of carefully prepared fringes. The light transmitted through these fringes is monitored by photoelectric current. The amount of light passing through the fiber sample is linearly proportional to the number of fibers in the light path. The changes in the photoelectric current are recorded graphically in the form of a Fibrogram,
as shown in Fig. 2.15. From this Fibrogram various length parameters of practical interest, such as mean length (OM), upper-half mean length (OR), and index of uniformity, given as the ratio of OM to OR, can be analyzed.

Flax

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

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

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

Originally, flax was used for sail cloth and tent canvas, sewing threads, fishing lines, table cloths, and sheets, while today linen is used for fine cloths and garments. In recent years, it has also been used in blends with cotton, silk, and polyester fibers for clothing. Owing to its high heat conductivity, the garments feel cool and comfortable in warm weather.
Fig. 2.15  Fibrogram. (From Refs. 5 and 11.)
Hemp

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

Hemp fibers are generally slightly coarser than flax. The color of the raw fiber varies depending upon the retting method and conditions. When
hemp fibers are viewed under the microscope, as shown in Fig. 2.17, cells exhibit a somewhat uneven width and also show many fissures and cross-markings. The lumen is usually indistinct and irregular. The fiber cells are more rounded than those in flax.

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

Jute

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

<table>
<thead>
<tr>
<th>Property</th>
<th>Hemp</th>
<th>Cotton</th>
<th>Flax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber fineness (denier)</td>
<td>3–20</td>
<td>1–3</td>
<td>2–16</td>
</tr>
<tr>
<td>Moisture absorption (%)</td>
<td>8</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Strength (cN/tex)</td>
<td>44–53</td>
<td>26–53</td>
<td>44–53</td>
</tr>
<tr>
<td>Extension at break (%)</td>
<td>2–3</td>
<td>3–7</td>
<td>~3</td>
</tr>
</tbody>
</table>

*Source: Ref. 55.*
world crop comes from India, Bangladesh, and Thailand. After harvesting, the fibers are separated from the stem by a retting process similar to that used for the extraction of flax.

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

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

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

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

![Fig. 2.18](image-url) Longitudinal and cross-sectional views of jute fibers. (From Ref. 41.)
has two coats, the long coarse fibers forming the protective outer coat are called hair, and the short, fine and delicate fibers of the undercoat that keep the animal warm are called wool. Modern cross-bred sheep of different varieties are reared primarily for wool only, where the outer covering of the fleece is relatively small and often totally absent, such as in case of merino wool. The breeds that have a relatively high proportion of coarse hair are generally considered to be of poor breeding. Among many different breeds developed in different parts of the world, the merino sheep is the most important source of quality wool because the outer coating of coarse hair in this breed is virtually absent. The merino sheep produces fine, soft, and delicate wool. Australia, South Africa, and South America, are the main countries where large flocks of merino sheep are raised.

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

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

\[
\begin{align*}
\text{R}_1 & \quad \text{CO} \quad \text{NH} \quad \text{R}_2 \\
\text{CH} & \quad \text{NH} \quad \text{CO} \quad \text{CH} \\
\text{CO} & \quad \text{R}_3 \\
\text{NH} & \quad \text{CO} \quad \text{CH}
\end{align*}
\]

The polypeptide chains of the keratin molecules are cross-linked to the adjacent chains through cystine linkages of the covalent disulfide type:
However, the intermolecular cross-linking known as salt linkages forms between free acidic and basic side chains, e.g., between those of glutamic acid and lysine [56]. Some cross linking can also occur due to hydrogen bonding between the hydroxyl groups (OH).

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

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

The outer sheath, or epicuticle, is a nonprotein thin water-repellent membrane acting as waterproof coating. However, this epicuticle has tiny microscopic pores through which water vapor permeates into the internal structure of the fiber. Thus, the water vapor from the perspiring human body is absorbed by this outer sheath into the interior of the wool fiber without a feeling of dampness. This absorbed water is eventually released slowly into the air. Beneath the epicuticle is the cuticle, scalelike cells which overlap each other like the shingles on a roof. The free end of these cuticular scales is pointed toward the tip of the fiber. This upward pointing of the free ends of these cells imparts a special frictional effect to wool fibers, particularly when they are rubbed in the direction opposite to the fiber tip, thus creating a differential frictional effect. The cortex—the core of the fiber—is enclosed within the cuticle and forms more than 90% of the total weight of the wool fiber. The cortex consists
of millions of long spindle-shaped cortical cells thick in the center and tapering toward each end. However, recent studies of detailed examination of very thin transverse and longitudinal section reveal that the cortical cells may be regarded as space-filling polyhedra with unlimited sharing of faces and corners [57]. These cortical cells are built up of fibrous components known as fibrils. The cortex of a wool fiber is shown to have a bilateral structure; one side is called paracortex and the other orthocortex. The chemical structures of proteins in these two forms are different. The orthocortex cells are clearly differentiated into macrofibrils, which are large aggregates of the microfibrils. The paracortex cells are packed more compactly, and division into large macrofibrils is indistinct [58–60]. The dyeing affinities of para- and orthocortex are different due to their different chemical compositions; the paracortex being more stable.
is less accessible to dyes than the orthocortex. This bilateral structure imparts
to the fiber a crimped form that is in phase with the mutual twisting of the
two components. Only coarse wool fibers have a hollow space in the center
running along the length of the fiber, which is known as medulla. Fine wool
fibers do not have a medulla.

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

The length of wool fibers varies between 38 to 125 mm (1.5–5 in.) for
fine wools, 65–150 mm (2.5–6 in.) for medium wools, and 125–375 mm
(5–15 in.) for coarse wools. The natural luster of wool varies and largely
depends on the type of wool and the surface of the fiber, which reflects light.
The density of the wool fiber is 1.32 g/cm³, which is slightly lower than that
of cotton. The wool fibers have relatively lower tenacity but high extensibility,
which are attributable to the chemical cross-linking of molecular chains of
protein molecules. Wool fibers do not show very good recovery under very
high stresses, particularly under humid conditions, but show reasonably large
recovery from high strains. This high resiliency of the wool fibers and their
characteristic of elastic deformations under small stresses make them highly
desirable for apparel fabrics.

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

Mohair

Although wool is the most widely used natural fiber from animal origin, other
animal fibers, such as mohair and cashmere, have carved out their own market
share in niche products. Mohair is considered a relatively luxury fiber compared to wool. The long, relatively finer, straight, smooth, and lustrous fiber in the single coat of the Angora goat is called mohair [61,62]. The Angora goat is a unique breed known to mankind in ancient times and is believed to have originated in the Asian Himalayan regions [62]. Good quality mohair is produced today in South Africa, Turkey, and the United States. South Africa accounts for a market share of about 60% of the world production of mohair [62].

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

Fig. 2.20  Structure of mohair fiber. (From Refs. 62 and 63.)
Mohair appears circular in cross section, with small spots caused by entrapped air bubbles, as shown in Fig. 2.21. The longitudinal structure exhibits scales at high magnification, as shown in Fig. 2.22. Due to its thinner scale structure compared to wool, mohair exhibits better luster, smoothness, and lower friction and felting properties. The length and fineness of mohair fibers vary according to the age of the animal. An Angora kid of about six months would yield fibers from 100 to 150 mm in length with fineness of about 25 to 30 \( \mu \text{m} \). Fully grown Angora goats would produce mohair fibers from 225 to 300 mm in length (12 months growth) with fineness of about 35 to 40 \( \mu \text{m} \). Most physical properties of mohair are generally similar to those of wool. For a detailed account of the physical and chemical properties of the mohair fiber, readers are referred to the review by Hunter [63] and recent publication by Hunter and Hunter [62]. However, mohair has better abrasion resistance than wool, attributed to its thinner scale structure, which in turn results in better wear resistance. Therefore, mohair finds its best application in products, such as fabrics for upholstery, throws, and carpets, where durability is the most important consideration. Mohair is generally more expensive than wool, so it is also used for blending in small proportion with wool for producing cost-effective apparel fabrics with desirable characteristics.

Cashmere

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

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

Camel Hair

Camel hair of textile value is produced from the two-humped Bactrian camel mainly found in Mongolia and Northern China. The camel grows two types of fibers, outer protective hair which is coarse and long and an insulating fine undercoat of medium length. This undercoat yields soft, fine, and long...
fibers of textile value used for producing blended fabrics, overcoats, dressing gowns, and knitwear. The hairs from the coarse outer coat are mainly used for ropes, tents, carpet backing, and heavier outer garments in the areas where these camels are reared. Unlike the shearing of wool, mohair, and cashmere, the harvesting of camel hair is a natural process. The camel molts when the fibers form matted tufts that hang down from the camel head, sides, neck, and legs. These fibers are harvested by pulling or by gathering the clumps [67]. Each animal yields about 2.5 to 5.0 kg of fiber per year.

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

Alpaca, Llama, Vicuna, and Other Fibers

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

![Fig. 2.23 Longitudinal and cross-sectional views of camel hair. (From Ref. 67.)](image)
gentina. Alpaca and llama are also raised in the United States, Canada, New Zealand, and the UK in small population.

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

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

Silk

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

The cocoons are soaked in hot water to soften the sericin gum around them. In turn the filaments from several such softened cocoons are thrown (i.e., twisted) and reeled in the form of skeins. The natural gum, sericin, is usually transferred onto the filament during this reeling process. It acts as a sizing material and prevents the yarn from mechanical damage during weaving.
Fig. 2.24  Longitudinal and cross-sectional views of (a) alpaca, (b) llama, and (c) vicuna fibers. (From Ref. 67.)
Therefore, silk fabric woven with sericin gum on it has a rough handle and harsh feel. The process of degumming may be carried out on yarns or fabrics by boiling with soap and water. There are some silk cocoons that cannot be extracted in the form of continuous filament yarn during the process of throwsting; such cocoons are used to produce waste silk which is then used in staple form.

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

2.2.4 Manmade Fibers

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

Fig. 2.25 Longitudinal and cross-sectional views of silk fibers. (From Ref. 41.)
other properties, such as thermoplasticity and unique surface characteristics, which require careful consideration when selecting sizing ingredients and slashing parameters.

Manmade fibers are usually described under two main headings:

1. Regenerated fibers
2. Synthetic fibers

Regenerated Fibers

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

Regenerated Cellulosic Fibers

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

Viscose Rayon. Viscose rayon is a regenerated cellulosic fiber. The cellulose comes from cotton linters or wood pulp. The cellulose from wood, straw, cotton linters, and similar sources usually contains gummy material known as lignin. Therefore, the first step in the production of viscose rayon involves the purification treatment of wood pulp with caustic soda, which converts it into alkali cellulose. After aging, the alkali cellulose is treated with carbon disulfide to form sodium cellulose xanthate and then dissolved in a solution of caustic soda. It is then allowed to ripen for several days at a controlled temperature. During the process of ripening, the solution is filtered repeatedly. The viscosity of this solution decreases initially and then increases nearly to its original viscosity; the solution is then spun into an acidic coagulating bath. The coagulating bath contains a predetermined mixture of sulfuric acid, sodium sulfite, zinc sulfate, and glucose, which precipitates the cellulose in the form of a solidified viscose filament. The filament is then drawn and wound on packages. Depending on the ways in which the filaments are treated after they emerge from the coagulating bath, the process is termed either pot or box spinning, bobbin spinning, or continuous spinning. The pot and bobbin
spinning processes are intermittent in nature since batches of spun filament are subjected to further treatment as and when they are available. Such batch processes are inevitably expensive in terms of labor and operating costs. Moreover, the discontinuous operation is susceptible to quality variations between batches. Therefore, modern manufacturers have adopted the continuous spinning technique for production. The spun continuous filaments can either be twisted to form continuous filament yarns or may be mechanically converted into staple fiber of the desired length for blending with other fibers to spin staple yarns.

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

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

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

**Cuprammonium Rayon.** This is a regenerated cellulosic fiber produced from cellulose dissolved in a mixture of copper sulfate and ammonia, called cuprammonium liquor or ‘‘cupro.’’ This liquor is extruded from a spinnernet to form filaments in the coagulating bath. The raw materials used are cotton linters and wood pulp. Purified cotton linters or wood pulp is mixed into the cuprammonium liquor at a low temperature, and it is then kneaded until it gives a clear blue solution. This solution is then deaerated and filtered through nickel gauze. This solution is stable even after long storage and does not
decompose, which is not the case when considering viscose solution. The
deaerated and filtered solution is metered by a pump into a nickel spinneret
and extruded into a stream of pure water to dissolve most of the ammonia and
some copper. This action solidifies the cellulose into pseudoplastic filaments,
which may be drawn to achieve the desired linear density. The drawn filaments
are then passed around a roller running in a trough of sulfuric acid, which
completes the process of coagulation of the cellulose and removes the remain-
ing copper and ammonium sulfate from the yarn. In batch processes, such as
reel or pot spinning, the filaments are wound either into skeins or cakes and
subsequently washed to eliminate any traces of acid, copper, and ammonium
sulfate, then softened by adding lubricants, and finally dried. In a continuous
spinning process, the filaments are never handled during the intermittent pro-
cess thus making regular, uniform, and good quality cupro filaments.

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

**Acetate and Triacetate.** Cotton linters and wood pulp are used as raw
materials for producing acetate and triacetate regenerated cellulose fibers.
However, unlike in viscose and cupro rayons, the wood or cotton cellulose is
chemically modified to a different substance—cellulose acetate—to make it
spinnable, and after spinning the cellulose is left in its modified form as a
fiber. The purified cotton linters or wood pulp is soaked in glacial acetic acid
to make it more reactive so as to readily acetylate. The cellulose fibers soaked
with an excess of acetic acid and acetic anhydride are transferred to a closed
reaction vessel fitted with a powerful stirrer. All the ingredients are thoroughly
mixed together; however, no chemical reaction yet begins. A small quantity
of sulfuric acid dissolved in roughly eight times its weight of glacial acetic
acid is added to initiate the acetylation process. The acetylation reaction is
highly exothermic in nature; the solution is maintained at a temperature below
20°C by cooling for the first hour and at 25 to 30°C for the next 7 to 8 h. This
reaction yields primary acetate (cellulose triacetate), in which three carboxyl
groups of each glucose unit are substituted by the acetate groups. The cellulose
triacetate is then partially hydrolyzed by allowing it to remain in water for up to 20 h. During this process, the completely acetylated cellulose triacetate is transformed into a secondary acetate. The secondary acetate is precipitated from an aqueous solution and then dried. The flakes of secondary acetate are ground and used in spinning acetate filaments by any of the three spinning processes, namely, dry spinning, wet spinning, or melt spinning. In addition, acetate fibers are also spun in various modified forms by manipulating the spinning process. Spun-dyed acetate fibers are produced by adding pigments to the spinning solution before extrusion. Titanium dioxide is added to diminish the natural luster. The orifices of the spinneret are modified to shapes other than circular to produce many variations in the cross-sectional shapes of the fibers. Fancy yarns, such as those with thick and thin places and slubs, are produced by varying the rate of feed of the solution to the spinneret.

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

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

Triacetate fiber shows striations along its length and has a multilobal cross section, as shown in Fig. 2.28. The properties of triacetate fibers are similar to those of acetate fibers except for handle, moisture absorption, and thermal behavior. Unlike the soft handle of acetate, triacetate has a firm and
crisp handle. Because of the nonavailability of hydroxyl groups, triacetate has poor moisture regain (2.5%) and water absorption characteristics. This makes it difficult to size. Triacetate is thermoplastic in nature and softens when heated to 170°C. During heating, the internal stresses generated in the manufacturing process are relieved, which allows the molecular orientation to take place along the fiber axis in the crystalline regions, resulting in increased crystallinity and better packing. The thermoplasticity of triacetate well below its melting point, technically known as heat setting, provides an excellent means of stabilizing shrinkage of fabrics, thereby imparting better dimensional stability. This heat-setting characteristic of triacetate fabrics can be advantageously used by inducing deliberate thermomechanical distortions to mold fabrics into desired shapes. The fabrics can be held permanently in that shape after setting, for example, in setting pleats and creases permanently in triacetate garments such as ladies’ skirts.

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

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

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

Fig. 2.28 Longitudinal and cross-sectional views of triacetate fibers. (From Ref. 41.)
pletely environmentally friendly unlike other synthetic fibers that contaminate the atmosphere, earth, and water due to emissions. Because it is produced from cellulose, it is biodegradable; though it will not disintegrate completely if disposed of in a landfill. The products made from lyocell can be recycled, incinerated, or digested in sewage. The degradation of the fiber takes place in about 8 to 10 days.

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

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

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

*Source: Ref. 69.*
characteristics can be enhanced further by surface effects and different textures to simulate silk, suede, and leather touch.

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

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

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

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

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

*Alachin.* Alachin is a protein obtained from groundnuts. The solution of groundnut protein in dilute caustic soda is allowed to mature for 24 h under
controlled conditions, until a suitable viscosity is achieved. This solution is filtered and then extruded from the orifices of the spinneret into an acid coagulation bath containing a solution of sulfuric acid, sodium sulfate, and other auxiliary chemicals. The temperature of the coagulating bath is maintained between 12 and 40°C. The groundnut protein fibers have a soft woollike handle and are primarily used advantageously in blends with wools because of their low cost. However, it is also used in blends with cotton and rayon for the production of fabrics for shirting, pajamas, dress materials, tropical clothing, sport shirts, carpets, etc.

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

Miscellaneous Regenerated Fibers

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

Alginate fibers are round to oval in cross section with a serrated outline. The tenacity of dry alginate fibers varies from 14.1 to 17.7 cN/tex (1.6 to 2.0 g/den) and elongation to break from 2 to 6%. However, the wet tenacity is very low (4.4 cN/tex). Alginate fibers are nonflammable but decompose to ash when
Alginate fibers are insoluble in water but readily dissolve even in a mild alkali such as soap water. This is a serious drawback, limiting its practical use for textile applications. However, alginate fibers are used in knitting hosiery such as socks to form the bridge between two units, thus enabling continuous production. The socks are later separated by cutting and dissolving the courses of alginate yarns in an alkaline solution. This enables the production of defect-free welts of socks of all types. In medical use, sodium/calcium alginate is used as styptic elastic dressings, which is nontoxic and absorbable in the bloodstream. It is also used in dental surgery for plugging cavities.

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

Carbon Fiber. Carbon fiber is defined as a fiber containing at least 90% carbon, obtained by the controlled pyrolysis of appropriate fibers. The term ‘‘graphite fiber’’ is applied to fibers that have more than 99% carbon. Large varieties of fibers called precursors are used to produce carbon fibers of specific characteristics. The most commonly used precursors are polyacrylonitrile (PAN), cellulosic fibers (viscose rayon, cotton), petroleum or coal tar pitch, and some phenolic fibers. The application of heat to the precursor removes the oxygen, nitrogen, and hydrogen to form carbon fibers. The production techniques used vary depending upon the precursor, but in general it involves the steps of oxidation and carbonization.
The properties of carbon fibers depend upon the type and properties of the precursor, the processing conditions and the degree of heat treatment. In general, the higher the tensile strength of the precursor, the higher is the tenacity of the carbon fiber. Tensile strength and modulus are significantly improved due to carbonization. The tensile strength of carbon fiber is almost three times that of steel, with density of only 1.75 g/cm\(^3\) (steel: 7.87 g/cm\(^3\)). This makes carbon fibers suitable for aerospace applications, where lighter materials in aircraft construction lead to fuel savings.

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

Glass Fiber

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

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

When used on its own in the form of single, plied, or cabled yarn, glass fiber can be woven, braided, or converted into sleeves. Glass fibers have found many applications as reinforcement in thermoplastic composites. The glass reinforcements are made in various forms in order to make them suitable for a variety of processes and to provide desired thermomechanical and electrical properties.
Notable textile applications of glass fibers are in printed circuit board, electrical insulation (tapes, fabrics, cable reinforcement, and braided tubes), air filtration, anticorrosion reinforcement, adhesive tapes, sports and leisure goods, roofing membrane reinforcement, coated fabrics, wall covering, decorative fabrics, clutch discs, brake linings, and other aircraft and marine uses.

Synthetic Fibers

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

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

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

\[
\text{NH}_2(CH_2)_6\text{NH}_2 + \text{HOOC(CH}_2)_4\text{COOH} \rightarrow \text{CONH(CH}_2)_4\text{NH CO(CH}_2)_4\text{CONH(CH}_2)_6\text{NHCO(CH}_2)_4\text{CO}\
\]

\text{Hexamethylene Diamine} \quad \text{Adipic Acid} \\
\text{---CONH(CH}_2)_4\text{NH CO(CH}_2)_4\text{CONH(CH}_2)_6\text{NHCO(CH}_2)_4\text{CO---} \\
\text{NYLON 6.6}
It is referred to as nylon 6.6 because each of the components contains 6 carbon atoms.

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

\[
\begin{align*}
\text{CH}_2 & \quad \text{CH}_2 \quad \text{CH}_2 \quad \text{CH}_2 \quad \text{CH}_3 \\
\text{CO} & \quad - \quad - \quad - \quad - \quad - \quad \text{NH}
\end{align*}
\]

\[\text{CAPROLACTAM}\]

\[\text{-NH(CH}_2)_5\text{CONH(CH}_2)_3\text{CONH(CH}_2)_2\text{NYLON 6}\]

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

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

1. The melting point of nylon 6.6 is higher (about 250°C) than that of nylon 6 (215°C). Therefore, nylon 6.6 has a better resistance to high temperature and can withstand higher temperatures without a loss in tensile strength.
2. Nylon 6 has a better elastic recovery and resistance to fatigue.
3. Both nylon 6 and nylon 6.6 suffer degradation and turn yellowish under ultraviolet light to varying degrees when exposed to sunlight for extended periods. Nevertheless, additives are used to stabilize yarns against degradation by ultraviolet radiation.
4. When dyed with acid dyes in the same dye bath, nylon 6 will pick up deeper shades than nylon 6.6, although the fastness is generally better for nylon 6.6.
5. Nylon 6 fibers blend more easily with other fibers than nylon 6.6. The softer handle of nylon 6 is advantageous in some applications, such as in the manufacture of tricot fabrics and in fabrics produced from false-twisted textured yarns.
Both nylon 6.6 and nylon 6 are produced to different fineness and either as staple fiber or as continuous multi- or monofilaments, as desired. The cross-sectional shape of nylon fiber is rodlike, round, and with a smooth surface, with no longitudinal striations, as shown in Fig. 2.30. Some special types of nylon fibers are produced with trilobal or multilobal cross sections (as shown in Fig. 2.31) for certain end uses.

Nylon fibers have tenacities varying from 40 to 50 cN/tex for low tenacity fibers to as high as 79.5 cN/tex for high tenacity fibers. The elongation at break of high tenacity nylon is about 19 to 24% as compared to 30 to 37% for regular filament and staple. The elastic recovery of nylon fiber is quite high, almost
100% at 8% extension for regular filaments. The initial modulus of regular nylon filaments varies between 350 to 530 cN/tex. Nylon has a moisture regain of only 4 to 4.5%, which is quite low in comparison with most natural fibers. Nylon can withstand temperatures of up to 150°C without appreciable loss in strength. Due to the thermoplasticity of nylon fibers, it can be readily heat set at 205°C for attaining desired dimensional stability and crease resistance in fabrics. The resistance of nylon to some chemicals such as alcohols, aldehydes, alkalis, ethers, dry cleaning solvents, soaps, detergents, etc., is quite good. However, concentrated hydrochloric acid and sulfuric acid (above 5.0%) degrade the fiber and cause a loss in tensile strength. Oxalic acid, even at a 3.0% concentration, causes severe deterioration at elevated temperatures of about 100°C. The burning resistance (flammability) of nylon fiber is considered very satisfactory for all textile applications because when ignited it melts and falls away, and the flame extinguishes itself and inhibits further flame propagation. Nylon has a very good dye affinity and may be dyed with a wide range of dyestuffs.

Nylon fibers and filaments are used in a variety of textile applications, such as woven and knitted apparel, furnishings, and household textiles because
of their excellent mechanical properties and wear resistance. They are also extensively used in carpets and industrial applications such as tire cords, hoses, parachutes, conveyor and transmission belts, and filter fabrics.

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

\[
\begin{align*}
\text{NH}_2 & \quad -NH_2 + \quad \text{ClCO} \quad \text{COCl} \\
\text{Amide} & \quad \text{Solvent} \\
\left[\begin{array}{c}
\text{NH} \\
\text{NH} \\
\text{CO} \\
\text{CO}
\end{array}\right] & \quad + \quad 2\text{HCl}
\end{align*}
\]

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

Kevlar fiber is used in fabric form for producing bullet-proof vests, and the Kevlar reinforced composite materials for other hard armor applications.
The ballistic resistance of Kevlar fiber–based material is found to be much higher than that of nylon-based fabric [72]. Other areas of application of Kevlar fibers are protective clothing, helmets, tire and drive belt reinforcements, structural supports for aircraft and boats, parachute fabrics, conveyor belts and high pressure hoses, automotive hoses, ropes and cables, automotive clutches, disk brakes, and brake shoes.

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

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

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

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

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

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

![Chemical Structure](image1)

Ethylene Glycol + Terephthalic Acid

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

![Chemical Structure](image2)

1,4 Cyclohexanediol + Terephthalic Acid

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

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

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

**Polybutylene Terephthalate (PBT).** The modification of polyester is an important area of research aimed at developing new fibers with new characteristics and performances. PBT is also a class of polyester obtained by the polymer-
ization of 1,4-butylene glycol with DMT or PTA. The resultant chemical structure of PBT is as shown:

\[
\begin{array}{c}
\text{CO} \quad \text{O} \\
\text{CO} \quad (\text{CH}_2)_4 \quad \text{O} \\
\end{array}
\]

**Polybutylene Terephthalate**

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

Polybutylene terephthalate is available in continuous filament form with different deniers and numbers of filaments. PBT can be textured due to its ther-
Fig. 2.33  Longitudinal and cross-sectional views of trilobal polyester. (From Ref. 6.)
moplasticity. PBT fiber has high stretch and recovery with low ductility, good
tensile strength, and resistance to chlorine, chemicals, and UV light. PBT fiber
is soft, supple, lustrous, and pleasant to the touch. Due to low humidity take-
up levels (~0.4%), PBT dries up very quickly. PBT fibers process well both
in weaving as well as knitting. Therefore, PBT fibers are used in sportswear,
gymnastic clothing, underwear, and swimsuits where good recovery and shape
retention are necessary.

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

\[
\begin{align*}
\text{Terephthalic Acid} & \quad + \quad \text{1,3-propanediol} \\
\begin{array}{c}
\text{HO} - \text{C} - \text{OH} \\
\text{HOCH}_2\text{CH}_2\text{OH}
\end{array}
\end{align*}
\]

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

Polytrimethylene terephthalate fibers have higher elastic recovery than
PET and nylon 6.6. Table 2.9 shows the comparison of some physical proper-
ties of PTT to polyester and nylon 6.6 [75]. Unique softness attributed to a low
Young’s modulus and excellent elastic recovery under low load of PTT fiber
creates a high wearing comfort and a rich drape. The unique tensile behavior
Table 2.9  Comparison of the Physical Properties of PTT, PET, Nylon 6.6, PEN, and Fibers

<table>
<thead>
<tr>
<th>Property</th>
<th>PTT</th>
<th>PET</th>
<th>Polyamide (nylon) 6.6</th>
<th>PEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (cN/tex)</td>
<td>33.5–37.1</td>
<td>37.1–44.1</td>
<td>41.5–45.0</td>
<td>80–90</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>36–42</td>
<td>30–38</td>
<td>32–44</td>
<td>5–8</td>
</tr>
<tr>
<td>Initial modulus (cN/tex)</td>
<td>230</td>
<td>970</td>
<td>310</td>
<td>2000–2300</td>
</tr>
<tr>
<td>Elastic recovery at 20% elongation</td>
<td>88</td>
<td>29</td>
<td>62</td>
<td>—</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.34</td>
<td>1.38</td>
<td>1.14</td>
<td>1.36</td>
</tr>
<tr>
<td>Moisture regain (%)</td>
<td>0.4</td>
<td>0.4</td>
<td>4.5</td>
<td>0.2–0.4</td>
</tr>
<tr>
<td>Shrinkage at boiling (%)</td>
<td>14</td>
<td>7</td>
<td>13</td>
<td>3–5</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>230</td>
<td>254</td>
<td>253</td>
<td>270–275</td>
</tr>
</tbody>
</table>

Source: Refs. 75 and 76.

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

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

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

Due to superior properties of PEN fibers, they are used in differentiating products such as tire reinforcement, geotextiles, high performance sailcloth, automotive seatbelts, hoses and drive belts, rope and cordage, composite reinforcement, and tents and tarpaulins.
Chapter 288

**Polyvinyl Derivatives.** The compound containing the vinyl group (—CH₂=CH—) having a double bond are polymerized to form a long-chain molecule by the process known as addition polymerization. The resultant polymers are called polyvinyl compounds. Addition polymerization is a process in which a polymer is formed by the addition of one monomer to another without the elimination of water or other molecules. Polyvinyl compounds have been used in the making of a number of synthetic fibers. Out of the many different classes of fibers spun from polyvinyl derivatives some of the most important fibers are discussed below.

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

**Acrylic Fibers.** Acrylic fibers are spun from polymers containing at least 85% by weight of acrylonitrile units (—CH₂—CH(CN)—). Earlier polyacrylonitrile fibers were spun by homopolymerization of 100% by weight of acrylonitrile units. However, all modern types of acrylic fibers are spun from at least 85% by weight of acrylonitrile copolymer. The other 15% of the comonomer unit may include any of the most commonly used monomer such as vinyl chloride, vinyl acetate, methyl acrylate, and 2-vinyl pyridine.

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

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

*Modacrylic Fibers.* These fibers are spun from many different co-polymers of acrylonitrile. The polymer contains less than 85% by weight of acrylonitrile units (—CH₂—CH(CN)—). However, like acrylic fibers, details of the chemical structure of individual modacrylic fibers are seldom made available by different manufacturers. Verel® is a modified acrylic fiber containing between 35 and 85% acrylonitrile, first introduced by Eastman Chemical Products Inc. This fiber is manufactured in staple form, but in various deniers ranging from 3 to 40 in bright or dull luster. The modacrylic fibers are spun in 100% form or in blends with wool, cotton, viscose, nylon, and polyester.

The most outstanding characteristic of modacrylic fibers is their good dyeability. These fibers generally have higher moisture regain (3.5 to 4.0%) in comparison with other acrylic fibers, their tenacity ranges between 15 and 21 cN/tex, and breaking extension of 30 to 35% under standard atmospheric conditions. Despite higher moisture regain of modacrylic fiber, its mechanical properties are only slightly affected. This fiber has very good flame retardancy as it self-extinguishes but does not get ignited easily.
Chapter 2

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

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

\[
\text{CH}_2 = \text{C} = \text{Cl} \rightarrow \text{CH}_2 - \text{CH} - \text{CH}_2 - \text{CH} - \cdots
\]

Vinyl Chloride \hspace{1cm} Polyvinyl Chloride (PVC)

Polyvinyl chloride fibers may be further classified as follows:

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

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

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

\[
\text{CH}_2 = \text{CHOH} \rightarrow \underbrace{\text{CH}_2 - \text{CH} - \text{CH}_2 - \text{CH}}_n \text{ OH} \quad \text{OH}
\]

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

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

**Polyethylene.** When gaseous ethylene or its copolymers are polymerized a solid substance is formed which can be extruded to produce fine fibers:
Polyethylene fibers are commonly produced in the following forms:

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

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

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

A recent development in this class of fibers is ultra high molecular weight polyethylene, commercially known as Spectra®. This fiber is characterized by ultra high strength and ultra low weight and is produced in a continuous filament form. On an equal weight basis, Spectra is 10 times stronger than steel. The tenacity of Spectra 900 and Spectra 1000 are 265 and 309 cN/tex, respectively, which is also slightly higher than that of Kevlar 29 (194 cN/tex). Elongation of Spectra 900 is 3.5%, and that of Spectra 1000 is 2.7%. The melting point of both Spectra 900 and Spectra 1000 is 147°C. The moisture regain of Spectra is only
1.0%. Spectra has excellent resistance to corrosive chemicals and solvents, a low dielectric constant, and excellent cut resistance. Spectra is most suited for ballistic applications, including armored panels, helmets, protective shields, and radomes. Due to its light weight and high strength it can be advantageously used in aircraft armor, vehicle armor, and naval armor. In composite forms, Spectra can also be used for boat hulls, sports equipment, structural supports, and pressure vessels. The high cut resistance of Spectra is useful in such applications as gloves for surgeons, tailors, and butchers.

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

\[
CH_2 = CH - \rightarrow -CH_2 - CH - CH_2 - CH - \cdots
\]

Propylene

\[
\text{Polypropylene}
\]

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

Polypropylene fibers can be produced in a number of different forms and physical properties by varying the conditions of polymerization, spinning, and processing. Polypropylene fibers are produced in the form of multifilament, monofilament, staple, and tow. The fibers are also produced in a wide range of pig-
mented and spun-dyed forms. In recent years, some dyeable forms of polypro-
pylenes have also been produced commercially. But such fibers usually have
poorer mechanical properties. Polypropylene fibers are produced in a variety of
different tenacities to suit specific end-use requirements. For general purpose
textile uses, fibers with a medium tenacity of 26 to 44 cN/tex are used. For certain
special applications, they are produced with a higher tenacity of up to 115 cN/
tex. The density of amorphous polypropylene is 0.85 g/cm³, and that of highly
crystalline polypropylene varies from 0.92 to 0.94 g/cm³. Thus polypropylene
fibers are lighter than water and have a covering power greater than that of any
other textile fiber. Polypropylene does not absorb any water, and its moisture
reagin is negligibly low. The softening point of polypropylene fibers is in the
region of 150°C, and the fibers melt between 160 to 170°C. Polypropylene fibers
burn when exposed to flame but extinguish when removed from the flame. Poly-
propylene has the lowest thermal conductivity and therefore exhibits the
“warmest” feel. It has excellent resistance to alkalis, acids, and general purpose
organic solvents and laundry agents. However, polypropylene fibers are prone
to UV degradation. Consequently, UV stabilizers and flame retardant additives
are blended with the polypropylene chips before melt spinning. Polypropylene
fibers have excellent processing behavior because their fiber-to-fiber friction is
high, and they have good crimp retention behavior. Polypropylene fibers have
high abrasion and bending resistance, which are particularly important for their
applications in carpets and floor coverings. Polypropylene fibers are extensively
used in blankets, upholstery, carpets, ropes, fishing nets, and fishing lines. In
apparel applications, 100% pure polypropylene fiber is used in the knitwear field
for sportswear, socks, stockings, and hosiery and in blends with other cellulosic
fibers, such as rayon.

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

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

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

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

\[
\begin{align*}
\text{Cl} & \quad \text{-} \quad \text{Cl} + \text{Na}_2\text{S} \quad \xrightarrow{\text{Heat}} \quad \left( \text{S} \right)_{n} \quad + \quad 2\text{NaCl} \\
\text{Para-dichlorobenzene} & \quad \text{Sodium Sulfide} & \quad \text{Polyphenylene Sulfide (PPS)}
\end{align*}
\]

The most outstanding property of polyphenylene sulfide fiber is its high heat and chemical resistance, self-extinguishing flame retardancy, electrical insulating...
property, and excellent resistance to acids, alkalis, organic solvents, and oxidizing agents, besides good mechanical and physical properties. This unique combination of various properties is advantageously used in woven or nonwoven form for applications subjected to elevated temperatures, for example, filter bags for filtration of flue gases from coal-fired boilers. Other important applications include papermakers' felts, protective clothing, composites, and electrical insulation materials.

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

![Polybenzimidazole Repeating Unit](image)

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

Polybenzimidazole fiber is produced both in filament and in staple fiber form with a round cross section. The stabilized variant of PBI sold as a staple fiber has a tenacity of about 2.3 cN/tex, with 30% breaking elongation and an initial modulus of 39.6 cN/tex. The density of the fiber is 1.43 g/cm³, and moisture regain is 15% at standard atmospheric conditions. PBI is intrinsically nonflammable in air [78,79]. However, the mechanical behavior of fibers at elevated temperatures is adversely affected. The tenacity of stabilized PBI drops by almost 75% when the fibers are heated from 100 to 450°C, whereas the elongation
of the fibers remains practically constant up to 350 to 370°C and then drops rapidly from 30 to 5% at 450°C [77]. PBI fibers exhibit outstanding chemical stability even in severe environments, and the fiber strength is unaffected by exposure to organic liquids at 86°C for 168 h [78,79]. The high moisture regain (15%) of PBI fibers together with their soft handle contribute to wear comfort, which is as good as that of cotton and rayon.

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

Polytetrafluoroethylene (PTFE). DuPont pioneered the development of PTFE, commercially marketed under the brand name Teflon®, as a nonstick coating for cooking utensils. It was observed that tetrafluoroethylene (CF₂=CF₂) gas when polymerized forms a waxy, insoluble and nonmelting powder with many useful attributes. It is a polymeric compound based on fluorine, which is highly volatile and reactive element in its natural gaseous state. Tetrafluoroethylene is polymerized to PTFE under heat and pressure with the aid of a catalyst. It is not possible to extrude PTFE into fiber as it cannot be melted or dissolved in other media. Teflon fiber is produced from a spinnable composition containing a blend of finely divided particles of Teflon resin with a matrix containing binder. Teflon (polytetrafluoroethylene) is made up of chains of carbon atoms fully saturated by fluorine atoms. The chemical structure of Teflon fiber is:

```
  F   F   F   F   F
   C   C   C   C
  F   F   F   F
```

**Polytetrafluoroethylene**

Teflon is produced in different forms, such as resin, dispersions, sheets, and fibers. Teflon fiber with circular cross section is available in multifilament yarns, staple, and flock, with different deniers, number of filaments, and staple lengths suitable for downstream processing into woven, knitted, and braided structures.
The color of Teflon fiber can be natural dark brown or in bleached white form, as required.

As fiber, Teflon contains long polymeric chains with high tensile and compressive strength. Teflon has a density of 2.2 g/cm³, and it displays an excellent combination of physical, chemical, and thermal properties. Teflon can withstand temperatures up to 260°C continuously for an extended time with a short-term peak temperature of 290°C. At very low temperatures of about −268°C, Teflon fibers become less ductile but still remain serviceable in certain applications. Teflon fiber is extremely resistant to direct sunlight; an exposure to direct sunlight and weather for a period of three years has shown negligible reduction in breaking strength (2%). The coefficients of static and dynamic friction of Teflon are the lowest among all known fibers. Therefore, it finds increased applications where maintenance-free, nonstick, and easy-slipping attributes are desirable. Teflon fiber exhibits an elongation at break of 19%, with a moderate tensile strength of about 13 cN/tex. The tensile strength is not affected much by moisture content. The thermal shrinkage of up to 25% at 300°C is useful for thermal setting during the texturing operation. The low electrical conductivity of Teflon makes it useful as an electrical insulation material, particularly at high temperatures ranging between 175–290°C. The chemical resistance of Teflon fibers to all known acids, alkalis, halogens, and oxidizing agents is far higher than any known organic fiber [80].

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

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

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

Polylactic acid is readily converted into a variety of fiber forms, using conventional melt-spinning processes. Monocomponent or bicomponent, con-
Table 2.10  Key Performance Features of PLA Fiber

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

Source: Ref. 82.

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

2.3  STAPLE YARN SPINNING SYSTEMS

Spinning is the final stage in the series of processing operations used for producing a staple yarn. In this process, two operations are performed consecutively, namely [86,87],
Table 2.11  Comparison of the Key Properties of PET and PLA Fibers for Apparel

<table>
<thead>
<tr>
<th>Property</th>
<th>PET</th>
<th>PLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture management</td>
<td>Good wicking</td>
<td>Better wicking</td>
</tr>
<tr>
<td></td>
<td>Contact angle = 0.135</td>
<td>Contact angle = 0.254</td>
</tr>
<tr>
<td></td>
<td>0.2–0.4% moisture regain</td>
<td>0.4–0.6% moisture regain</td>
</tr>
<tr>
<td>Flammability</td>
<td>Burns 6 min after flame</td>
<td>Burns 2 min after flame</td>
</tr>
<tr>
<td></td>
<td>removal</td>
<td>removal</td>
</tr>
<tr>
<td>Resilience</td>
<td>51% recovery at 10% strain</td>
<td>64% recovery at 10% strain</td>
</tr>
<tr>
<td>Renewable resource</td>
<td>Petroleum based</td>
<td>Dextrose based (corn)</td>
</tr>
<tr>
<td>Drape/hand</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Luster</td>
<td>Medium to low</td>
<td>Very high to low</td>
</tr>
<tr>
<td>Crease resistance</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.34</td>
<td>1.25</td>
</tr>
</tbody>
</table>

*Source:* Refs. 77 and 81–85.

1. Drafting (or attenuation) of an input fiber strand, usually a sliver containing anywhere from 20,000 to 40,000 fibers in the cross section, to a desired linear density of a yarn comprising approximately 100 fibers in the cross section

2. Providing cohesion to the fibers achieved by either twisting, entangling, wrapping, or bonding the fibers

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

- Drafting
- Twisting
- Winding.

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

### 2.3.1 Drafting and Fiber Transport

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

\[
\text{total draft} = \text{break draft} \times \text{main draft} = \left( \frac{V_{\text{middle}}}{V_{\text{back}}} \right) \times \left( \frac{V_{\text{front}}}{V_{\text{middle}}} \right) = \frac{V_{\text{front}}}{V_{\text{back}}}
\]

where \( V \) is the surface speed of the respective roller pairs.

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

Fig. 2.35  Schematic diagram of drafting system.
the fibers between two pairs of rollers move forward in only a partially controlled manner, giving rise to irregularity. During the process of drafting, fibers are transported between the rollers by the drafting forces. The considerable length variation between fibers poses a formidable problem for the effective and controlled transportation of fibers between rollers. Fibers having a length greater than the nip to nip distance between the two pairs of rollers are transported in a much more controlled and guided manner since any end of the fiber may be gripped by either of the nips. If such longer fibers are gripped at both ends by the nips, with one pair of rollers moving at a higher speed, the fibers are likely to be stretched if the exerted drafting force exceeds the elastic limit of such fibers; otherwise the fibers will be pulled out from the back nip due to differential tensions. Such fibers once pulled out of one nip will drag other fibers in their vicinity and form a clump. The fibers shorter than the nip to nip distance move uncontrollably and are commonly termed “floating” fibers. Such floating fibers, moving at different speeds, are responsible for causing unevenness.

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

2.3.2 Twisting

The type of spinning system determines the twisting process, which varies as the underlying principles of various systems used are inherently different. In ring spinning, the ring and traveler form a twisting unit. In its passage from the nip of the front rolls to winding on the spinning bobbin, the yarn is threaded through a traveler. Therefore, for every rotation of the bobbin mounted on the spinning spindle, the traveler also rotates and one twist is inserted. The traveler is negatively driven by the dragging force of the yarn while the differential in the rotational speed of the spindle and the traveler helps accomplish winding of the yarn on the bobbin. Though this twisting method is simple and well proven for twist insertion, the productivity of ring spinning is limited due to the following two reasons:
1. For higher productivity, an increase in spindle speed is limited by the speed of the traveler, which cannot rotate faster than 35 to 40 m/s on a nonlubricated ring. At higher speeds, burning of the traveler may occur more frequently due to the heat generated by the friction between the ring and the traveler. The obvious answer to this problem may be to use a rotating ring; however, it does not reduce the cost of yarn manufacturing.

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

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

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

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

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

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

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

---

Fig. 2.36  Yarn formation in self-twisting spinning. (From Ref. 81.)
travels around the ring, and then onto the bobbin mounted on the spindle. The spindle rotates at anywhere from 10,000 to 20,000 rpm. The higher speeds have been possible due to the new design of the ring and the individual spindle drive where vibrations due to the tape drive have been eliminated. The yarn rotates between the nip and the traveler by virtue of the movement of the traveler around the ring. The twist so inserted flows to the nip of the front rollers. The differential in speed between the traveler and the spindle controls the rate of winding the yarn onto the bobbin.

Ring spinning has been encountering tough competition from modern spinning systems, which operate at higher throughput rate, provide larger package size, and yield good quality yarns. Consequently, developments have also been taking place continuously in ring spinning. Such developments include balloon breaking devices, better control of yarn tension, an improved top-arm drafting system for better fiber control, and better design of the ring spindle.
and bolster. Recent developments have included doffing and donning mechanisms to automate the operations to reduce human involvement and thereby increase spindle allocation. The successful linking of the ring spinning frame to the winding unit has made the two processes continuous, thereby eliminating the need to have manual transportation of the materials between them. The use of an individual motor-driven spindle has helped eliminate the package-to-package irregularity which is commonly encountered in tape-driven spindles. However, further developments of the ring frame to increase speed have reached their limits, and further radical changes in the basic spinning systems are not anticipated.

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

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

2.3.4 Open-End Spinning

The theoretical basis of the open-end spinning principle is the introduction of a ‘‘break’’ in the otherwise continuous process of drafting, fiber transportation,
twisting, and winding. The schematic diagram illustrating the underlying principle is shown in Fig. 2.39. As the fibers flow from the supply strand, commonly a sliver, discontinuity is introduced at point A before transporting them to point B, where they are collected before being subjected to the twisting element. This creates a small open end of the yarn. It is much easier and more economical to rotate this open end to impart twist than to rotate the whole yarn package as occurs in the conventional ring-spinning system. A characteristic of
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Fig. 2.39 Schematic of (a) ring spinning and (b) open-end spinning principles. (From Refs. 91 and 93.)

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

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

Rotor Spinning

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

The phases of operations in any rotor spinning system can be divided into six parts, namely, (1) drafting, (2) fiber transport, (3) fiber consolidation, (4) twisting, (5) yarn removal, and (6) winding. The feed sliver with a linear density of 3 to 4 ktx (3–4 g/m) is subjected to drafting by the opening roll containing metallic wires, as shown in Fig. 2.40. The opening roll, operating between 6000 and 8000 rpm subjects the input sliver to a combinglike action to ensure individual fiber separation. The fibers should be completely peeled off from the opening roll and transported to the rotor without disturbing their orientation. This is achieved by means of an air flow with a velocity exceeding that of the velocity of the fibers lying on the surface of the combing roll. This in turn is achieved by the vacuum generated inside the rotor moving at a very high speed. The fiber transport passageway from the opening roll to the rotor should be smooth and straight to ensure deposition of fibers straight on the V-shaped inside wall of the rotor. The fibers entering this collecting surface of the rotor are in a thin stream, and it may take several such streams to make up sufficient mass to make the yarn. The V-shaped groove of the inside wall of the rotor and the centrifugal force generated due to its rotation lay the fibers compactly. The process is similar to that of doubling and drafting, which take place in traditional roller drafting to even out short-term unevenness in the yarn. For every rotation of the rotor, the actions of depositing fibers on the collecting surface of the rotor and the peeling off of the yarn from this collecting surface cause interference. These incoming fibers come into contact with the rotating yarn tail, which facilitates the peeling-off of the fibers and getting them incorporated into the body of the yarn, as shown in Fig. 2.41. Each
rotation of the rotor causes approximately one turn of twist to be inserted and a yarn length equal to one turn of twist to be taken off. The yarn is then withdrawn through the nonrotating doffing tube, more commonly known as a navel (Fig. 2.40), at the center of the rotor and onto the winding package. The withdrawing of the yarn can be performed either in an axial or tangential direction; however, the latter is preferred as it enhances the fiber orientation and parallel arrangement [94]. The winding function of an open-end spinning machine is separated from the twisting, and the yarn is usually taken up at a constant speed as it is delivered from the feed tube. This permits the building up of a large surface-driven yarn package resting on the rotating grooved drum of the yarn winder. The yarn package is generally a cross-wound cheese or cone weighing approximately 3.5 kg.
The factors which affect the spinning and yarn quality in rotor spinning are opening roll speed, rotor diameter, yarn tension, and the number of fibers in the yarn cross section. Typical rotor speeds of up to 150,000 rpm are used depending upon the type of fibers and the yarn count being spun. Very high opening roll speed will tend to cause fibers to rupture, thereby adding short fibers giving rise to yarn unevenness. The rotor diameter normally varies between 35 and 50 mm. The lower rotor diameter limit is determined by the staple length of the fiber being processed, and the higher one by the power consumption required to rotate it at high speeds. The rotor diameter and the angular velocity affect the spinning tension, $P$, which is generated in rotor spinning. This relationship is expressed by

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

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

The sliver fed to the rotor spinning machine should be well cleaned. Excepting in very coarse count spinning, where strength is not very important, finisher drawn sliver is often used. Some rotor spinning machines have an opening roll equipped with a cleaning edge or cleaning aperture built into it to extract a large proportion of the heavy trash. However, it is still important...
that the input fiber mass is well cleaned during the early preparatory processes such as opening, cleaning, and carding. Otherwise the heavy build-up of deposits of dust particles and trash in the rotor wall affect the deposition of incoming fibers and hence the evenness of the outgoing yarn linear density. This poses a significant quality assurance problem in rotor spinning.

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

### 2.3.5 Air-Jet Spinning

Air-jet spinning in some ways is similar to ring spinning, although the yarn structure is similar to that of a rotor yarn. The successful development and commercial implementation of this new system is based on a fasciated yarn technology [95,96] in which the sheath fibers are wrapped around the core by a rotating air jet. In the fasciated yarn system developed by Du Pont [95,96], the false twisting zone consists of a pair of drafting rolls, an air jet, and take-up rolls, as shown in Fig. 2.43. The amount of twist inserted in one direction before the air jet is canceled by an equal amount of opposite rotations following the air jet. Du Pont’s fasciated yarn technology was not exploited commercially. Consequently, there was a hiatus in the use of air as a media to twist fibers together to form a yarn until the development of the present air-jet spinning system. The fiber strand emerging from the delivery rollers of the drafting system is subjected to the twisting zone. The twisting element constitutes a pair of air-jet nozzles blowing strong air currents in opposing directions. Figure 2.44 shows the schematics of the air-jet spinning principle originally patented by Nakahara and Morihashi [97]. The figure shows the staple fiber sliver being drafted in the drafting system. The parallel and well-oriented drafted fibers emerging from the front rolls of the drafting unit are then passed
Fig. 2.42  Relative Uster evenness of rotor yarn as a function of the mean fiber length. (From Ref. 101.)

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

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

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

In the twisting zone, the drafted strand of fibers passes through a pair of air-jet nozzles. The compressed air at high pressure is blown through these nozzles in mutually opposite directions to produce swirling air currents. The first jet—closest to the delivery rolls of the drafting system—imparts twist to the leading ends of protruding fibers from the emerging strand while trailing ends are still gripped by the front rolls. Such fibers, usually lying at the edges of the ribbon, will not be subjected to the full twisting action imparted to the body of the yarn by the second jet and hence receive less twist than those in the body [95]. The second jet imparts false twist to the whole yarn flux in the opposite direction. Because of the higher air pressure used in the second jet, the false twist inserted runs back toward the front roll. As the yarn emerges out of the second jet the false twist is removed, and the body twist is reduced to zero. At this point, the low-twist surface fibers, which were twisted by the first nozzle, are untwisted to a greater degree than their original twist; this results in a true twist in the opposite direction to that of the twist imparted by the first nozzle [98–100]. The twisting nozzle requires a comparatively low yarn tension of the order of 10 cN for achieving good twisting efficiency. A lower yarn tension is beneficial with regard to spinning performance; however, it negatively affects yarn strength because in the twisting process fibers do not pack closely. In a less compact yarn structure, the frictional forces between the fibers are weak, which leads to poor yarn strength as a result of easy fiber slippage [101].
Chapter 2

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

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

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

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

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

The essential features of the friction spinning principle are shown schematically in Fig. 2.47. The input sliver is fed to the spiked opening roll which opens it up. Similar to the opening roller of rotor spinning, here also the opening
Fig. 2.46  Schematic diagram showing action of a vortex. (From Ref. 104.)

Fig. 2.47  Principles of friction spinning. (From Ref. 109.)
roller treats both short and long staple fibers in the same way. From the opening system, the fibers are carried with an air current through the feed tube toward the collecting surfaces, usually a pair of perforated drums. The yarn formation takes place in this area due to frictional forces between the frictional surfaces and the yarn tail forming an open end. Each revolution of the yarn tail around its own axis inserts one true twist in the yarn. Suction holds the tail end between the V of the pair of rotating drums. The yarn so formed is then withdrawn along the axis of the friction cylinders and wound onto a suitable package.

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

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

Fig. 2.48  Fiber transfer from feed channel to yarn. (From Ref. 110.)
In a nutshell, friction spinning is fairly flexible with regard to fiber length, but is best suited for handling short and medium staple fibers. Like rotor spinning, friction spinning is more economical and limited to coarse and medium count yarns and for producing specialty fancy yarns for household textiles.

### 2.3.8 Wrap Spinning

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

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

Even though the whole package of the filament yarn is required to be rotated, the energy consumption is relatively low. This is due to the fact that a larger quantity of finer filament yarn can be accommodated on a relatively smaller package. The filament package is enclosed, which helps to lessen the air drag and therefore the energy consumption.

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

### 2.3.9 Compact or Condenser Spinning

All the new spinning systems, particularly rotor and air-jet spinning, considered as breakthroughs, were developed during the past few decades and were
Fig. 2.49 Principles of wrap spinning. (From Ref. 110.)

aimed at improving spinning productivity. However, ring spinning has always remained at the forefront both as the most popular spinning process and as the quality benchmark. Ring-spinning frames produced by different textile machinery manufacturers may differ in respect to their engineering design, which may be evaluated in terms of reliability, spindle speed, power consumption, maintenance and repair characteristics, etc. However, even today little difference can be found in terms of the technological principles employed. Compact spinning represents a new process using the basic components of
the ring spinning system [111–116] but producing better yarn quality through the compacting of the yarn structure. This novel compacted structure produces yarns with higher strength and elongation, and reduced hairiness.

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

![Spinning tension](image)

**Fig. 2.50** Spinning triangle in conventional ring spinning. (From Ref. 112.)
main drafting zone plays the major role in determining the width of the fiber streams emerging from the delivery end. Immediately after fibers emerge from the nip of the drafting system, the yarn formation process begins. The fibers from the front roll nip are collected in the spinning triangle and integrated into the yarn structure by the twist imparted by the rotating spindle. For a given yarn count, the width of the spinning triangle, \( b \), depends upon the spinning tension, \( P \), exercised by the rotating end, and is in fact inversely proportional to the spinning tension. The higher the spinning tension, the lower the width of the spinning triangle and vice versa. In ring spinning, this difference \((B - b)\) is always greater than zero, and therefore the spinning triangle cannot capture all the fibers delivered by the front nip. As shown in Fig. 2.50, many peripheral fibers emerging from the nip of the delivery rollers are either lost or are so uncontrolled that they are only loosely attached to the yarn being twisted in the spinning zone. Therefore, the structure of the ring-spun yarn is far from ideal, since many such loosely embedded fibers do not contribute to the yarn strength and also increase the yarn unevenness. In general, the strength of the spinning triangle is only about one-third of the strength of the yarn being spun. This is attributed to the fact that the fibers in the center of the spinning triangle are practically without any tension, so they are bound together without suffering any elongation, whereas the fibers from the center of the ribbon to the outer side of the spinning triangle suffer increasing tension. The fibers at the edge of the spinning triangle have to withstand all the spinning tension imposed during the process of yarn formation. Obviously, the short fibers within the spinning triangle do not contribute toward the strength of the spinning triangle. Thus, the spinning triangle is a potential weak spot and adversely affects the process stability [116].

In principle, the problems associated with the spinning triangle in conventional ring spinning should be eliminated if better yarn is to be produced. Some concepts in this direction were advanced by the Fehrer/Rieter and the ITV processes [111]. In the former, the compaction was achieved by suction onto a perforated steel drum and in the latter by means of perforated ribbon aprons. More recently, commercially available compact spinning frames have come to the market such as Rieter’s Com4® and Suessen’s EliTe®, as shown in Fig. 2.51. Both systems have attempted to eliminate the shortcomings of the yarn formation process in conventional ring spinning by reducing the adverse impact of the spinning triangle. An intermediate condensing or compacting zone is introduced between drafting and yarn formation. In this condensing zone, the drafted fibers are compacted by means of aerodynamic forces, as shown in Fig. 2.52. The condensing of the width of the fiber streams, \( B \), is achieved, and it is converged to the width of the spinning triangle, \( b \), such
Fig. 2.51  Suessen’s EliTe® and Rieter’s Comfor® Systems. (Courtesy of Suessen and Rieter, respectively.)
that the difference \((B-b)\) tends to zero. This has led to the formation of a negligibly small spinning triangle or it is virtually eliminated. Therefore, all the fibers delivered by the front nip line are collected by the spinning triangle and thereby fully integrated into the twisting yarn. This has also led to a virtually perfect yarn structure of the compact spun yarn. All fibers are arranged parallel to the core and twisted together, thus contributing fully to the yarn properties.

The technological advantages that resulted from such compact yarn structure are

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

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

The physical and mechanical properties of yarns are strongly influenced by the properties of the constituent fibers and their disposition in the body of the yarn, i.e., yarn structure [2]. The mechanical resistance of the yarn to tensile, compressive, bending, and shear stresses and physical properties, such as appearance, handle and feel, and dye-uptake, are dependent on the yarn structure.

The arrangement of fibers in the yarn matrix, referred to as migration in technical terms, is in turn determined by the processing dynamics, spinning geometry, and the principle of yarn formation used in the specific staple yarn spinning systems. The yarns of identical linear density made from the same raw fiber stock but on different spinning systems are usually different in their mechanical response and physical characteristics.

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

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

The structures of yarns spun on different spinning systems are shown in Fig. 2.53. The ring-spun yarn has relatively regular and well-defined twisted structure, similar to that found in twisted continuous filament yarn but with
Fig. 2.53 Structures of different staple yarns. (From Schlafhorst Technical Bulletin and Refs. 117,120,122, and 125.)
discontinuities at the fiber ends, as shown in Fig. 2.53a. Ring-spun yarns are assumed to have a uniform, homogeneous, coherent, and coaxial helical yarn geometry [127]. The packing density of fibers in the yarn, however, is somewhat irregular, which disturbs the idealized twisted structure. The density of packing of fibers is maximal in the core and steadily decreases toward the periphery of the yarn. The distribution of fibers in a yarn follows a parabolic model [128]. Detailed studies of tracer fiber paths in the yarn matrix have shown that the fiber migrates from the inside to the outside of the yarn, occupying different radial positions within the yarn. Such coherent ring-spun yarn structure is relatively strong but expected to have lesser water absorption capacity, which results in a lower size pick-up during slashing. A thorough knowledge of the relative structural disparities and nuances between different types of yarns is essential for setting up the sizing recipes and assuring sufficient size pick-up and performance on the slasher.

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

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

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

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

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

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

2.5 PROPERTIES OF STAPLE YARNS

2.5.1 Mechanical Properties of Staple Yarns

During the process of textile slashing and weaving, the yarns are subjected to a variety of both simple and complex mechanical deformations, such as tensile, bending, compression, and torsion. The ability of textile yarns to withstand such cyclic tensile, bending, compressive, and torsional stresses is of prime importance for successful slashing and subsequent weaving. An understanding of a yarn’s performance during the subsequent processes is therefore never complete without taking into account the mechanical response of the yarn to such deformations. The mechanical behavior of staple fiber yarns is strongly influenced by the properties of the constituent fibers and their relative disposition in the body of the yarn [2,86].
The tensile strength of fibrous materials such as yarns is most commonly used to gauge the quality. Though the strength is of great importance for ensuring the satisfactory processing performance of staple yarns, it should be emphasized that other mechanical properties such as bending modulus and flexibility, resilience, torsional flexibility, elastic recovery, and initial tensile modulus and physical characteristics such as moisture sorption, hairiness, and evenness are also very important. Nevertheless, the measurement of the tensile strength of staple yarns is most common and widely measured in research and industry.

**Tensile Strength**

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

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

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

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

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

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

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

However, in textile materials it is very difficult to practically estimate the cross-sectional dimensions. Besides, the weight (linear density) but not the
cross-sectional dimension is important for textile materials. A more convenient form to express stress is therefore the stress per mass of unit length, expressed as

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

The units used for specific stress are grams weight per tex and newtons per tex.
The tensile strain is a nondimensional quantity expressed as the ratio of elongation to initial specimen length, either expressed as a fraction or more commonly as a percentage:

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

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

**Strength.** Strength is a measure of the force required to rupture a yarn. It is expressed in N/tex and is called specific stress or tenacity at the break point. Alternatively, the breaking length is also used to express the tenacity. When the strength is expressed on the basis of cross-sectional area, it is called the ultimate tensile stress, measured in the unit of kg wt/mm² or kPa. However, the use of ultimate tensile stress in textiles is not very common because it is difficult to estimate the diameter of a fiber in a yarn.

![Stress–strain curve of a yarn](image)
Elongation at break. This may be expressed by the ratio of actual increase in length to original specimen length expressed as a fraction or more commonly as a percentage. It is also called the breaking extension.

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

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

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

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

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

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

\[
\text{work factor} = \frac{\text{work of rupture}}{\text{breaking load} \times \text{breaking elongation}}
\]
Chapter 2

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

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

\[
\text{elastic recovery} = \frac{\text{elastic extension}}{\text{total extension}}
\]

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

### 2.5.2 Irregularity in Staple Yarns

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

![Fig. 2.56 Work factor. (From Ref. 131.)](image-url)
these two principal variations. The irregularity in staple yarns is attributed to the inherent variation in the input material and the manufacturing process. The variation in fiber characteristics, such as fiber length, fineness, maturity, and trash content; the variation in spinning parameters, such as draft and spindle revolutions per minute; and the random distribution of fibers in the prespinning processes are major factors that cause yarn irregularity. The variation in fiber fineness produces variation in the number of fibers in a cross section and therefore variations in linear density causing characteristic thick and thin places. The twist in the yarn is inserted in a certain yarn length in such a way that the twist factor is kept constant. This implies that the thin places will have more turns per unit length than thick places; therefore thin places are relatively hard whereas thick places are bulky and soft. Besides thin and thick places, the yarn also exhibits faults called “neps” often resulting from the immaturity of the cotton fibers.

Importantly, the yarn irregularity affects further processing performance and the appearance of the finished products. Higher yarn variation will exhibit higher breakage rate in subsequent processing and therefore lower productivity. Thick places will be constricted or may be caught in heddle eyes, knitting needles, and travelers and thus cause yarn breakage. Irregular yarns having
nonperiodic variations will cause visible defects such as streaks, and yarns having periodic variations will cause barè and diamond patterns in a fabric, which will be enhanced after dyeing. Yarns not having a high degree of periodic variations but large amounts of nonperiodic variations will produce a patchy, streaky, or cloudy fabric.

2.5.3 Yarn Hairiness

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

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

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

- Optical methods
- Photographic methods
Properties of Fibers and Yarns

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

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

Sources of Hairiness

The contribution of different spinning stages to yarn hairiness has been studied extensively by researchers [135,143]. More drawframe passages lead to greater parallelization of the fibers with a resultant reduction in the number of hooks and lower hairiness [135]. A reversal of card sliver prior to the drawing operation also reduces hairiness—the effect is equivalent to the effect of an additional drawframe passage [133,135]. The roving operation further reduces hairiness by consolidating the fiber flux in condensers. Yarn spun directly from the drawframe slivers leads to greater yarn hairiness. The combing operation eliminates short fibers and thereby reduces hairiness. The addition of short fibers and comber waste results in an increase in hairiness [135]. Spinning tension, spinning speed, and the weight of traveler have the most profound influence on the hairiness of yarns. An increase in spindle speed generally increases yarn hairiness, this being attributed to the increase in centrifugal force, higher air resistance, and greater friction between the yarn and the ring [135,143,144]. The spinning tension affects the hairiness: the lower the tension, the greater is the yarn hairiness. Eccentricity of the spindle increases yarn hairiness. The hairiness increases almost exponentially with the increase in eccentricity beyond 0.5 mm [143,145]. Besides eccentricity, increased vibrations of the spindle and the ring also tend to increase the hairiness. The effect of an increase in ring weight at a constant spindle speed is a reduction in yarn hairiness, attributable to the combination of the distribution of tension and twist during yarn spinning [133]. The weight of the ring that can be used is limited by the end-breakage rate on spinning frame. The balloon separators also increase the hairiness because the yarn is constantly beaten against them. The traverse cycle of the ring rail also affects the periodic variations in hairiness [4,143,145,146]. The nature and the properties of the fibers being spun, notably fiber length and fineness, affect yarn hairiness, for example, cotton fibers may produce more hairy yarn than the long staple acrylic fiber.
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3
THE CHEMISTRY OF SIZING COMPOUNDS

3.1 INTRODUCTION
Up until the development and commercial use of manmade fibers, the sizing materials employed in the textile industry had to meet the needs of the natural fiber weaving industry. The sizing material used primarily in the cotton manufacturing industry used natural starches. The natural starches such as corn, wheat, tapioca, and the like have a tendency to form very stiff films. To overcome the stiffness of the natural starches, weaving was carried out at very high humidities. Nevertheless, natural starches performed a useful function, and they still do in the cotton industry. Because the starches have a chemical nature that is similar to that of cotton, the starches adhere very well to cotton as well as to rayon—the first commercially made manmade fiber which has a chemical structure similar to cotton.

The desizing of starch can be carried out by enzymatic treatment and making the degraded product water soluble. The starch materials are relatively inexpensive and they still find widespread use in the textile industry. The starches need to be cooked and applied at a relatively high temperature, which poses some processing problems for rayon. For sizing of rayon a gelatin type natural protein sizing material derived from hides and skins of animals was developed. This material could be applied at temperatures lower than that used for natural starches. This material proved adequate for sizing rayon without causing any “hot-wet” damage. A protein-digesting protein is employed to
desize the material. This state of affairs prevailed until the 1940s when the first truly synthetic fibers appeared on the scene.

In 1938 nylon fiber, which is thermoplastic in nature, appeared on the scene, requiring the development of sizing material that could be applied at lower temperatures and also adhered to the hydrophobic surface of the fibers. The new types of sizing materials included such chemical compounds as carboxymethyl cellulose (CMC), polyvinyl alcohol (PVA), copolymers of acrylic acids, and other such water-soluble materials that did not require cooking before use. The chemistry of these materials made the desizing simpler and easier. By controlling the degree of polymerization of these compounds, sizes with considerably different physical and solubility properties have been made. Some of these sizes are also blended with starches to balance the cost of sizing while at the same time improving the processing properties of yarns during weaving.

Another class of materials called “binders” has also been developed to improve adhesion and properties of size films formed by synthetic materials. The chemical sizing materials available in the market offer the textile technologists to engineer the sizing ingredients to meet the processing requirements of various types of fibers and high speed weaving. In this chapter, the chemical nature and the various chemical and physical properties of the sizing ingredients will be discussed.

### 3.2 PROPERTIES OF SIZE MATERIALS

There are a number of desirable properties which a warp size should possess. These are summarized in Table 3.1. A good sizing material should have most if not all of these properties; however, sizes that are deficient in some of these properties still may be used. For example, starch is a useful sizing material even though it has a high biological oxygen demand (BOD), lacks bacterial resistance, and is sensitive to overdrying; cannot be recovered; and must be cooked to achieve uniform properties besides other disadvantages. Yet it is a useful size material primarily because it is inexpensive, is easily desized, is a renewable resource, has good adhesion to cellulosic fibers, and can be modified and/or derivatized to yield a wide range of size film properties. In other words the usefulness of a size material for a specific application will depend upon the nature of the fibers of yarns being sized (e.g., cellulosic, nylon, polyester, etc.), the type of yarn (ring-spun, open-end, air-jet), the type of weaving machine being employed (shuttle, air-jet, rapier, projectile, etc.), and the characteristics of the fabric being woven (style, construction, weave, twist, yarn count, etc.) [1]. For example, what may be a suitable size for a ring-spun yarn
The primary size materials that act as “film formers” are

- Starch (modified and unmodified)
- Polyvinyl alcohol
- Carboxymethyl cellulose
- Acrylic (various addition polymers)

The properties of these materials are discussed in subsequent sections. Other sizing agents are utilized as binders to improve the adhesion aspects of the film-forming sizing agents.

### 3.3 STARCH

Starch was at one time the primary sizing agent for textiles, and it is still used extensively either alone or in blends with other sizing agents. Large quantities are also used by the paper and food processing industries, for medicinal and adhesive applications, in the fermentation of alcoholic beverages, and even as
explosives. It is one of the most abundant agricultural “renewable” resources found in nature. Starch occurs widely in plants but is found in its purest form in the seeds (such as in wheat, corn, rice, and sorghum), in the roots and tubers (such as in potato, tapioca, and arrowroot), or in the stem pith of plants (such as in sago). These sources constitute the bulk of the world’s supply of commercial starches. In the United States, the endosperm portion of the kernels of the hybrid yellow dent corn (which is about 90% starch) provides the major source of starch used in textile applications.

3.3.1 Chemical Structure of Starch

Cellulose and starch have identical chemical constitution. They are both polymers of glucose, a sugar found in its pure form in grapes and often referred to as grape sugar. Glucose is only one of a family of ringed six carbon sugars that are referred to as carbohydrates because each carbon is associated with a molecule of water and have the empirical formula \([\text{C}_6\text{H}_{12}\text{O}_6] = \text{C}_6(\text{H}_2\text{O})_6\). The glucose molecule can exist in two structural (anomeric) forms dictated by the location of the hydroxyl group located on the C1 carbon of the pyranose ring, as shown in Fig. 3.1. This carbon is actually part of a cyclic hemiacetal involving the ring oxygen. It is possible for the hydroxyl group on C1 to be above or below the ring through an interconversion with the ring oxygen, a phenomenon called mutarotation. All of the other hydroxyl groups on the pyranose ring, at C2, C3, and C4, are fixed at the up or down position. In fact, exchanging the location of say the \(\#4\) hydroxyl from the down position (as on the glucose molecule) to the upper bond position (exchange the hydrogen and hydroxyl groups) gives a different sugar galactose, similar to one of the sugars found in milk (Fig. 3.1).

![Fig. 3.1](image_url) The sugars glucose and galactose differ only in the position of the hydroxyl on the C4 of the pyranose ring.
The two anomers of glucose are normally labeled α and β. Condensation of glucose to form linear starch chains occurs between the C1 and the C4 hydroxyls through elimination of a water molecule. For starch (α form) both of these hydroxyls are down with respect to the next glucose molecule; hence no change in the orientation of the glucose units is necessary for the condensation to occur. In the β form—cellulose—the hydroxyl group is up at C1 and down at C4; therefore, every other glucose unit must flip over before the 1,4 hydroxyls can match up for condensation, as shown in Fig. 3.2. Once condensation has occurred to yield the polymer chain of cellulose or starch the bond at C1 can no longer interconvert.

Fig. 3.2 Reactions of the alpha and beta anomers of glucose to form starch and cellulose. (*)Note that unlike the α–D–glucoses, every other β–D–glucose must rotate 180° before the 1–4 hydroxyls can condense to form the cellulose chain.
The glucose units in cellulose and starch do not actually exist in the plant, as shown in Fig. 3.2 (often used for structural simplicity), but instead exist in the more stable chain form. Comparison of the accepted conformations for the linear chain structures for cellulose and starch are shown in Fig. 3.3. It should be noted that due to their physical and chemical similarity they will have high adhesion for each other. As a result, starches are excellent size candidates for cellulosic fibers such as cotton and rayon.

In addition to the linear form of the starch polymer chain, called amylose, produced by the plant, there are also highly branched chain forms, called amyllopectin containing several thousand glucose units. The branched points involve condensation at the C1 through the C6 hydroxyls (alpha) while the linear chains are α – 1,4 linkages, as shown in Fig. 3.4. Starches from various sources differ in the amount of amylose and amyllopectin found within the granule, as shown in Table 3.2 [2,3]. Amylopectin, because of the high branching which occurs every 9–20 glucose units of the molecule [4], prevents rapid gelling, i.e., retrogradation or microcrystallization of starch pastes, of the cooled size. And amylose, because of its linear nature, contributes significantly to the size film strength. Genetic plant breeding has allowed the development of plant variants that produce starches approaching virtually 100% of either

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**Fig. 3.3** Comparison of the glucosidic chain structures of cellulose (β) and starch (α). See insert for locations of hydrogens (H) and hydroxyls (OH).

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Fig. 3.4 Linear starch, amylose, and branched starch, amylepectin.
Table 3.2  Amylose/Amylopectin Content, Granule Size and Gelatinization Temperatures of Starches

<table>
<thead>
<tr>
<th>Starch source</th>
<th>Starch type</th>
<th>Amylose/amylopectin (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Size diameter (μ)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Gelatinization temperature (°C)&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>Cereal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pearl</td>
<td></td>
<td>27/83</td>
<td>5–26 (15)</td>
<td>62</td>
</tr>
<tr>
<td>Waxy</td>
<td></td>
<td>0/100</td>
<td>5–26 (15)</td>
<td>63</td>
</tr>
<tr>
<td>High amylose</td>
<td></td>
<td>55–85/15–45</td>
<td>3–24 (12)</td>
<td>67</td>
</tr>
<tr>
<td>Oxidized</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low conversion</td>
<td></td>
<td></td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>High conversion</td>
<td></td>
<td></td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Hydroxyethyl</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS = 0.05</td>
<td></td>
<td></td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>DS = 0.09</td>
<td></td>
<td></td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Cationic (DS = 0.046)</td>
<td></td>
<td></td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>Crosslinked</td>
<td></td>
<td></td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Acid modified</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40F</td>
<td></td>
<td></td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>60F</td>
<td></td>
<td></td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>80F</td>
<td></td>
<td></td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Potato</td>
<td>Tuber</td>
<td>20/80</td>
<td>15–100 (33)</td>
<td>59</td>
</tr>
<tr>
<td>Wheat</td>
<td>Cereal</td>
<td>25/75</td>
<td>2–35</td>
<td>58</td>
</tr>
<tr>
<td>Tapioca&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Root</td>
<td>17/83</td>
<td>5–25 (20)</td>
<td>49</td>
</tr>
<tr>
<td>Sago</td>
<td>Pith</td>
<td>26/74</td>
<td>15–65</td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>Cereal</td>
<td>18.5/81.5</td>
<td>3–8 (5)</td>
<td>68</td>
</tr>
<tr>
<td>Sorghum</td>
<td>Cereal</td>
<td>22/78</td>
<td>5–25</td>
<td>68</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>Tuber</td>
<td>18/82</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>From Refs. 2, 15, and 21.
<sup>b</sup>Number in parenthesis is average size. From Refs. 48 and 21.
<sup>c</sup>Temperature when swelling begins. From Refs. 14 and 76.
<sup>d</sup>Brazilian origin.

Amylose or amylopectin chain structures. High amylose starches require cooking temperatures of greater than 150°C for dissolution but retrogrades (gels) rapidly if cooled [5,6]. The proof of structure for amylose and amylpectin has been extensively reviewed by Peters [7]. Current knowledge of starch architecture and structure differs considerably from the earlier ideas and theories [8,9]. The starch granules produced by the various plants are actually
The Chemistry of Sizing Compounds

spherocrystals with limited crystalline order in which the two types of chain structures are compacted into stratified layers formed around a nucleus [10]. The amyllose and amylopectin chains are compressed into a parallel array of double helices with the 1–6 branch points being located in the amorphous regions [4]. Each plant produces a starch granule having features specific to that starch source, e.g., corn, sago, potato, etc. Typical examples of starch granules from various sources are illustrated in Fig. 3.5. Under polarized light each granule type gives a specific birefringence pattern, as shown in Fig. 3.6. The shape and birefringence pattern is useful in starch identification [11–13].

The starch granules are not materially changed by the wet milling or mechanical/chemical processes required for separation, recovery, or modification of the starch from the seeds, tubers, or piths of various plants. Raw, unmodified starch is designated as pearl starch and can be marketed as fine or coarse, dustless powders. Like cellulose, the starch can absorb/desorb water depending upon the ambient temperature and relative humidity. When sold, the starch must be controlled to the limits of commercial acceptance of approximately 12% moisture.

Unmodified (pearl) starch has high water bonding or thickening power when cooked. Cooking provides the thermal energy necessary to permit water molecules to penetrate the compacted stratified layers, as shown in Fig. 3.7. The temperature at which enough thermal energy is available to overcome hydrogen bonding within the chain structure is called the gelatinization, or pasting, temperature. More precisely, the gelatinization temperature is taken as the point where birefringence in the granule disappears [14]. This temperature will depend upon the ratio of amyllose/amylopectin and the arrangement of these molecules within the starch granule structure. The gelatinization temperatures for various starches are given in Table 3.2 [2,15].

Profound changes in starches occur as the water begins to enter and swell the granule. The viscosity of the solution shows a marked increase, as most of the provided water is absorbed by the continuously swelling granule. This process is summarized in Fig. 3.8. The granule continues to swell as the temperature increases beyond the gelatinization point, as marked by point A in Fig. 3.8. That is, the increase in thermal energy overcomes the intermolecular bonding resisting hydration of the amyllose and amylopectin chains. As the granules swell to point B along the curve, the viscosity of the mixture continues to increase to a maximal level up to point C. Finally the super-swollen granule, under the influence of the shear force applied during cooking, bursts like a balloon, dispersing the swollen amyllose and amylopectin chains into the size mixture, thus lowering the viscosity of the size solution [16]. With continued heating and agitation the viscosity finally levels off as all of the granules...
Fig. 3.5  Scanning electron photomicrographs of starch granules: corn (1000×), tapioca (1000×), sago (1600×), potato (500×), rice (2000×), and wheat (1000×). (Courtesy of Seydel Woolley & Co. for supplying the starches and M.E. Miller for the SEM work.)
Fig. 3.6 Under polarized light, starch gives birefringence patterns that are specific to the starch genera. Shown are the birefringence patterns for potato (a), canna (b), and tapioca (c). Upper photograph is polarized light, and lower is incandescent light.
Fig. 3.6 Continued.
Fig. 3.6  Continued.
Fig. 3.7  In order to dissolve, the solvent must break all the polymer–polymer interactions and replace them by polymer–solvent interactions. Chains are totally surrounded by solvent.

rupture, marked by point E in Fig. 3.8). At this point a stable “leveling-off viscosity” is obtained and the starch size mixture is ready for use in sizing.

If the kinetic energy is removed from the cooked (swollen) size, such as when the solution is cooled, the possibilities for multiple points for intermolecular chain contacts occur, and a rigid interlocked chain structure composed of a microcrystalline, micellelike structure having hydrogen bonding networks is formed, and the starch mixture gels. When size of this gel structure is applied to the yarns, the gel dries and forms a film around the yarn. At high starch concentrations this network causes the cooled paste viscosities to be too high to be effectively handled for sizing purposes (point F in Fig. 3.8). When the hot gel structure is applied to the yarns followed by drying, a protective film is formed around the fiber bundle. The sizing process for starch is shown schematically in Fig. 3.9.

The propensity of raw (pearl) starches to produce high viscosities can be reduced or eliminated by modifying the starch by any one of the following processes:
Acid modification
Conversion to gums
Enzyme treatments
Derivatization (chemical modification), e.g., oxidation

3.3.2 Modification of Starch

Acid Modification

In acid modification, an aqueous suspension of the starch granules are reacted under varying conditions of time, temperature (below the gelatinization point), and hydrochloric acid concentration to reduce the molecular weight of the starch chains, while no apparent change occurs in the granule when viewed microscopically [13]. By reducing the chain lengths the viscosity of the cooked starch solution can be substantially lowered (Fig. 3.10). In addition to reducing the viscosity, such a modification provides the textile mill with size solutions having a high solids content, (i.e., high-solids, low-viscosity size; Fig. 3.11. Such sizes are ideal for loading up the woven fabric with a high size content for loom finished goods such as denim. Weaving efficiencies may also be improved. For example, the lower viscosity sizes can provide for a more con-
Mechanics of starch sizing. (A) Raw starch: the amyllose and amylopectin chains are thought to be compressed as double helices into layered growth rings within the starch granule. (B) High temperature hydration (cooking) swells the granules, ultimately releasing the chains to give a cooked paste with weak attractions between the molecules (represented by the dotted lines). (C) Removing the energy (cooling) causes retrogradation (chains collapses and gels) due to the formation of micelles (represented by the thickened areas). (D) Upon drying, the gel chain structures totally collapse to give a protective size film around the yarn.

trolled penetration into the warp threads. A moderate reduction in the degree of polymerization (DP), or chain length of the starch, only slightly reduces the strength of the film, as shown in Table 3.3, but offers an easier break, or separation of adjacent yarns, of the "dry" size during leasing on the slasher. Such materials may be conveniently added to other size formulations and may help in reducing the energy required to separate the yarn sheets at the lease rods. It may also help in attaining lower yarn hairiness, less size shedding at the loom, and eventually easier and more efficient desizing operation. Depending upon the amount of starch hydrolysis that is allowed to occur, a wide range
Fig. 3.10  Effect of acids, enzymes, or oxidizing agents on the length of cellulose or starch chains. The viscosity of the solutions are decreased.

of fluidities result. Starch viscosity, $\eta$, is defined by textile mills in terms of fluidity, which is defined as the reciprocal of viscosity, i.e., fluidity = $1/\eta$. A high fluidity means a low viscosity and vice versa (Fig. 3.12).

The higher the fluidity number, which for acid-modified starches ranges from 20 to 90 g/dl, the greater the acid modification and lower the viscosity of the cooked mixture. Thus more 90 fluidity starch can be added to the size cooking

Fig. 3.11  Effect of the chain length of the size molecule on obtaining high solids low viscosity size formulas.
## Table 3.3  Strength, Elongation and Viscosity Properties of Some Starches

<table>
<thead>
<tr>
<th>Starch</th>
<th>Strength (kg/mm²)</th>
<th>Elongation (%)</th>
<th>Viscosity [η] (dl/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(unmodified)</td>
<td>4.67</td>
<td>3.2</td>
<td>1.73</td>
</tr>
<tr>
<td>Acid Modified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15F</td>
<td>4.67</td>
<td>2.7</td>
<td>1.21</td>
</tr>
<tr>
<td>34F</td>
<td>4.45</td>
<td>2.6</td>
<td>1.06</td>
</tr>
<tr>
<td>50F</td>
<td>4.94</td>
<td>2.7</td>
<td>0.88</td>
</tr>
<tr>
<td>71F</td>
<td>4.57</td>
<td>2.9</td>
<td>0.67</td>
</tr>
<tr>
<td>89F</td>
<td>4.58</td>
<td>2.2</td>
<td>0.32</td>
</tr>
<tr>
<td>Chlorine oxidized</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>low</td>
<td>4.87</td>
<td>3.0</td>
<td>0.47</td>
</tr>
<tr>
<td>high</td>
<td>4.50</td>
<td>2.3</td>
<td>0.25</td>
</tr>
<tr>
<td>Hydroxyethylated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unmodified (DS = 0.05)</td>
<td>4.74</td>
<td>2.5</td>
<td>1.66</td>
</tr>
<tr>
<td>Acid modified (DS=0.05)</td>
<td>4.18</td>
<td>2.6</td>
<td>0.38</td>
</tr>
<tr>
<td>Waxy maize (Amioca)</td>
<td>3.49</td>
<td>1.7</td>
<td>1.50</td>
</tr>
<tr>
<td>Tapioca</td>
<td>4.40</td>
<td>3.4</td>
<td>2.03</td>
</tr>
<tr>
<td>Potato</td>
<td>4.42</td>
<td>3.1</td>
<td>2.20</td>
</tr>
<tr>
<td>Wheat</td>
<td>2.00</td>
<td>2.9</td>
<td>2.00</td>
</tr>
<tr>
<td>High amylose</td>
<td>5.03</td>
<td>2.5</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Kettle than a 40 fluidity; yet the final solution viscosities of the two size mixtures could be the same (Fig. 3.11). Because of the reduction in viscosity with increasing modification these types of starches are sometimes referred to as “thin boiling” starches. Fig. 3.13 shows a comparison of the various starches and modified derivatives in terms of parts of water required to achieve comparable viscosities. For example, a 40 fluidity starch cooked in 8 parts of water has the same viscosity as the pearl corn starch cooked in 14–15 parts water.

\[
\text{fluidity} = \frac{1}{\text{viscosity}} \quad \text{or} \quad \frac{1}{\eta}
\]

**Fig. 3.12**  Relationship between fluidity and viscosity. When viscosity is large (high number), fluidity is small (low number, \(1/\eta = 0\)). When viscosity is small (low number, \(0.0000001\)), fluidity is large (high number).
Fig. 3.13  Parts of water required to achieve comparable viscosities of various starches.
Gums

If the starch granules are roasted, often in the presence of acid, the DP of the starch chains is reduced but recombine to form highly branched systems that are soluble in cold water, as shown in Fig. 3.14. These operations are not performed by the textile mill but are carried out by the starch suppliers. Most gums have low film strengths; nevertheless, they are used in modifying the characteristics of stronger size materials and to provide high solids/low viscosity sizes for a more efficient slashing processing. Further thermal degradation gives dextrins that do not have any sizing uses. Gums are easily desized in warm water.

In addition to the starch gums there are a number of natural gums that at one time were used as binders and starch film modifiers. For the most part these products have been virtually supplanted in their sizing applications by the synthetic binders. The chemistry and sizing applications of the natural gums (gum arabic, tragacanth, locust bean, algin-alginic acids, guar, carra-
geenan, karaya, tamarind, xanthan) have been reviewed and are available in the published literature [8,17].

Enzyme Modification

Some mills start with inexpensive pearl corn starch and modify the starch themselves during the cooking cycle. This can be conveniently done by adding heat-resistant fungal or bacterial enzyme to the cooking kettle. As the size is heated, the enzyme breaks down the starch chain structure to give a higher fluidity size. Care must be taken to program the cook cycle to provide the same rate of temperature rise from batch to batch in order to achieve reproducible results. At temperatures near boiling the enzyme activity is destroyed and the chain scissions stop to prevent continuing breakdown during storage and use.

Derivatized Starches

The starch molecule has three hydroxyl groups per glucose unit that can undergo reactions analogous to those in cellulose. In fact, many of the derivatization reactions which can be successfully made for cellulose can be repeated with starch. Although numerous starch derivatives are known, only a few have practical application for sizing. The advantages offered by derivatization include:

- Lower gelatinization and cook temperature
- Rapid attainment of a stable use viscosity
- Reduced gelling (congealing or retrograde)
- Lower viscosity upon cooling
- Improved water holding ability
- Increased paste cohesiveness
- Improved film-forming characteristics
- Clearer films
- Compatibility with other size materials
- Facilitated desized

The pendant groups derivatized onto the starch chains act as if they were wedges and prevent the coalescing or association of the starch chains either in the cooked pastes or when cooled, as shown in Figs. 3.15 and 3.16. Their retrogradation and gelling tendencies are minimized or eliminated. The chain structure can be more easily penetrated by water, reducing the gelatinization temperature, improving the water holding ability, and providing an easier desize. Water holding ability can be considered an advantage as it can help lower the humidity in the weave room. Also the films do not tend to shrink.
Figure 3.15 Types of pendant groups (derivatives) which can be attached to the size polymer chain.

upon drying, thus cracking and shedding of the size film is reduced. Typical derivatives used for sizing include oxidation, esterification, cross-linking, and cationic starches. A brief discussion of some of the derivatives follows.

**Oxidized Starch.** The starch derivatives made by oxidative processes find limited use in textile sizing because they are more expensive to produce as compared to the other starch modifications which can give essentially similar properties to high solids/low viscosity cooks [5]. Instead of using acid to reduce the starch chain length, sodium hypochlorite, an oxidizing agent, is employed. In addition to chain scission, some of the primary hydroxyls at C6 are oxidized to a carboxylic acid, while carbonyls are produced at C2 and C3 hydroxyls [18]. The resulting carboxylic acid group at C6 is highly polar and larger than the original primary hydroxyl; thus sufficient wedging action occurs to prevent congealing, resulting in clear cooked pastes. During oxidation, the starch granule does not undergo any apparent structural change [19] and maintains its cold water insolubility. Further, high oxidative conversions can produce size solutions with very high solids at low viscosities [19]. Yet, because of the significant scission of the starch chains that occurs during the oxidative reactions, the granules disrupt easily upon heating so that they have short cook times. These properties of oxidized starches are more useful in the food industry [20]. The oxidized starch films are transparent and stronger. The lower fluidity oxidized starches find use in textile applications on dyed cotton yarns.
where the transparent films do not mask the brightly colored yarns on certain styles of fabrics.

*Starch Acetates (Esters).* Starch acetates can be thought of as the starch equivalent of partially hydrolyzed polyvinyl alcohol (PVA). Instead of removing the acetate groups, as occurs in the manufacture of PVA, they are added to the starch chains by one of several chemical routes [21]. Starch acetates used for warp size applications have a low degree of substitution (DS), the
average number of acetate groups per glucose molecule of the starch. Starch acetates are available in a wide range of fluidities and possess the characteristics expected of derivatized starches; that is, the wedging effect of the acetyl groups (\(-O\mathrm{C}==O\mathrm{CH}_3\)) decreases the chain association (Fig. 3.16) and thus prevents congealing or gelling, etc. Depending upon the number of acetyl groups on the starch chain, the adhesion to materials such as polyester and hydrophobic sizes improves. The acetate derivatives give good viscosity stability, lower pasting temperatures, and strong flexible films.

**Starch Ethers.** Starch ethers are also used in sizing applications. For example, hydroxypropyl potato starches of low DS are soluble in hot water and thus are easily desized. This advantage has found particular use in the desizing of denim fabrics during garment laundering processes to provide prewashed jeans without having to use an enzyme wash cycle [22].

**Cross-Linked Starch.** Corn starch is cross-linked to suppress swelling in hot water swelling and to provide stronger size films over a wide range of weave room humidity conditions. During conventional cooking, a high viscosity-to-solids ratio is obtained that makes this size variant well suited for low size add-ons with the heavier weight fabrics.

The cross-linking reaction must be precisely controlled. Only a few cross-links can have a significant effect on the size viscosity. Thus small changes in the reaction condition could mean large differences in the final viscosity of the size mixture. This problem resulted in a slow growth for the textile uses of cross-linked starches. The starch cross-linking reactions are summarized in Fig. 3.17.

The reagents of choice which give good results for cross linking starch are phosphorous oxychloride and sodium trimetaphosphate. Small amounts of these reagents have a marked effect upon the behavior of cooked starch [23].

**Cationic Starches.** The cationic starches are relatively more expensive than the other starch derivatives; consequently they do not find widespread use in sizing. The positive charge of the cationic group on the starch gives it excellent adhesive characteristics due to its high affinity for the negative charge on textile fibers. The higher adhesion provides for greater abrasion resistance and decrease size usage [24]. Static electricity in the sized yarns is eliminated, and the sized fabric has better softness. The more useful cationic starches are those containing tertiary amino or quaternary ammonium salts [20]. These starches are primarily used to size glass filaments and other fibers having low adhesion for traditional sizes.

**Genetic Variations.** Amylose and amylopectin have properties which are uniquely different, but they are both useful in slashing. Amylose provides
most of the properties of strength and flexibility of the film in the starch. Amylopectin is responsible for increased viscosity and noncongealing aspects of the size mixture. The need for an amylopectin type starch as a replacement for tapioca, a starch having a high amylopectin content as shown in Table 3.2, led to the development of a hybrid genetic mutant from a waxy corn variety found in China that contained essentially 100% amylopectin [25].

Although primarily used in the food industry, this starch finds application in textile sizing because of its ease of cooking. Further, it provides pastes that set to a soft gel upon cooling and is more easily desized. As expected for a highly branched chain configuration, amylopectin films have low strength. Amylopectin sizes are used in modifying the properties of sizes containing stronger film formers or to increase the paste viscosity without greatly increasing the solids content of the size mixture.

There are two high amylose genetic mutants available commercially. They contain either 55 or 70% amylose, although one variety containing 85% has been cited [26]. It is also possible to obtain chemically fractionated amylose.
starch. Pure amylose starches cannot be cooked using conventional starch cooking equipment even for long periods at the boil. Instead, high temperature and pressure cookers, such as jet cookers, are required to give useful dispersions. Even then, the starch has little application for sizing because of the high propensity of amylose starches to rapidly retrograde with cooling. Modifications by derivatization, however, provide starches having lower gelatinization temperatures than regular corn starches with no retrogradation problems [6]. The derivatized amylose starches have good film strengths, have acceptable viscosities, and are easily desized.

3.4 POLYVINYL ALCOHOL

3.4.1 Introduction

Polyvinyl alcohol (PVA) has been one of the most versatile size materials available for warp sizing formulations since it was commercialized as a textile warp sizing agent sometime around 1965. A review of the discovery and uses of PVA as a textile warp size is available in the published literature [27]. The versatility of PVA arises from the fact that it can be manufactured into a variety of modified forms and can be utilized alone or in combination with other size materials, e.g., starch, polyester resins, acrylic copolymers, and CMC, or as a binder with numerous fiber substrates, e.g., glass, acrylic, polyester, cellulose acetate, nylon, and numerous styles, as shown in Table 3.4 [28,29]. High-speed looms require yarns with strong flexible films, which makes the use of some grade of PVA in the size mixture a virtual necessity.

3.4.2 Chemistry and Manufacturing of PVA

Polyvinyl alcohol is manufactured by the process of addition polymerization of vinyl acetate rather than the highly stable vinyl alcohol [30]. The resulting vinyl acetate polymer is hydrolyzed under varying conditions of catalyst, time, and temperature to remove varying amounts of the acetate (ester) radical (−O−C═O−CH₃) and replace them with the hydroxyl groups (−OH), as shown in Fig. 3.18. By controlling the length of the PVA chain—DP or n in Fig. 3.18—and the degree of hydrolysis of the acetate groups, a family of PVA warp sizing grades can be manufactured, thus allowing the size to be tailored for specific sizing needs. For example, by allowing some of the acetate groups to remain on the PVA backbone chains, they can act as wedges to prevent other neighboring chains from the close associations that would allow for intramolecular hydrogen bonding that would prevent easy water penetra-
Table 3.4  Typical Uses for PVA Sizes

<table>
<thead>
<tr>
<th>100% PVA</th>
<th>PVA blends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton fabrics</td>
<td>Twill fabrics</td>
</tr>
<tr>
<td>Corduroy</td>
<td>Muslin sheeting</td>
</tr>
<tr>
<td>Percale sheeting</td>
<td>Batiste styles</td>
</tr>
<tr>
<td>Fine broadcloth</td>
<td>Print cloth</td>
</tr>
<tr>
<td>Tight poplin</td>
<td>Heavyweight apparel fabric</td>
</tr>
<tr>
<td>Rayon (100% spun and filament)</td>
<td>Denim</td>
</tr>
<tr>
<td>Triacetate (filament)</td>
<td>Lightweight 100% cotton</td>
</tr>
<tr>
<td>Polyester</td>
<td></td>
</tr>
<tr>
<td>100% industrial</td>
<td></td>
</tr>
<tr>
<td>100% spun</td>
<td></td>
</tr>
<tr>
<td>Polyester/cotton (fabrics and towelling)</td>
<td></td>
</tr>
<tr>
<td>Polyester/viscose</td>
<td></td>
</tr>
<tr>
<td>Glass (filament and fabrics)</td>
<td></td>
</tr>
</tbody>
</table>

Source: Ref. 29.

tion needed for rapid dissolution. In other words, the hydroxyl groups that are left are too far apart to achieve much intrachain hydrogen bonding, as explained in Fig. 3.19.

Another factor that assists the ready dissolution of PVA in hot water is the fact that the polymerization of vinyl acetate produces mostly an atatic chain structure [30]. The acetate or the hydroxyl groups, after saponification, are randomly distributed left or right on the carbon polymer backbone chain thus substantially reducing molecular order which would allow for greater hydrogen bonding, as shown in Figs. 3.20 and 3.21. As a result only a few nonhydrolyzed acetyl wedges remaining on the PVA chain can have a considerable effect on the properties of the size.

The chain disrupting effect of a properly selected comonomer polymerized into the PVA structure was recognized by the Du Pont company about 1972 [31]. Du Pont began to produce a PVA grade used exclusively for warp sizing in which a comonomer was introduced into the PVA chain structure [32]. The comonomer not only reduced the molecular fit between the chains even further, but additionally provided a nonhydrolyzable wedge that improved water solubility and resolubility needed for easier desizing as well as greater specific adhesion to polyester and other hydrophobic fibers.

Physical properties of the copolymer size are similar to the intermediate hydrolyzed (IH) grades [32,33]. The methacrylate comonomer appears to meet
Chapter 3

Fig. 3.18  Chemistry of polyvinyl alcohol manufacture.

Fig. 3.19  Effect of degree of hydrolysis on the ease of dissolving (redissolving) and humidity sensitivity of polyvinyl alcohol. (a) Segment of fully hydrolyzed PVA chain. Water must break intrachain hydrogen bonding. (b) Segment of a partially hydrolyzed chain. Acetate radical forces neighboring chains to exist further apart, facilitating water penetration and dissolving (redissolving), thus lowering the strength but improving adhesion to hydrophobic fibers.
Fig. 3.20 Hydrolysis of polyvinyl acetate. Carbon and hydrogen atoms on the backbone chain omitted for clarity (see insets).

these requirements quite well [34]. For example, methacrylate copolymers are resistant to, possibly due to steric hindrance of the pendant methyl group, the hydrolytic conditions necessary for saponification of the acetate groups of PVAc [35,36] as well as having the correct reactivity ratios necessary for random atmospheric copolymerization with PVAc [36]. The latter comonomer appears ideal because it has an additional interchain disrupting group (methyl wedge) associated with the acrylate ester (—C—O—R). A few mole percent of such a comonomer may produce its maximal effect on the sizing properties of the PVA copolymer. Regardless of the comonomer employed, it must

- Be stable to the hydrolysis reaction which converts PVAc to PVA
- Not hinder the purification steps
- Be as compatible as regular PVA to other size ingredients
- Not be labile to the high temperatures employed (cooking, size box, dry cans, etc.) in sizing
- Not be chemically altered by recovery (ultrafiltration) processes
- Not cause size preparation problems (foaming, sticking to dry cans, etc.)
- Be consistent in properties from batch to batch (i.e., be reproducible)
- Have good water dispersibility and desizeability
Fig. 3.21 Three-dimensional structure of atatic PVA. Hydroxyls must match up to achieve any hydrogen bonding in the molecule.

The grades of PVA with respect to chain length (molecular weight), degree of hydrolysis, and viscosities for warp sizing are given in Tables 3.5 and 3.6. A superhydrolyzed grade of PVA will have only four of every 1000 original acetate groups still remaining on the PVA chain; fully hydrolyzed, 12–20 acetyl groups, etc. This could be visualized as only 12 acetyl groups remaining along a superhydrolyzed chain (36–60 for a FHA grade) that had a DP of 3000. These small amounts of remaining acetyl groups have essentially no practical effect on the overall properties of PVA. It should be noted that copolymer type PVA will also have a high degree of hydrolysis of acetyl groups. A small number of residual acetyl groups will still be present on the copolymer chain; however, most of the acetyl groups will have been replaced by the comonomer. The comonomer group will not be saponified under the mild conditions employed.
for acetate groups. Further, the comonomer radical is more effective at achieving solubility characteristics than the acetates due to its size, reactivity, and randomness of the distribution on the PVA backbone chain.

Polyvinyl alcohol grades are normally available in viscosities ranging from a low of 5 cp to intermediate ~14 cp, medium ~25 cp, and high ~40 cp, approximately. For practical reasons most of the PVA used for warp size applications will consist primarily of the intermediate and medium viscosity grades since they are the only ones that have the proper viscosity range necessary for most sizing applications. Usually it is a practice to blend the low viscosity grades with the high viscosity types. The low viscosity types are not used alone for sizing since they provide too thin a size mixture that can result in excessive penetration of the size into the yarn bundle. On the other hand, high viscosity types are more difficult to process and mostly result in surface sizing without sufficient penetration in the yarn bundle to achieve proper anchoring of the resulting size film.

**Table 3.6**  Effect of Chain Length (DP) of PVA on Viscosity

<table>
<thead>
<tr>
<th>Viscosity type</th>
<th>DP (n in Fig. 3.18)</th>
<th>Molecular weight (viscosity average)</th>
<th>Viscosity (CP) of 4% solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>500–900</td>
<td>22,000–31,000</td>
<td>4–8</td>
</tr>
<tr>
<td>Intermediate</td>
<td>1200–1800</td>
<td>50,000–65,000</td>
<td>13–16</td>
</tr>
<tr>
<td>Medium</td>
<td>2200–2500</td>
<td>77,000–79,000</td>
<td>21–32</td>
</tr>
<tr>
<td>High</td>
<td>2800–3000</td>
<td>106,000–110,000</td>
<td>40–65</td>
</tr>
</tbody>
</table>

*Not a usual textile grade after about 1985.

Source: Ref. 2.
The most important properties of a size necessary for textile processing and weaving are tensile strength, extensibility, recovery from extension, abrasion resistance, and ease of removal [37]. Addition of PVA significantly enhances these size properties.

The tensile strengths of the PVA film increases as the chain length (DP) of each grade increases and as the percentage of acetyl removal increases. Intermediate hydrolyzed (IH) grades are 7–10% weaker, while partially hydrolyzed (PH) grades are 20–25% weaker, than the fully hydrolyzed (FH) grades [38]. Nonetheless, the PH grades are significantly stronger than other size materials, as shown in Table 3.7. Thus PVA can be added to weaker sizes such as starch to improve the performance of these size products. A plot of tensile strengths as a function of the degree of acetyl hydrolysis of the various grades is shown in Fig. 3.22. One of the added advantages of PVA is its compatibility with most of the other film formers employed in sizing (see Section 3.7.8 on polyvinyl acetate binders and Fig. 3.43). Because PH grades are weaker than FH grades, they can actually decrease the energy to break at the bust and lease rods. This could result in a measurable decrease in yarn hairiness and clinging in the loom, key requirements in air-jet weaving [39].

Adhesion of PVA

The adhesion of PVA to various substrates depends primarily upon the number of acetyl groups and the fiber substrate to which it is being applied. For example, on hydrophilic fibers such as cotton and rayon, FH and IH grades exhibit good adhesion. This is because these PVA grades will have a higher number of hydroxyl groups still remaining on the polymer chain. Consequently the size will have better specific adhesion because of the potential for hydrogen bonding at the size–fiber interface. On the other hand, hydrophobic fibers

<table>
<thead>
<tr>
<th>Size</th>
<th>Tensile strength (psi)</th>
<th>Elongation (%)</th>
<th>Moisture Content at</th>
<th>50% RH</th>
<th>65% RH</th>
<th>80% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVAa</td>
<td>7,000–15,000</td>
<td>100–150</td>
<td>8–9b</td>
<td>16–17b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starch</td>
<td>600–900</td>
<td>8–12</td>
<td>15–20</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMC</td>
<td>2,000–4,000</td>
<td>10–15</td>
<td>14</td>
<td>15–20</td>
<td>30.5</td>
<td></td>
</tr>
<tr>
<td>Acrylic</td>
<td>1,000–2,000</td>
<td>100–600</td>
<td></td>
<td>17–21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

aAt 70°F and 65% relative humidity.

bDepending upon the degree of hydrolysis.
exhibit poor wetting characteristics toward water-based sizing agents, resulting in lack of adhesion to the FH and IH grades.

Fig. 3.18 shows that the acetyl units remaining on the PVA chain contain ester groups. Thus, the PH grades should have a corresponding greater affinity for polyester fibers and other hydrophobic fibers, as well as have greater resistance to the force required to peel the size film away from the yarn at the bust rods, as shown in Fig. 3.23. This factor, coupled with the lower tensile strength of the PH grades, provides for a lower breaking energy and thus less shedding and yarn hairiness, but not at a sacrifice of "yarn" strength. Since the PH grade has better adhesion to polyester fibers, they can actually improve the sized yarn strength (Table 3.8) [39].

A comparison of the adhesion of CMC versus various grades of PVA to typical hydrophobic fibers is given in Table 3.9. The PH grades show excellent adhesion, while the copolymer types are better than the FH grades. All PVA grades are superior in their adhesion to hydrophobic fibers than the CMC. The superior adhesion and strength of PVA films may cause problems
such as increased hairiness when the sized yarns are separated at the bust rods. Fig. 3.24 shows a comparison of the ease of sheet separation at the bust rods for the three major film formers used in sizing. Thus, PVA size formulas may need to be modified if a softer sheet separation is required. Alternatively, greater yarn spacing in the size box and on the drying cans should be employed.

**Table 3.8**  Breaking Strength and Elongation of Sized Yarns at 70°F and 65% relative humidity

<table>
<thead>
<tr>
<th>PVA grade</th>
<th>Breaking strength (g)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partially hydrolyzed</td>
<td>263.8</td>
<td>10.5</td>
</tr>
<tr>
<td>Fully hydrolyzed</td>
<td>252.1</td>
<td>12.3</td>
</tr>
</tbody>
</table>

*Note: 65/35 polyester/cotton; yarn count 37’s, 14% add-on.*
Table 3.9  Adhesion of Medium Viscosity Polyvinyl Alcohol and CMC to Synthetic Films

<table>
<thead>
<tr>
<th>Film</th>
<th>CMC</th>
<th>Partially hydrolyzed PVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetate</td>
<td>0.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>2.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Acrylic</td>
<td>1.5</td>
<td>9.0</td>
</tr>
<tr>
<td>Polyester</td>
<td>0.5</td>
<td>7.0</td>
</tr>
</tbody>
</table>

*Note: Conditions: 65% relative humidity, 20°C.  
Source: Ref. 40.*

Fig. 3.24  Separating force (bust and lease rods).
Water Solubility and Resolubility of PVA

Polyvinyl alcohol with less than 88% hydrolysis, i.e., the PH grade, is not 100% soluble in cold water (≈70°F). As the percent hydrolysis increases, however, the water solubility decreases such that the fully hydrolyzed PVA have high water resistance, as shown in Fig. 3.25. In hot water (≈140°F), all grades of PVA above 88% hydrolysis are water soluble (see Fig. 3.26). Heat setting of PVA in the greige cloth can reduce the resolubility of FH grades and will require a higher temperature for solubility in water in order to achieve acceptable desizing, as shown in Figs. 3.27 and 3.28. The copolymer sizes can be considered comparable to the partially hydrolyzed grades as far as resolubility is concerned (Tables 3.10 and 3.11). Generally, temperatures in the range of 170 to 190°F are required to achieve acceptable desizing of most grades of PVA. The solubility of the FH grades of PVA can be improved by the addition of polyester resins [41].

Size Recovery

One of the major advantages of PVA is that it can be recovered by ultrafiltration techniques. Ultrafiltration is a membrane separation process that selectively filters chemicals according to the molecular size. The ultrafiltration membranes suitable for PVA recovery include carbon tubes manufactured by Gaston

![Fig. 3.25 Water solubility of PVA at 70°F.](image)
Fig. 3.26 Water solubility of PVA at 140°F.

Fig. 3.27 Water solubility of heat-set films.
County [42], stainless steel and inorganic membrane manufactured by Carre-Du Pont [43], and spiral wound polymeric types manufactured by Abcor [44,45]. These systems can recover about 94–97% of the PVA from desize liquors. PVA can be removed from the cloth with as little as 0.5–0.6 gallons of hot water per pound of fabric, allowing recovery of about 90–95% of the PVA removed by the desize operation [32]. ‘‘Actual’’ recovery is somewhat less since allowances for loom shed, desize washer efficiency, etc., must be made. Generally, 10–20% virgin PVA is added to the recovered size to make

### Table 3.10 Percent Size Removal from Non-Heat-Set Fabric (Not Steamed) at 150°F

<table>
<thead>
<tr>
<th>Number of washes</th>
<th>Homopolymer high viscosity</th>
<th>Homopolymer medium viscosity</th>
<th>Copolymer medium viscosity</th>
<th>Partially hydrolyzed high viscosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90.1</td>
<td>90.9</td>
<td>93.5</td>
<td>88.0</td>
</tr>
<tr>
<td>2</td>
<td>93.3</td>
<td>94.8</td>
<td>94.8</td>
<td>92.6</td>
</tr>
<tr>
<td>3</td>
<td>98.7</td>
<td>97.6</td>
<td>97.3</td>
<td>98.1</td>
</tr>
<tr>
<td>5</td>
<td>100.0</td>
<td>99.4</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

*Note: Percentages based on total water extractables in greige fabrics.*
Table 3.11 Percent Size Removal from Heat-Set Fabric (Not Steamed)

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>Number of washes</th>
<th>Homopolymer high viscosity</th>
<th>Homopolymer medium viscosity</th>
<th>Copolymer medium viscosity</th>
<th>Partially hydrolyzed high viscosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>1</td>
<td>11.2</td>
<td>13.3</td>
<td>16.1</td>
<td>50.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10.4</td>
<td>10.3</td>
<td>10.9</td>
<td>42.7</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>18.4</td>
<td>18.2</td>
<td>37.6</td>
<td>70.1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>16.1</td>
<td>19.2</td>
<td>45.9</td>
<td>78.1</td>
</tr>
<tr>
<td>150</td>
<td>1</td>
<td>19.3</td>
<td>20.0</td>
<td>40.3</td>
<td>62.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>16.9</td>
<td>17.6</td>
<td>59.6</td>
<td>71.2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>15.8</td>
<td>18.6</td>
<td>56.3</td>
<td>70.3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>16.6</td>
<td>20.0</td>
<td>60.4</td>
<td>80.0</td>
</tr>
<tr>
<td>170</td>
<td>1</td>
<td>18.6</td>
<td>29.5</td>
<td>80.3</td>
<td>71.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>14.8</td>
<td>20.0</td>
<td>84.5</td>
<td>73.2</td>
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<tr>
<td></td>
<td>3</td>
<td>17.8</td>
<td>22.6</td>
<td>89.6</td>
<td>74.9</td>
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<tr>
<td></td>
<td>5</td>
<td>18.4</td>
<td>20.2</td>
<td>91.6</td>
<td>78.2</td>
</tr>
<tr>
<td>190</td>
<td>1</td>
<td>51.2</td>
<td>67.5</td>
<td>74.7</td>
<td>63.9</td>
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<tr>
<td></td>
<td>2</td>
<td>60.5</td>
<td>78.6</td>
<td>88.3</td>
<td>70.1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>57.0</td>
<td>77.2</td>
<td>89.6</td>
<td>70.1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>63.9</td>
<td>82.7</td>
<td>91.5</td>
<td>70.9</td>
</tr>
</tbody>
</table>

*Note:* Percentage based on total water extractables in greige fabrics. Most desize temperatures range from 170 to 190°F.
About 65% of all chemicals entering a finishing plant effluent is size related; yet, desizing uses only 10–15% of the total water. Waste treatment plants average about 75% treatment efficiencies. One reason is that bacteria acclimated to degrade PVA are temperature dependent and are not as efficient during the colder winter months. Size reclamation can substantially reduce waste treatment loads and save water and energy during preparation. A plant using 3 million pounds of size per year (36 million pounds of woven fabric per year) can pay for the recovery equipment in less than 2 years [49]. The distance the recovered size must be transported from the recovery site to the mill is an additional consideration [50]. A typical PVA size recovery system is shown in Fig. 3.29.

3.5 CARBOXYL METHYL CELLULOSE

3.5.1 Introduction

Carboxyl methyl cellulose (CMC) is the cold water–soluble carboxymethyl (ether) derivative of cellulose. It is an excellent film former and has numerous
textile and nontextile uses. Cellulose like starch is a renewable natural product. CMC is not a major textile sizing agent in the United States. The nontextile uses have virtually supplanted its markets, primarily for price considerations. It is now used where the special properties of the size are the overriding considerations. For example, in loom finished goods, the cost of the size can be partially recovered. CMC still has considerable markets overseas, principally in Europe and the Far East, where the economics of the raw materials are somewhat different than in the United States. About 90% of the CMC produced in the United States is highly purified material used in food, pharmaceutical, and cosmetic applications. The remaining 10% is a crude grade of CMC that finds uses in detergents, anti–soil redeposition agents, oil drilling [51], etc., while a semirefined grade (90–95% CMC) is used for textile warp sizing [34].

3.5.2 Chemistry and Manufacturing of CMC

The synthesis of CMC from cellulose is shown in Fig. 3.30. The starting material for CMC manufacture is either wood pulp or cotton linters or similar cotton waste. In either case the cellulose must be purified. Cotton cellulose contains waxes and pectins among other impurities, while wood pulp contains lignin and hemicellulose. Fortunately all of these impurities are soluble in concentrated caustic soda (NaOH), which both helps in the removal of impurities and converts cellulose into its alkali cellulose or “soda” cellulose intermediate form. In this form soda cellulose reacts with monochloroacetic acid (MCAA) under controlled reaction conditions to form the carboxymethyl derivative.

Depending upon the DP of the cellulose source and the extent of the degree of substitution, e.g., in the DS range 0.7–1.2, of the MCAA onto the cellulose chain, a family of stable CMC products is obtained that finds wide applications in textile and nontextile uses. Most warp size grades of CMC have a DS in the 0.65–0.85 range [52]. The grades of CMC depend upon the length of the cellulose chain or molecular weight, which control the solution viscosity; the degree of substitution, which determines the solubility or insolubility and moisture sorption; and the purity, which controls the salt content, etc.

The carboxymethyl group preferentially attaches to the cellulose chain at the C6 primary hydroxyl through a stable primary ether linkage. The carboxymethyl derivative of cellulose is considerably more stable toward removal than the more labile acetate ester found on the partially hydrolyzed PVA chain.
Fig. 3.30  Carboxymethyl cellulose manufacture from purified cellulose.
During the derivatization reaction, the sodium hydroxide greatly swells the cellulose destroying all of the cellulose crystalline order. Attachment of the carboxymethyl groups to the chain acts to wedge them apart, preventing the cellulose chain from recrystallizing by reforming the original ‘‘hydrogen bonds.’’ Thus, even cold water can now penetrate and surround the CMC chains, causing dissolution at low energy levels. The material now acts as if it were a ‘‘cold water–soluble cotton.’’ CMC finds advantage in the sizing and finishing of shrink-sensitive fabrics such as acetate and viscose rayons because to remove other types of sizes during the desize step in finishing it is necessary to use hot water. Hot water, enzymes, and chemical additions are not required for desizing of CMC. Further, being a natural product, CMC is biodegradable yet has a considerably lower biological oxygen demand (BOD) than does starch.

CMC is generally used in textile sizing as a more water-soluble sodium salt derivative. Occasionally the product is contaminated with considerable salt (sodium chloride) that is produced in the carboxymethylation reaction and can cause corrosion problems on slashing and weaving machines [53].

Properties of CMC

Like starch, CMC can be obtained in high solids low viscosity grades while providing the same sizing properties as conventional CMC grades [54]. The tensile strength, elongation, and moisture-related properties of CMC compared to other film forming sizes are given in Table 3.7. The tensile strength of CMC films falls somewhere between starch and PVA. When dried on the slasher, the CMC films split easily at the lease and bust rods, but after regaining the moisture lost in drying the CMC recovers its strength and abrasion resistance to protect the yarn on the loom. Its high water-binding ability makes it less sensitive to low weave room humidities (ca. <50% RH) but can give problems at high humidity conditions, especially above 80% RH employed in ‘‘wet’’ weave rooms. This can be somewhat reduced by blending 25–50% starch to give warp that has good weaveability at most weave room humidities [54]. If CMC sized warps are to be used under conditions that favor mold or mildew, a preservative (antiseptic) may be required to prevent yarn damage.

Carboxyl methyl cellulose is not heat set in the greige fabric as are some of the PVA type sizes and remains water soluble after being heated and dried. Cooked mixes are quite stable and need not be dumped at the end of a set or on weekend shutdowns. They can be cooled and reheated with no gelling or skinning [55]. The cooked size has less tendency to stick onto the hot drying cylinders compared to PVA. Thus soft waste can be minimized. CMC sized
warps are split at low energy (soft split) at the bust or lease rods (Fig. 3.24). The water solubility of CMC compared to PVA is shown in Figs. 3.31 to 3.33 [56]. The size has significant cold water solubility. Only at 180°F does the solubility of PVA approach that of the CMC.

Chemically, CMC is a hydrophilic type size that has good adhesion to polar fibers, e.g. cellulosics. As the amount of hydrophobic fibers in a blend of polar fibers increases, the adhesion of the CMC to the yarn bundle will decrease. This loss of adhesion can be somewhat mitigated by the addition of acrylic, polyester, or vinyl binders to the CMC size formula. A comparison of the adhesion of CMC versus other sizing agents and binders is given in Table 3.12. The adhesion of CMC to cotton is good but poor on the polyester fiber. Addition of binders to the CMC will improve the adhesion to the more hydrophobic fibers.

Blending with Other Sizes

Although CMC is cold water soluble, the size is generally prepared in hot water for most sizing applications. CMC is readily soluble in hot water; however, for rapid dissolution, CMC may be added to half a kettle of cold water with good agitation. Then the mixture may be heated to dissolve the size followed by

![Graph](image)

*Fig. 3.31* Removal of CMC versus PVA sizes at 80°F.
Fig. 3.32  Removal of CMC versus PVA sizes at 140°F.

Fig. 3.33  Removal of CMC versus PVA sizes at 180°F.
slow addition of the remaining water. For blends of CMC with other size materials such as starch, the kettle needs to be heated to \( \sim 95–98^\circ C \). This temperature has no adverse effect on CMC, which may be blended (25–50\%) with the starch. CMC can be used in sizing as a viscosity builder or modifier with other size materials. For example a 4.2\% solution of CMC is approximately equivalent to a 10.2\% solution of a 30 fluidity corn starch [55]. CMC readily blends with PVA. Usually a 75\% PVA/25\% CMC blend can be used to provide a size having excellent abrasion resistance with good slashing performance.

Desizing and Recovery

Carboxyl methyl cellulose can be easily removed in cold water (\( \sim 27^\circ C \)) during desizing. Wax used in sizing is generally not removed at this temperature; however, it can be effectively removed in the scouring and bleaching steps at finishing. Thus a significant savings of energy used in finishing can be realized for CMC sized warps [57]. Often, such savings are overlooked by the greige mill management, as cost savings in a downstream process is not perceived as significant. CMC, being a natural product, is totally biodegradable.

Carboxyl methyl cellulose also lends itself to economical recovery by ultrafiltration techniques [55]. The cold/warm water solubility and low water volume overflows [58] used in finishing allow the total water volume used for desizing to be reduced by as much as two-thirds [56]. Flux rates for CMC recovery have been found to be 30–50\% higher than for PVA [58]. The membrane and pumping costs are thereby reduced. Wax elimination from the recovered desize liquor at finishing should further increase the flux efficiency of the process.

---

### Table 3.12

<table>
<thead>
<tr>
<th>Material</th>
<th>Adhesion to polyester (Force (kilopascal))</th>
<th>Material</th>
<th>Adhesion to cotton (Force (kilopascal))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastman WD</td>
<td>15</td>
<td>PVA</td>
<td>4.9</td>
</tr>
<tr>
<td>PVA</td>
<td>10</td>
<td>CMC</td>
<td>3.9</td>
</tr>
<tr>
<td>Polyacrylate</td>
<td>5</td>
<td>Starch</td>
<td>3.6</td>
</tr>
<tr>
<td>CMC</td>
<td>4</td>
<td>Polyacrylate</td>
<td>3.5</td>
</tr>
<tr>
<td>Starch</td>
<td>3</td>
<td>Eastman WD</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*Source: Ref. 22.*
Another method of size recovery for CMC makes use of its water insolu-

bility at low pH. CMC is normally used for sizing as it is a highly water-soluble
neutral sodium salt. Upon acidification to pH 2–3, the CMC precipitates and

can be recovered by decanting the water layer and redissolving the precipitate
as the sodium or ammonium salt [59].

The CMC can also be recovered by chemical coagulation. Heavy metal
ions such as silver, copper, lead, or zirconium and the trivalent ion such as
aluminum, iron, or chromium will cause the CMC to precipitate from solution
as salts of these metals. The CMC is more tolerant toward calcium ions [60].
Aluminum ions, Alum, are the ions of choice for the recovery process using
the ion precipitation method. The size is recovered and reused with only a
slight loss in properties [61]. The degradation of properties are probably due
to the occlusion of other metal ions normally found in water that cause hard-
ness, which may be prevented by using deionized water in the recovery process.
As with PVA, virgin CMC (ca. 5–8%) must be added to the reclaimed CMC
after each cycle. The various recycling methods for warp sizes have been
reviewed elsewhere [61].

3.6 ACRYLICS

3.6.1 Introduction

The term “acrylic” is a generic term for sizing materials that contain polya-
crylic acid (PAA) and its derivatives as a homopolymer or copolymer. In some
cases the acrylic size is used alone as the primary film former or as a binder
component of the size to improve the adhesion between a primary base sizing
agent (film former) and the yarn. Acrylics even at high molecular weight
produce solutions of low viscosity and give clear, colorless, mildew- and mold-
resistant thermoplastic films having good strength, in the range of 1000 to
2000 psi, elongations in the range of 100 to 600%, and flexibility. They can
be made readily water soluble or insoluble and have excellent compatibility
with other sizing materials and generally improve their performance.

Acrylic sizes do not require cooking but can be heated up to 100°C for
dispersing wax or lubricants as well as with other sizes, e.g., starch, with which
it may be blended. Perhaps its greatest advantage is the high binding strength
to a number of manmade fibers under weave room conditions, yet it has low
dry bonding strength on the slasher, facilitating easy splitting at the bust rods.

The acrylic sizes can be broadly divided into two classes, namely, water
or alkali soluble or water insoluble. The alkali soluble types will have acrylic
acid or its ammonia or sodium salt or other water-soluble derivative (such as
acrylamides) as a major component of the polymer chain. The insoluble size materials contain acrylic esters or acrylonitrile derivatives. The copolymers can vary widely in composition (ester, amide, nitrile, acid, etc.) to give a large family of “acrylic” polymers useful as sizing materials. Some typical comonomers useful as acrylic binder components are illustrated in Fig. 3.34.

### 3.6.2 Characteristics and Properties of Acrylic Sizes

The two important factors that affect the size properties are the molecular weight and the chemical composition of the size. The water-soluble size consists primarily of the sodium and ammonium salts of acrylic acid, as shown in Fig. 3.34. These are the primary film formers and are used as the primary size for nylon filament yarns. The low molecular weight materials also form excellent binders with other sizes, particularly starch. Figure 3.35 shows why the acrylic sizes, particularly the ammonia salt, are excellent for filament nylon or as binders for spun yarns containing nylon as one of the blend components.

**Viscosity**

The effect of molecular weight on the viscosity of sodium and ammonium salts of acrylic acid that are the water-soluble forms are shown in Fig. 3.36 [62]. As would be expected, viscosity increases with molecular weight and

![Fig. 3.34](image-url)

*Fig. 3.34* Some of the “acrylic” family of copolymers useful in sizing. (a) Polya-
ylic acid (PAA); (b) PAA sodium salt (or ammonium salt); (c) acrylamide; (d) methyl ester (methyl acrylate); (e) methyl amide (methyl acrylamide); (f) nitrile (acrylonitrile); (g) C₂ substituted ester (N-methyl methacrylate); (h) C₂ substituted amide (N-methyl methacrylamide). a, b, and c are water soluble; d, e, f, g, and h are water insoluble.

*Derivatives other than methyl include ethyl, propyl, n-butyl, isobutyl, and 2-ethylhexyl, among others.*
size concentration. The ammonium salt derivatives have higher solution viscosity than the corresponding sodium forms. It can be noted that even a small amount of a high molecular weight acrylic size can have a significant effect on the solution viscosity; thus it can be utilized as a viscosity builder at low concentrations. Alternatively, a high amount of low molecular weight material as a binder or adhesion promoter can be added to the size formula without

Fig. 3.35 Structural features of nylon and acrylic acid affecting adhesion of sizes to fiber. (a) Acrylamide (moderate adhesion). (b) Acrylic acid (sodium salt) (poor adhesion). (c) Acrylic acid (good adhesion).

Fig. 3.36 Effect of molecular weight on the viscosities at (80°C) of polyacrylates.
any significant effect on the size viscosity. Size materials normally have viscosity in the 50–500 cps range. Thus, acrylic size materials can cover a wide variety of sizing conditions.

Solubility

The water solubility of the acrylate sizes compared to CMC or another derivatized starch, pearl starch, and PVA are given in Table 3.13. Even the high molecular weight acrylics are significantly more cold water soluble than the other size materials. At 50°C the size films have almost immediate solubility. Heat-set acrylamide films are more easily solubilized than heat-set PVA [63].

Tensile Properties

The relationship of molecular weight to strength and extensibility of acrylic sizes is given in Fig. 3.37 [62]. As the molecular weight of the acrylic sizing material increases so does the extensibility. At very high molecular weight, however, the extensibility decreases and the films become brittle and are no longer useful for sizing.

### 3.6.3 Sizing of Nylon Filament

Most nylon filament yarns woven on non-water-jet looms are sized almost exclusively with acrylic sizes because of high adhesion and abrasion resistance.

<table>
<thead>
<tr>
<th>Table 3.13</th>
<th>Comparison of Solubility of Acrylic Films Versus Other Sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size</strong></td>
<td><strong>Solubility of Size Film (min/mm²) at 25°C/50°C</strong></td>
</tr>
<tr>
<td>Acrylics</td>
<td></td>
</tr>
<tr>
<td>Low viscosity</td>
<td>10/ &lt;2</td>
</tr>
<tr>
<td>Medium viscosity</td>
<td>17/ &lt;2</td>
</tr>
<tr>
<td>High viscosity</td>
<td>22/ &lt;2</td>
</tr>
<tr>
<td>Sodium CMC</td>
<td></td>
</tr>
<tr>
<td>Low viscosity</td>
<td>&gt;25/ 14</td>
</tr>
<tr>
<td>Medium viscosity</td>
<td>&gt;25/ 49</td>
</tr>
<tr>
<td>Starch</td>
<td></td>
</tr>
<tr>
<td>Pearl</td>
<td>&gt;25/ &gt;120</td>
</tr>
<tr>
<td>Starch ether</td>
<td>&gt;25/ 52</td>
</tr>
<tr>
<td>PVA (partially hydrolyzed grade)</td>
<td>&gt;25/ 14</td>
</tr>
</tbody>
</table>

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of these sizes. Some nylon filament yarns are designed to be woven on a water-jet loom without size. Yet size applied to the warps can increase weaving efficiency by preventing any broken ends from peeling back at the heddles or reeds causing fuzz balls and eventually causing yarn breakage. Broken ends can also interfere with the path of the filling yarn, thus causing a warp related filling stop.

The ammonium salts of acrylic acid copolymers are the size of choice for water-jet weaving applications. Inevitably, the size must be water soluble and wet out the filaments during application in the size box. Yet the size must then lose its water solubility on the sized warp so that the nylon can be woven without size removal that can build up on the heddles. During weaving, the size must still bond to the nylon filaments. Then the size must be again made water soluble for desizing. The ammonium derivatives are quite suitable for this amazing task.

The ammonium salts used in sizing of nylon are designed to have high water solubility. When heated over 100°C on the drying cylinders much of the ammonia is lost, and the size is converted into the insoluble free acid copolymer form, which still has high adhesion to nylon, as shown in Fig 3.35. Ordinarily PAA is water soluble; however, by copolymerizing 10–20 mole percent of an insolubilizing monomer, such as an acrylate ester, the copolymer size becomes water insoluble after loss of ammonia. In other words, depending upon the final acrylic acid/copolymer content, surfactant system employed, and the amount of ammonia removed during drying, a water-resistant size having high adhesion to nylon remains to protect the yarn during weaving.
The most important consideration is not to have the acrylic size shed off of the yarns during weaving and build up on the loom parts. When this occurs, the deposits slough off into the water-jet system, which can cause weaving problems or dye resist spots since these small size particles are not easily resolubilized during desizing. During alkaline desizing the free acid form of the size is resolubilized as the soluble sodium salt and becomes removable. This process is shown schematically in Fig. 3.38. The ammonium PAA copolymer is also suitable for water-jet weaving of polyester filaments, although composition changes are necessary to reach optimal performance.

3.6.4 Acrylic Sizes for Spun Yarns

For spun yarns, the PAA in the molecular weight range of 200,000, which is relatively high, have been found to be the most suitable. However, acrylic acid copolymers are manufactured with molecular weights numbering in the millions for nonsizing applications, e.g. printing, while very low molecular weight PAA are employed as surfactants. The 200,000 molecular weight range provides a viscosity that gives suitable penetration into the yarn bundle while providing a soft break and the bust at lease rods.

Ordinarily the sodium salt of PAA along with polyester binders are the two types of size that are the most suitable for the dry weaving of polyester spun yarns. The advantage of the sodium salt over the ammonium form is that the size can be heated to higher temperatures during cooking and sizing or drying without loss of the sodium anion that occurs with the ammonium salt. Studies with acrylamide sizes indicate that it can replace PVA for spun yarns using PVA/starch blends [63].

![Fig. 3.38](http://www.dekker.com/image500.jpg) (a) Water-soluble size having high affinity for nylon. (b) Loss of ammonia during drying provides a water-insoluble polymer usable on water-jet looms. (c) Alkaline desize removes the size as the water-soluble sodium derivative.
Generally, the selection of the grade of acrylic size will depend upon the slasher and weaving style. For example, low twist yarns will require a higher viscosity size having lower film strength in order to obtain a softer break at the bust and lease rods than will stronger yarns having a higher twist.

3.7 BINDERS

3.7.1 Introduction

There are a number of polymeric materials that can be used in sizing as binder materials. Binders are true film formers but are generally not used alone for sizing, although some sizes (e.g., acrylics) are useful as both a primary size and as a binder. Binders are typically used to increase weaveability by promoting the adhesion of the primary “film-forming” size (starch, PVA, CMC, acrylic) to a specific fiber substrate while reducing the cohesion between sized yarns. By judicious selection of a binder, additional sizing advantages can be realized, such as

- Splitting more easily at the bust or lease rods — reduced cohesion
- Greatly reduced shedding
- Easier application and removal of size
- Improved weaving efficiencies
- Improved fabric quality
- Reduced hairiness
- Improved size film/solution viscosity properties, e.g., strength and elongation
- Desizeability, etc.
- No blocking
- No sticking on the dry cans
- Better warps (loom build-up, clinging, and fuzz balling eliminated)
- No downstream processing problems (preparation, dyeing and finishing)
- Reduced costs while improving compatibility with other size box ingredients
- Improved sizing properties — no size migration or foaming; better penetration and leveling, film flexibility, and fiber lay; reduced friction; decreased moisture sensitivity; etc.

Note that some of the advantages cited transcend the weaving operation. To save money in weaving and then lose it and more because of finishing problems...
does not make sense. Table 3.14 summarizes the sizes for spun yarns which function as primary sizes or as binders. In some cases the primary size components can be blended together to modify the size film properties. For example, the weaker starch sizes can be blended with PVA to reduce cost, obtain a softer yarn split at the lease rods, and improve adhesion, etc., with no reduction in weaving efficiencies.

### 3.7.2 Acrylics as Binders

Acrylic compounds used as binders generally consist of lower molecular weight polymers, as shown in Fig. 3.36. Also, acrylics may be copolymerized with other monomers to further modify their properties. For example, as the molecular weight of the acrylic is reduced, the strength and flexibility decreases. One of the advantages of the acrylic binders is their compatibility with most primary size and other binder materials, including the following [64,65]:

- Pearl corn starch
- Modified starch
- Starch derivatives (ether, acetates, etc.)
- Polyvinyl alcohol (all grades FH to PH, copolymer)
- CMC

### Table 3.14  General Classification of Size Materials as Primary Size, Binder, or Other

<table>
<thead>
<tr>
<th>Primary size</th>
<th>Binder</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spun yarns</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starch</td>
<td>Acryllics</td>
<td>Styrene/maleic anhydride</td>
</tr>
<tr>
<td>PVA</td>
<td>Polyester resin</td>
<td>Polyamides</td>
</tr>
<tr>
<td>CMC</td>
<td>Vinyl acetate</td>
<td></td>
</tr>
<tr>
<td>Acrylic</td>
<td>Starch derivative</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Starch gums</td>
<td></td>
</tr>
<tr>
<td><strong>Filament yarns</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poly acrylic acid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyester</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyvinyl acetate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Polyesters
Vinyls
Flow (viscosity) control agents

By selection of the proper acrylic, proper adhesion, cohesion, and plastic properties can be controlled to yield films that are as stiff as glass or as soft as chewing gum. The range of properties include [62,65]

- Hard/slick
- Soft/tacky
- Strong/weak
- Brittle/flexible
- Tough/elastic
- Water soluble/water insoluble

There is a considerable number of acrylic binders marketed with a wide range of different sizing properties (Fig. 3.39). An understanding of these properties is necessary in order to select the correct variant for the proper sizing of the warp. For example, as the acrylic acid component of the size increases, the size adhesion and resolubility increases; however, the sensitivity to moisture also increases.

![Diagram](image)

Fig. 3.39 Effect of the length of pendant ester group on the properties of an acrylic size.

Me = Methyl, Et = Ethyl, Bu = Butyl, 2EHx = 2 Ethyl Hexyl

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Acrylics are marketed as both sodium and ammonium salts. The sodium salt is more water soluble and also has greater weave room moisture sensitivity. The ability to pick up water can improve the antistatic propensity of the sized synthetic fibers, but can result in tacky films at high weave room humidities. The heating of the ammonium salt in the cooking kettle or size box must be carefully monitored, especially in starch blends. Heating near the boil can cause these size materials to prematurely lose ammonia, causing potential foaming problems as well as insolubilizing the size. Agitation in the kettle or size box can break up the now-insoluble size into small ‘gritlike’ particles that can build up on the yarn while sloughing off at the bust and lease rods or on loom parts to cause yarn breaks at the slasher or the loom.

Acrylic/Starch Binders

Acrylic binders are often blended with starch to promote better adhesion to the more hydrophobic fibers in a blended yarn such as polyester/cotton. Yarns sized with starch generally require high weave room humidities for good weaving results. The use of starch blended with the acrylic binder thus reduces the size sensitivity to high humidities. The sodium salts are more humidity sensitive than the ammonium salt. Other advantages of starch/acrylic blends include

- Better stability; more stable than PVA blends.
- Retrogradation of the starch is reduced.
- Skinning in the size box is reduced or eliminated.
- Smash outs due to skinning are avoided.
- Weaving performance is improved.
- Size film properties are improved.
- Productivity is improved.
- Desizing is improved.

The diversity of available acrylic sizes allows the manufacturer to select the materials to achieve the desired characteristics. Tables 3.15 and 3.16 illustrate the effect of additions of low and medium molecular weight binders on the viscosity and the abrasion resistance of starch films [62].

3.7.3 Polyester Resin Binders

Polyester resins used as binders for size applications are very similar in their chemistry to the ‘polyester fibers.’ Polyester as a generic class is one of the most important textile fibers that is produced worldwide. Polyester employed in fibers is synthesized from the condensation of ethylene glycol and terephthalic acid to give polyethylene terephthalate (PET) type polyester. At high
molecular weights, this polymer can be extruded into strong hydrophobic fibers. The molecular chains comprising the polyester fibers have high stereoregularity and thus have excellent fit between themselves. Since the molecules have a rigid chain structure, much like two flat rulers, the chains align themselves to maximize their intermolecular bonding, and the fiber possesses excellent crystallinity when the chains are properly oriented, as shown in Fig. 3.40. For sizing, the polyester polymer must have a different molecular structure and orientation. For example, the polyester resin size must as a minimum be water or solvent soluble or dispersible. This is accomplished by adding to the molecular chains solubilizing groups which destroy the molecular fit and act to wedge open the chain structure (much like acetate groups on a PH grade of PVA) [66]. Generally aromatic sodium sulfonate (SO$_3$Na) groups are used to provide the water solubility, chain flexibility, and reduction in the chain “fit” needed to make the polyester resin useful for sizing. A typical polyester resin based upon 1,3 isoterephthalic acid which has been reacted with glycol or glycol ether units and modifiers and polymerized to a molecular weight of 5000–7000 is shown in Fig. 3.41 [66]. Oddly, the sodium salt is employed when the potassium salt would give even greater wedging and solubility char-

<table>
<thead>
<tr>
<th>Size</th>
<th>PAA sodium salt, low MW (cps)</th>
<th>PAA sodium salt, medium MW (cps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch ester</td>
<td>40</td>
<td>180</td>
</tr>
<tr>
<td>Pearl corn starch</td>
<td>150</td>
<td>600</td>
</tr>
</tbody>
</table>

*Note: 5% Solution, 70/30 blend of starch/acrylic at 85°C.*
acteristics. The molecular weights of sodium and potassium are 23 and 39, respectively. Odd numbered glycol or glycol ether units are used to reduce the molecular fit inherent in fibrous polyesters (which use an even numbered glycol unit). Such comonomer arrangements produce the greatest flexibility and ease of dissolving and redissolving needed for sizing and desizing. The use of mixed glycols and/or aromatic acids reduces the polyester chain fit even further, thus lowering the second order or glass transition temperature ($T_g$) to give a size candidate with optimal sizing properties. The proper formulation of the base resin and knowledgeable neutralization and reduction of the polyester resin system into water can provide an excellent “polyester” binder that does not give the problems formerly experienced with poor desizeability or other difficulties. The more stable and useful polyester resin systems avoid the use of cosolvents in their manufacture. In fact, the resin can function as a detergent when the desize is conducted at pH above 7.0 to provide a cleaner desized fabric and assist in the dispersing of lubricants, etc., employed in sizing. This factor also assists in optimizing the size rheology [67].

As expected, polyester resins make excellent size “binder” candidates for polyester fiber, either spun or filament yarns. The use of polyester resins was first introduced by Tennessee Eastman. The history of polyester resins has been reviewed elsewhere [67].

Since an alkaline desize is required for the polyester resin binder system, they are not suitable for use in sizing wool or wool blends. Some polyester resins require the use of an organic cosolvent to accomplish viscosity reductions, dissolving of the polyester resin (to stabilize), and resin acid removal from the cooking kettle. Additions of polyester resins to PVA and PVA/starch blends can measurably assist the redissolving of the size during the desizing operation. As little as 10% of polyester resin added to fully hydrolyzed PVA sizes or PVA/starch blends can affect a considerable reduction in the time and temperature for redissolving the size film, as shown in Table 3.17.

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Fig. 3.41  Synthesis of a typical polyester resin.

![Chemical structure of polyester resin](image)

Table 3.17  Desizeability of PVA and PVA/Starch Films Containing Polyester Resins

<table>
<thead>
<tr>
<th>Film</th>
<th>Time(s)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully hydrolyzed PVA*</td>
<td>386</td>
<td>85</td>
</tr>
<tr>
<td>90% fully hydrolyzed PVA/10% Polyester resin</td>
<td>165</td>
<td>72</td>
</tr>
<tr>
<td>PVA/starch film</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% fully hydrolyzed PVA/50% modified soluble starch</td>
<td>75</td>
<td>68</td>
</tr>
<tr>
<td>45% fully hydrolyzed PVA/45% modified soluble starch/10% polyester resin</td>
<td>45</td>
<td>66</td>
</tr>
</tbody>
</table>

*Fully hydrolyzed grades are not generally used in sizing applications and are shown here to better illustrate the effect of the polyester resins toward improved desizeability.

Source: Ref. 41.
The primary advantages cited for polyester resins are [41,67,68]:

To provide high adhesion to hydrophobic fibers
To plasticize the primary film former
To provide for significant reduction in warp stops
Stabilization of size temperature/viscosity parameters
To optimize size cook rheology properties
To make compatible with other film formers and size additives
Increased abrasion resistance during weaving
Better matching of size film strength and elongation with yarn employed
Easier desizeability
Improved leasing ease (softer break at the bust and lease rods)
Reduction in yarn hairiness
Faster and more uniform drying on the slasher
Potential cost savings in blended size formulations with PVA
To make some sizes recoverable by ultrafiltration

3.7.4 Vinyl Acetate Resins

Polyvinyl acetate (PVAc) polymers are effectively utilized as binders to improve the adhesion of the primary size agent to the yarn. Structurally, the same stereochemistry considerations described for PVA are operative for the PVAc polymer. That is, the chain structure is atatic, and the comonomers are randomly distributed along the chain, greatly reducing chain fit regularity. The primary advantage of vinyl polymers is that the vinyl acetate is relatively inexpensive vis a vis other polymers employed in sizing. The vinyl acetate homopolymer is not water soluble; hence, the monomers must be copolymerized with mono- or dicarboxylic acids (usually as their monoester), acrylic esters, or other vinyl monomers to achieve useful size properties [69], as shown in Fig. 3.42. If acid units are employed as comonomers in the polymerization, the resulting vinyl resin is solubilized as an alkali metal salt. Care must be exercised in the neutralization step (pH 8.0–8.5) in order to prevent the removal of the acetate groups, as is done in the hydrolysis of PVAc into PVA. If ammonia is used for neutralization, then the size finds applications in water-jet weaving, since the ammonia will be lost in a manner similar to the ammonium acrylate to give a water-insoluble size. The ammonium derivative is also usable as a permanent size for loom finished goods.

The vinyl acetate binders are useful sizing agents for both filament and spun yarns. Because of their weak film strength, PVAc polymers are used as sizing agents on acetate and polyester filament yarns and as binders for fiberglass, polyester, and blended spun yarns.
### 3.7.5 Sizing of Acetate Yarns

The excellent adhesion of PVAc to secondary acetate and triacetate fibers is obvious. Both the polyvinyl acetate size and the acetate textile fiber are highly acetylated derivatives (contain O–C=O–CH₃ groups). The adage “like likes like” certainly is operative for these fibers. Acetate and triacetate fibers have relatively lower tensile strength than any other manufactured textile fibers. A 4–5% add-on of PVAc size is weak enough (i.e., has low enough cohesion) to separate the “bone dry” sized sheet at the front of the slasher without breaking the fragile acetate filaments or causing size separation from the fibers of the yarn. It has high adhesion properties which will prevent peel back problems if any filaments are broken during weaving. Another advantage of PVAc sizes is that they can be utilized at low size box temperatures, a must in sizing acetate yarns since they are highly sensitive to stretching under hot/wet conditions [70]. Other combinations of sizes useful for acetate fibers are blends of PVAc with either acrylic or styrene/maleic anhydride (SMA) sizes. The SMA produces a hard and brittle film which can be effectively modified by additions of PVAc to this size.

### 3.7.6 Sizing of Polyester Fibers

Polyvinyl acetate has also been effectively used for sizing texturized polyester filaments (again like likes like) [71]. The producer-applied finish on the polyes-
ter fibers can sometimes be removed by bleeding into the size box. This can result in modification of the PVAc size film that may cause a build-up of size on the loom parts. Other additives used with the PVAc when sizing polyester yarns include penetrants, plasticizers, lubricants, and antistatic agents. Size box temperatures in the range of 120–165°F are generally utilized.

Flat yarn polyester fibers are more difficult to size with PVAc due to the higher solution viscosity required for these types of yarns. For this reason, the acrylic and polyester type sizes have better application for these types of yarns.

When the choice is between the PVAc size or the polyester resin, the cost advantage generally will favor the PVAc sizes due to the lower costs and the easier desizeability. For economy, some size suppliers will do their own sodium or ammonium conversion. Offering the PVAc size as liquid products can reduce the costs such that they can compete favorably with other liquid binder systems.

When PVAc is added to PVA sizes, significant improvement in the adhesion to polyester fibers is obtained while also lowering the bone dry size film strength. This facilitates a softer split at the bust rods without removal of the size film from the polyester fiber. When the yarn is then conditioned in the weave room, the adhesion characteristics are recovered, providing for excellent weaving performance.

### 3.7.7 Sizing of Fiberglass

Blends of PVAc (ammonium salt) and PVA (50/50 to 85/15 PVA/PVAc) at 8–9% solids have been successfully used to size fiberglass. The size with a 2–3% add-on to the weight of yarns is typically removed by flame desizing. The ammonium salt provides virtually an ash-free desize.

### 3.7.8 Sizing of Spun Yarns

It is in the sizing of spun yarns that the PVAc sizes find their major niche as a binder. The PVAc reduces or eliminates size box skinning with starch and/or PVA on 100% polyester and their blends, especially at creep speeds. The size, because of its ester chemistry is a significant adhesion promoter for polyester (as well as other hydrophobic) fibers and their blends. The PVAc has high compatibility with the PVA, particularly the PH grades because of their similar chemistry. Further, PVAc reduces the viscosity of PVA sizes [71] (Fig. 3.43) and because of its hydrophobic nature improves the speed and uniformity of drying.
Compatibility with other size ingredients is important because noncompatible size films are not smooth and uniform in appearance. For noncompatible size mixtures the chances of sized yarns passing unhindered through the loom without problems is decreased.

### 3.7.9 Drying and Size Box Skinning Considerations

High tensile strength hydrophilic size films are difficult to dry on the slasher. This is due to the fact that the size rapidly forms a dryer surface film through which the remaining trapped moisture must diffuse in order to become evaporated. This problem is mitigated by as much as 25% by the addition of PVAc to PVA sizes. Thus, up to one-quarter of the drying cylinder requirement is eliminated, giving the possibility for increasing slasher speeds.

The PVAc functions to interrupt some of the strong hydrogen bonding in the drying of the primary size, thus the surface filming cannot occur as readily. It is this same mechanism which also results in the reduction of size box skinning. During creep speeds, the exposed surface of the size in the size
box can cool down due to low agitation. This can allow the cooler size to congeal and develop a thick skin of size, which can cause roll marks and hard size spots that can often cause yarn breaks at the split rods on the slasher or at the loom.

### 3.7.10 Desizing and Recovery of PVAc

Ordinary desize procedures at the finishing plant readily removes the PVAc size. The size does not react or cross-link with the fibers or other size box ingredients, e.g., lubricants. Although PVAc has been shown to be recoverable by ultrafiltration techniques in the same ratio as is found in the desize liquor, it is not being presently recovered by any mills in the United States [69].

### 3.8 STYRENE/MALEIC ANHYDRIDE SIZES

Styrene/maleic anhydride (SMA) copolymers are the size of choice for acetate rayon continuous filament yarns. The size is the copolymer of styrene and maleic anhydride, which is employed as either the water-soluble ammonium or sodium salts, as shown in Fig. 3.44. Other terpolymers include acrylics or methacrylic acid. The optimal styrene content is about 1.8 to 4.0 mole percent [61].

![Styrene/maleic anhydride](image)

**Fig. 3.44**  Styrene/maleic anhydride. (a) Styrene/maleic anhydride; (b) sodium; (c) ammonium. The sodium and ammonium are water soluble.
The ammonium salt of SMA is particularly suitable for water-jet weaving because the ammonia can be lost when the yarn is heated on the drying cylinders, converting it into the water-insoluble form. The ammonium derivative is also effectively employed for loom finished goods or as a permanent stiffening agent, such as acetate taffeta.

Generally a lubricant and a plasticizer are added to the SMA size formulation [72]. A typical size formulation [72] is

Styrene/maleic anhydride 45–55 lb.
Lubricant 0–10 lb.
Urea 0–15 lb.
Finished product 100 gallons

When urea is used as a plasticizer, it can reduce static build-up at the slasher and on the loom [73].

Because of the easy stretchability of acetate under hot/wet conditions [70] the sizing of acetate must be done at 58–62°C. Liquid vinyl/maleic copolymer sizes have been effectively used to size acetate. They have been shown to give equal or better sizing parameters with the advantage of faster drying. Further, they give the mill the advantage of a one-piece product which readily lends itself to computer automation of sizing [72].

Styrene/maleic copolymer sizes are easily desized using mildly alkaline detergent at 70–80°C. More severe desize conditions can result in damage to the acetate fabric or affect the fabric dyeability. For example, increasing the alkalinity of desizing can remove some of the acetate groups on the backbone polymer chain, causing it to become regenerated cellulose having a different dyeability or nondyeability with certain dyestuffs.

3.9 SIZE RECOVERY AND DESIZE

3.9.1 Other Size Recovery Methods

The most efficient method of size recovery is by ultrafiltration or some similar techniques. However, any method to recover size prior to desizing can reduce the amount of size in the effluent, thereby reducing treatment costs. Perkins [74] has shown that the use of a vacuum slot extractor can reclaim approximately 50% of low viscosity PH grade PVA at 10–15 in. of mercury vacuum. The recovered size is lower in viscosity than the original size, indicating that only the low molecular weight fractions are preferentially removed. Fabric
structural parameters such as type of fiber yarn and weave have an effect on recovery efficiencies.

Approximately 10–15% of size can be removed by merely beating the dry sized fabric with hexagonal beater bars followed by vacuuming the fabric [75]. Some size materials, notably hydroxypropyl cellulose (HCP), are cold water soluble but precipitate in hot water, leading to a novel sizing and recovery system [76]. Other cellulose ethers have similar properties. The use of solvent systems other than water for sizing and desizing has been shown them to be economical alternatives to water-based systems [52]. The most viable system uses chlorinated hydrocarbons, which must meet present day environmental concerns [52].

### 3.9.2 Treatment of Desize Wastewater

There was a time when desize wastewater could be dumped directly into the nation’s rivers and streams. This practice was no longer possible after the Clean Water Act of 1972, which placed stringent government regulations on mill effluent discharges. Desized waste constitutes the bulk (at least 65%) of the discharge effluent (solids) of a finishing plant yet constitutes only 10–20% of the total water usage [49]. The typical BOD contributions of various textile processes are provided in Table 3.18. To meet the present-day zero discharge requirements a plant may

1. Upgrade the treatment facility of the plant to an advanced tertiary type. This requires a considerable capital outlay with no return on investment. Further, waste treatment involves considerable operating costs.

2. Employ size materials that are less polluting or use no size at all. The pounds of oxygen requirement of one pound of various warp sizes are given in Table 3.19. There is a significant difference in the five-day biological oxygen demand (BOD$_5$) requirements of size materials, with starch having the greatest BOD$_5$. Some of the latest works in this area consider the three-day BOD (BOD$_3$) along with the ultimate BOD requirements.

   This must be considered, however, along with the chemical oxygen demand (COD) loading. PVA is the highest in this regard. It is the total oxygen demand (TOD), which is the sum of the BOD and COD, that a mill must be concerned with. In this regard, PVA has the greatest TOD. Most size materials can be effectively broken down using bacteria in an activated sludge that has been acclimated under conditions attainable in mill treatment facilities. These mi-
### Table 3.18  Typical Biological Oxygen Demand Contributions of Various Textile Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>BOD produced per 100 lb fabric (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singe</td>
<td>None</td>
</tr>
<tr>
<td>Desize (woven only)</td>
<td></td>
</tr>
<tr>
<td>enzymem/starch</td>
<td>67</td>
</tr>
<tr>
<td>starch/CMC mix</td>
<td>20</td>
</tr>
<tr>
<td>PVOH or CMC only</td>
<td>0–5</td>
</tr>
<tr>
<td>Scouring</td>
<td>40–50</td>
</tr>
<tr>
<td>Bleaching</td>
<td></td>
</tr>
<tr>
<td>Peroxide</td>
<td>3–4</td>
</tr>
<tr>
<td>Hypochlorite</td>
<td>8</td>
</tr>
<tr>
<td>Mercerizing</td>
<td></td>
</tr>
<tr>
<td>No caustic recovery</td>
<td>15</td>
</tr>
<tr>
<td>With caustic recovery</td>
<td>6</td>
</tr>
<tr>
<td>Heat-setting</td>
<td>0</td>
</tr>
<tr>
<td>Dyeing</td>
<td>50–100</td>
</tr>
<tr>
<td>Finishing</td>
<td>0–50</td>
</tr>
</tbody>
</table>

*Source: Ref. 78.*

### Table 3.19  Waste Treatment Requirements for Various Sizes

<table>
<thead>
<tr>
<th>Size material</th>
<th>BOD₅ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch</td>
<td></td>
</tr>
<tr>
<td>Pearl corn</td>
<td>500,000</td>
</tr>
<tr>
<td>B2 gum (starch dextrins)</td>
<td>610,000</td>
</tr>
<tr>
<td>Keofilm No. 40</td>
<td>550,000</td>
</tr>
<tr>
<td>Penford gum 300 (starch ether)</td>
<td>360,000</td>
</tr>
<tr>
<td>Wheat starch</td>
<td>550,000</td>
</tr>
<tr>
<td>Polyvinyl alcohol (PVA)</td>
<td>10,000–16,000</td>
</tr>
<tr>
<td>Carboxymethyl cellulose (CMC)</td>
<td>30,000</td>
</tr>
<tr>
<td>Polyvinyl acetate (PVAc)</td>
<td>10,000</td>
</tr>
<tr>
<td>Hydroxymethyl cellulose (HEC)</td>
<td>30,000</td>
</tr>
<tr>
<td>Sodium alginate</td>
<td>360,000</td>
</tr>
<tr>
<td>Acrylic</td>
<td>205,800</td>
</tr>
</tbody>
</table>

*Source: Ref. 78.*

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crobes are temperature sensitive, however, and are not as effective during the cold winter months. In addition to the oxygen demand required by the size materials and the other additives in the size mix such as lubricants, humectants, antistats, defoamers, etc., must also be considered.

3. Use a lower add-on of the size. By substitution of sizes and adjusting formulations, it may be possible to reduce the amount of size, thus reducing the waste treatment requirements. However, other factors such as the effects on weaving efficiencies must be considered. Trials necessary to properly evaluate sizing formulations are expensive and time consuming. For example, 24,000 loom hours are required to properly evaluate a size candidate if only warp stops are considered (55,000 h for all stops) [77]. In order to cut down on the time requirements, several looms may need to be dedicated for a trial. Thus, development of alternative low TOD formulas that can still give high weaving efficiencies are time consuming and expensive and provides little economic incentive for a textile mill.

4. The size can be reclaimed and reused. This is the only practical option for a textile mill. Today, only PVA is being recovered and reused by the U.S. textile industry, although all sizes except for starch (e.g., acrylic, polyester, vinyl acetate, etc.) have been shown to be recoverable and reusable either alone or along with blends of PVA. Starch products are enzymatically or chemically broken down during desizing in order to solubilize them for removal from the fabric. Since this degradation is time, temperature, and process related, it is not possible to achieve a desized product that is useful for recycling. Even the highly water-soluble starches that do not require enzyme or chemical desizing are not usable since they break down or change in composition during the ultrafiltration process.

By recovering and reusing the size, the plant reduces the cost of the sizing process as well as reduces the wastewater treatment requirements. As a consequence, the payback for a reclamation system can be less than 2 years [49]. Weaving results have shown that the recovered sizes perform at equal or better efficiencies as the virgin sizes on most fabrics [78].

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4

WINDING, WARPING, AND SIZING

4.1 INTRODUCTION

A plain woven fabric is produced by interlacing two sets of threads, commonly known as warp and weft (or filling). Warp usually runs along the length of the fabric and the weft or filling essentially at a right angle to warp across the width of the fabric, as shown in Fig. 4.1a. The process of interlacement (Fig. 4.1b), commonly known as weaving, transforms the individual yarns into a woven fabric. Although there is a large variety of different ways to interlace two sets of threads to produce different types of fabric structures, a plain weave is the most widely used.

A fabric usually consists of several thousand warp yarns across the whole width. It is in no way practically feasible to weave a fabric by placing several thousand warp yarn packages side by side at the back of a weaving machine, i.e., the loom, for numerous reasons. The weaving process, therefore, requires the preparation of a weaver’s beam which is placed at the back of the loom. The weaver’s beam contains the exact number of warp yarns (ends) required to produce a fabric of the given specifications. To assemble the weaver’s beam containing several thousand warp yarns and to make it sufficiently strong to withstand mechanical stresses and abrasion during weaving, the warp yarns generally need to be sized with chemicals by the process known as sizing or slashing. It is also not practically feasible to place several thousand warp yarns at the back of the sizing machine. So a number of flange beams, called warper’s beams, containing several hundred warp yarns are placed at the back of the
sizing machine. A single warper’s beam is assembled by placing in the creel as many packages as required by the number of yarns in it. The packages placed in the creel of the warping machine are large wound packages in the case of ring-spun yarn or direct packages from modern spinning systems such as open end, friction, and air jet. Therefore, in a nutshell the process of weaving requires certain preparatory steps to transfer the spun yarns from the spinner’s
package to a weaver’s beam ready for weaving [1]. The processes involved are

1. Winding
2. Warping
3. Sizing
4. Drawing-in and tying

The success of the weaving operation is considerably influenced by the quality of yarn and the care taken during the preparatory weaving processes, such as winding, warping, and sizing. Also, careful consideration of the sizing ingredients, size add-on levels, process of slashing, and slasher-related parameters are a few of the several variables that must be controlled precisely for the success of an efficient weaving operation. The yarn supplied from the spinning machines should be sufficiently strong, uniform, smooth, knot-free, and slub-free to withstand the cyclic stresses and abrasion the yarns are subjected to during the process of weaving. Table 4.1 summarizes the characteristics of a good warp yarn for efficient weaving. A poor quality yarn will cause excessive breakages during weaving no matter how carefully the warp has been assembled during the preparatory weaving processes.

The warp yarn supplied to the warping machine should be uniform, free of all objectionable faults, and wound on a reasonably large package of a suitable build that unwinds trouble-free in the warping creel. Also, the knots or splices, introduced for removing faults and tying-in yarn from a number of bobbins during the winding operation, should be reasonably small and sufficiently strong so as to allow them to freely pass through the heddle eyes and dents of reed and withstand the weaving operation. The warp beams prepared during the warping operation should have a large length of yarn with all the warp yarns laid parallel with sufficient space between them. The density of

<table>
<thead>
<tr>
<th>Table 4.1</th>
<th>Characteristics of a Good Warp for Efficient Weaving</th>
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<tr>
<td>Strong</td>
<td>Uniform</td>
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<tr>
<td>Smooth</td>
<td>Knot-free</td>
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<tr>
<td>Slub-free</td>
<td>Withstands abrasion of moving loom parts</td>
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<td></td>
<td>Withstands cyclic strains and stresses of loom</td>
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the warp beam should be uniform from the start to finish to ensure trouble-free unwinding in the creel of the sizing machine. A carefully prepared warping beam with a uniform density and no broken ends or cross-ends contributes toward the success of slashing and weaving. The following sections give a brief discussion of the winding, warping and sizing processes.

4.2 WINDING

Unevenness in traditionally spun staple yarns is a natural phenomenon usually induced by the process of manufacturing (spinning). Although with modern process controls and machines many imperfections in the spun yarns can be controlled, some still remain in the final yarns. Most common of all imperfections are thin or weak places, thick places, slubs, neps, and wild fibers, as shown schematically in Fig. 4.2. During the subsequent processes of winding, warping, and slashing, not all but some of these imperfections create obstacles to steady and smooth working. Therefore, it is important to classify, quantity, and remove those imperfections which may cause the interruption of the operation. In other words, only “objectionable” faults need to be removed for trouble-free processing of the yarns.

The ring-spinning operation produces a ring bobbin containing just a few grams of yarn which is unsuitable for the efficiency of further processing, such as warping, twisting, and quilling. This necessitates the preparation of a dense and uniform yarn package of sufficiently large size which can unwind in the subsequent operations without interruptions. The packages prepared for warping are normally cross-wound, containing several kilograms of yarns. This implies that a number of knots or splices are introduced within each final package. Bear in mind, each knot or splice itself is an artificially introduced imperfection; therefore, the size of this knot or splice must be precisely controlled to avoid an unacceptable fault in the final fabric. In modern winding machines, knots and splices are tested photoelectrically for size, and only acceptable knots and splices are allowed to pass on to the winding package. In modern spinning processes, such as open end, friction and air jet, the spinning process itself produces a large cross-wound package, thus eliminating the winding operation. Nowadays splices are used on all the spinning systems including ring, open end, and air jet for repairing ends down during spinning. In the absence of winding, it is pertinent to note that the yarn spun on such modern spinning systems must have no or only a small number of objectionable imperfections. In most modern spinning machines, the manufacturers have incorporated devices that continuously monitor the quality of the yarn being spun, thus assuring fault-free spun yarns.
Fig. 4.2  Schematics showing typical yarn faults.

4.2.1 Functions of the Winding Operation

Important functions of the winding operation are
1. Clearing of yarn faults
2. Making larger wound packages
3. Preparing soft packages for dyeing

Clearing

Clearing is a process of removing imperfections from the spun yarn. The clearing operation must be carried out during the winding process only because the cost of the winding/clearing operation is usually far lower than that of the subsequent operations, such as warping, slashing, and weaving [1]. Moreover, attempting to clear faults at a later stage (e.g., in warping) will be inefficient.
as a number of good warp yarns will become inoperative. For example, a break of a single warp yarn on the loom brings the entire loom to a stop, thus reducing the efficiency of the loom.

The imperfections or faults which occur in spun yarns include slubs or thick places, weak or thin places, neps, and wild fibers, as shown in Fig. 4.2. Thin places in the yarn are usually weak spots, making the yarn susceptible to breakage during subsequent preparatory and weaving operations. Therefore, such thin places which are weak should be replaced with a strong knot or splice. Some of these thin places which are not unacceptably weak can be covered by the application of size during the slashing operation. The thin places are usually removed by applying tension to the yarn during the winding process. The level of tension applied determines the number of thin places (weak spots) removed. Thin places having a breaking strength lower than the tension applied are usually broken during the winding operation. Thick places and slubs are the places in the yarn having a diameter significantly greater than the normal diameter of the yarn. Such faults are removed either electronically (using optical or capacitance sensors) or mechanically. In the latter case, the yarn is passed through a small slit, usually twice or more the size of the diameter of the yarn during its travel from the ring tubes to the winding package, as shown in Fig. 4.3. Those slubs and thick places larger than the opening of the slit are cut and replaced by a knot or an end-to-end splice. Otherwise, in modern winding machines thick places and slubs are measured by a photoelectrical device which continuously senses the diameter of the yarn being wound and compares the cross section of the yarn with that of such faults.

Making Larger Packages

Making larger packages is an essential function of winding, especially for staple yarn spun on a ring-spinning system. Smaller ring bobbins containing relatively short lengths of yarn are cross-wound onto a larger wound package, usually a cone or parallel wound or flanged cylindrical package. These wound packages, as shown in Fig. 4.4, are made up of several ring bobbins by joining the ends. Such increased lengths of yarns will ensure continuous operation in subsequent mass production processes such as warping, twisting, quilling, and weaving.

The type and quality of package prepared during winding depend upon the winding systems employed. There are three principal types of winding that are commonly used on modern winding machines, namely,

1. Random or open winding
2. Precision winding
3. Digicone winding
In random or open winding the package is surface driven by its frictional contact with the driving cylinder or drum, as shown in Fig. 4.5. In the case where a plain driving cylinder is used for driving the package, the yarn guide is driven by belts or gears to impart one full traverse along the length of the package. However, in most modern winders the driving drum is grooved so as to guide the yarn for a full traverse across the length of the package. More often, the drum is driven by a shaft, running at a constant speed, across the whole length of the winder or by an individual motor attached to each drum. In this type of winding, the ratio between the package revolutions per minute and the double traverse, known as winding ratio, changes constantly during the entire process of winding. For a bigger package, this winding ratio is small and vice versa. The helix angle—half of the crossing angle—does not change throughout the build of the package. As the double traverse remains constant,
the increase in the package diameter has to be compensated with a constant decrease of revolutions per double traverse, this results in gradually decreasing winding ratios. When this winding ratio becomes a whole number, such as 1:1, 2:1, 3:1, and so on, the yarn is laid over the yarn wound in the previous traverse, resulting in the formation of a “ribbon”. This ribbon zone has a higher winding density and poor unwinding behavior caused by “sluff-off” of the yarn. Prevention of ribbon formation is achieved by several methods, namely, (1) modulating the yarn guide frequency, (2) creating slippage between the package and grooved drum, and (3) lifting the package away from
the driving drum at fixed time intervals. All these methods momentarily alter the winding ratio, thereby avoiding ribbon formation [2–4].

In precision winding, the package itself is driven by a train of gears, and the yarn guide is directly connected as shown in Fig. 4.6. The ratio between the package revolutions and the double traverse—the winding ratio—remains constant, whereas the helix angle changes constantly throughout the package build, higher (open) at the smaller package diameter and lower (close) at the higher package diameter. Because the package itself is driven, the rotational speed (rpm) of the package has to be decreased constantly with the increase in the package diameter so as to maintain constant winding speed. The major

**Fig. 4.5** Random winding. (From Refs. 4 and 5.)
advantage of this type of winding is that there is no ribbon formation because the winding ratio remains constant throughout the package. However, the major drawback of this type of winding is constantly increasing density of the package as the package grows larger because of the constantly decreasing helix angle [2–4].

A more recent development of winding type is ‘Digicone’ winding, where the control systems, consisting of digital microprocessor, produce well-built packages of uniform density. A schematic of Digicone winding is shown in Fig. 4.7 The control system consists of two sensors, \( n_1 \) and \( n_2 \), to register the revolutions of the package and variable drive, \( P \). The microprocessor calculates and analyzes the signals provided by the sensors, placed near the package holder and the traverse mechanism. These values are in turn compared with the programmed values (in EPROM), and the drive system is activated as

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**Fig. 4.6** Precision winding. (From Refs. 4 and 5.)
necessary. On the Digicone winder the most appropriate helix angle for a particular end-use application can be ascertained. For difficult-to-dye yarn, a crossing angle of 18° is proved to be best. On the other hand for accommodating longer lengths of yarn on the package the crossing angle may be decreased to as low as 10°. On the Digicone system, any crossing angle between these two extreme limits (10 to 18°) can be easily set by changing the appropriate pulley on the shaft of the driving drum, D. The crossing angle remains constant because the drive to drum and the yarn guide are connected through the variable drive and belts, as shown in Fig. 4.7. The mechanism allows the process to achieve correct winding speed and traverse of the yarn guide to maintain constant crossing angle [2–4].

In Digicone winding, the mechanism begins with a precision winding operation such that a crossing angle of α₁ is set initially. As the winding progresses (the package diameter increases), the crossing angle decreases until

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**Fig. 4.7** Digicone winding. (From Ref. 6.)
a programmed crossing angle of $\alpha_2$ is reached. At this stage, the microprocessor will reset the drive to change the crossing angle back to the same level as in the beginning, i.e., $\alpha_1$. Again the precision winding is continued until a preprogrammed crossing angle of $\alpha_2$ is reached, and so on until the final package diameter is reached. Figure 4.8 graphically displays this process of package building. The difference between $\alpha_1$ and $\alpha_2$ is set to such a small value that no appreciable density difference occurs. This results in stable, uniform, and well-built packages, leading to optimal performance during weaving, knitting, and dyeing operations [5,6].

Soft Packages for Dyeing

For cloth produced from dyed yarn, the preparation of the yarn packages ready for dyeing is usually carried out at the winding stage. The packages to be dyed should have a low but uniform winding density from start to finish, uniform package build, and identical packages and tube dimensions. These factors influence the level and uniformity of dyeing within and between the packages and also between batches. The soft wound packages allow the dye liquor to freely circulate between the layers of yarn so as to yield uniform and level dyeing of the yarns. The density profile of the package is shown in Fig. 4.9. The density varies gradually from the inside to the outside of the package as shown. Any loss in the density of the package in the inner layers is compensated for by the increased density in the outer layers.

Fig. 4.8  Relationship between winding ratio and package diameter for digicone and precision winding. (From Ref. 6.)
For producing low density packages the most important parameter to control is the winding tension and the pressure between the package and the winding drum. Usually dyeing packages are wound with a minimum of winding tension; there is, certainly, a danger of allowing some weak places to be wound on the packages. A reasonable trade-off between the minimization of the winding tension and passing-on of the weak places to the packages should be maintained. On modern winding machines, as the diameter of the wound package increases, the pressure of the package to the winding drum is automatically reduced. This prevents the outer layers of the dyeing packages from having more compact winding than the layers beneath them.

For ensuring uniform dyeing of the yarns closer to the bare package, it is customary to use perforated tubes or cones, as well as coiled spring tubes covered with a paper or knitted material. Such packages allow dye liquor to freely circulate from the inside to the outside of the package, thus ensuring uniform and level dyeing. Before dyeing, the packages are usually subjected to a prewetting and scouring treatment. Due to the wetting, the yarn swells and shrinks, thus resulting in an increase in packing density resulting in higher resistance to flow of dye liquor. Therefore, sufficient allowance should be
made for the yarn to shrink due to swelling, without adversely affecting the
dyeability of the wound packages.

In a nutshell, the purpose of the winding operation is to supply adequate
length of yarn to the warping operation which requires yarn that is uniform,
is free of all objectionable imperfections, and has as few knots or splices as
practically feasible. The wound packages should have a satisfactory build so
as to allow uniform unwinding in the creel of the warping machine. Also, the
knots or splices introduced during the winding operation should be small
enough, thus enabling them to freely pass through the heddle eyes and the
reed dents of the loom, as well as be strong enough to withstand the weaving
operation.

4.2.2 Knotting/Splicing

The process of piecing (joining) two yarn ends—resulting from yarn breaks,
removal of a yarn defect, or due to the end of the supply package—has received
considerable attention in the past two decades. An ideal yarn piecing would
be one which can withstand the subsequent processes without interruption and
which does not lead to any deterioration in the quality of the finished product
[7]. The yarn joining or piecing technique should be suitable for all fiber types
irrespective of yarn structure and linear density. Earlier attempts in this area
were directed to tying two ends by a weaver’s knot or fisherman’s knot such
that the ends do not slip apart. However, the size of the knot, which depends
on the type of knitter and the linear density of the yarns, would normally be
two to three times the diameter of the single yarn, leading to a characteristic
objectionable fault in the finished product. Knots have a detrimental effect on
quality; they are obstructive because of their prominence and so frequently
cause breaks due to catching in thread guides or even being sheared off. This
leads to time-wasting stoppages of the machinery during warping, sizing, and
weaving. Due to the above-mentioned drawbacks of knotted yarns, knotless
yarn joining methods have received considerable attention by researchers
[7–9].

Methods for Producing Knot-Free Yarns

The development of methods for producing knotless yarns began during the
early 1970s. Various methods have been used for producing knot-free yarn
piecing, including [8]

1. Wrapping
2. Gluing
3. Welding or fusing
4. Splicing
   a. Mechanical splicing
   b. Electrostatic splicing
   c. Pneumatic splicing

In the wrapping method, two yarn ends are overlapped, and an auxiliary yarn is wrapped around them to produce a joint of high strength, as shown in Fig. 4.10a. This method produces a thick and rigid joint, and the mechanism involved is very complicated. The auxiliary thread often causes problems during subsequent processing. In the gluing method, two overlapped ends of yarns are glued by a special adhesive, as shown in Fig. 4.10b. This technique produces a thick joint and rigid structure because of the rigidity of the glue (adhesive) used. Also, drying of the adhesive takes a long time, resulting in lower productivity of the process. In the welding technique two yarn ends are welded together by a melting process, as shown in Fig. 4.10c. Although this technique produces a short but high strength joint, it can be applied only for thermoplastic fibers (e.g., nylon), and the welded portion has a different structure due to the melting process [8]. The first three methods listed above are no longer used in practice because the pieced portion (joint) is thicker and more rigid and also in one case contains an extraneous material, namely, the adhesive.

Splicing

In splicing, the joint is more or less like the yarn itself and produces sufficiently strong piecing without adversely affecting the appearance of the final fabric, and consequently it is more widely used in modern winders. The concept of splicing is similar to the method of joining rope (or cable) ends together. For the purpose of joining, the two ends of a rope are untwisted and then intermingled by some mechanical means. The methods of yarn splicing involve mechanical, electrostatic, and pneumatic systems [7].

Mechanical Splicing. In mechanical splicing the yarn ends are untwisted to open the fibers. Two ends are overlapped and then twisted together again to essentially the same twist level as in the basic yarn, as shown in Fig. 4.10d. The fibers at the end of the yarn are used to bind the splice joint resulting in a corkscrew-like appearance. The disadvantages of this system are (1) it is difficult to open up the yarn ends consistently due to irregular twist distribution; (2) it is possible to achieve proper separation of fibers at yarn ends only for short staple fibers—for long staple yarn it is somewhat difficult to separate fibers at the yarn ends, which has a negative effect on binding of fibers; (3) different twisting wheels are required for opening and twisting of yarns of
different twist levels and made from different staple length fibers, involving costly adjustments; (4) in this splicing technique it is not possible to splice plied yarns as opening by untwisting is not possible; and (5) mechanical splicers require more frequent maintenance and servicing due to the entry of dust and fly [8].

**Electrostatic Splicing.** The yarn ends are separated and untwisted in the opening zone. The opened-up yarn ends are then spread out evenly in an electrostatic field, after which they are intermingled and bound again by a pole change, while simultaneously twist is inserted corresponding to the twist in the basic yarn, as shown in Fig. 4.10e. Theoretically, this method of splicing is very suitable as it provides ideal blending of fibers in the splice zone, but it suffers from some practical drawbacks; these include

1. Required opening and separation of fiber ends for effective spread-out in the electronic field is not always achieved satisfactorily. This is due to irregular twist distribution in the base yarn.
2. For a yarn containing a large number of fibers in the cross section

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Fig. 4.10  Different methods for producing knot-free yarn. (From Refs. 7 and 8.)
the intermingling of prepared fibers at the yarn ends is a problem as fibers obstruct one another.

3. Plied yarns cannot be spliced due to difficulty in opening fibers at the yarn ends by mechanically untwisting.

4. The time taken to splice the yarn is quite long, thus decreasing the efficiency of the winding process. Also, high voltage is required to achieve the desired charge. The climatic condition of the winding room has an obvious effect on the electrostatic field [8].

**Pneumatic Splicing.** In this method, the yarn ends are inserted into a splicing chamber and then overlapped to join them together by means of a strong current of compressed air, as shown in Fig. 4.10f. The splicing time and air pressure are determined according to fiber type and yarn characteristics [8]. The splicing operation consists of the vertical application of air to the fibers and a simultaneous rotational movement of the air to twist/untwist the yarn. This type of air movement is achieved by the position of the blower.
apertures and the design of the shape of the splicing chamber. Pneumatically spliced yarn produces a joint that can meet all the requirements in subsequent processing, both in terms of strength and appearance. The time taken to carry out efficient pneumatic splicing is relatively short, thus winding efficiency is not severely limited. Moreover, pneumatic splicing can be applied to a wide range of fiber and yarn types without requiring precise adjustments or settings, thus facilitating efficient winding [8].

*Double Splicing.* This splicing technique has attained considerable importance in the synthetic fiber manufacturing industry because knots have a detrimental effect on quality. A new splicing technique called “double splice”, based on the principle of pneumatic splicing, is normally used in joining continuous filament yarns and tire cords. In this technique, yarn filaments are intermingled by using an air splicer, leaving virtually no protruding ends [9].

### 4.3 WARping

Warping is a process of transferring yarn from a predetermined number of single-end packages, such as cones or cheeses, into a sheet of parallel yarns of a specified length and width. The individual warp yarns are uniformly spaced across the whole width of the beam. In warping, the sheet of parallel yarns is wound onto a flanged beam called a warper’s beam [10]. The function of warping is primarily to transfer large lengths of yarns from a number of large wound packages to a warper’s beam containing a predetermined number of yarn ends (threads), so that it runs without interruption at a high speed. Removing faults from yarns during warping is not recommended because it affects the efficiency of the process. A single break makes several hundred other good warp yarns inoperative, thus affecting productivity.

#### 4.3.1 Warping Systems

There are two basic systems of warping, namely, the direct system and the indirect system, as shown in Fig. 4.11. In the direct system the warp yarns from a creel are wound directly onto a flanged warper’s beam. This system is most widely used for mass production of warper’s beams containing only one type of warp yarns. Because of the difficulties involved in setting up a pattern of different types and colors of warp yarns, the direct system is not normally used for the preparation of a patterned warper’s beam [1]. Any pattern that is required to be produced is adjusted by combining beams of different colors during the slashing operation. The cumbersome work of setting the pattern at the slashing stage is time intensive and inefficient. In the indirect
Fig. 4.11 Warping systems.
system, a number of sections of patterned warp, containing different colors, are wound sequentially on a section beam, as shown in Fig. 4.11. Once a desired number of sections (desired number of total ends) are wound on a section beam, the warp is transferred onto a weaver’s beam.

Direct System

In the direct system of warping, a predetermined number of yarn packages are placed in a large creel, as shown in Fig. 4.12. Each yarn package is firmly inserted on a package holder, as shown in Fig. 4.13. The yarn from each package is then threaded through its own stop motion and a tensioner at the front of the creel, as shown in Fig. 4.14. Yarns from all packages are brought together to form a warp sheet, which is taken to the head stock where it is uniformly spaced by passing through dents of a comb and where the actual winding of the yarn sheet on a beam takes place. The beams thus prepared are known as section beams, warper’s beams, or back beams. The required
number of these beams is placed at the back of the sizing machine. The type of creel, tensioner, warp stop motion, head stock, and control devices on warping machines may vary depending on the manufacturer; however, their basic functions remain the same.

Indirect System

Unlike the direct system, warping and the preparation of a weaver’s beam takes place on the same machine but in two consecutive steps. In the first step, the warp is prepared in sections on a large drum with one conical end, as shown in Fig. 4.15. Then the rewinding of the entire warp sheet from this
drum to a weaver’s beam is done in the second step. The operations in the first and the second step are commonly known as warping and beaming, respectively.

For preparing the sections on a drum, the warp yarn is withdrawn from the creel through a tension device and stop motion (similar to the one described in the previous section) and is in turn passed through a leasing reed. Then all

Fig. 4.14  Stop motion. (Courtesy of West Point Foundry and Machine Company.)
the sectional warps are condensed into a section of the desired width by passing them through a V-shaped reed guide and over a measuring roller to the drum. The density of the warp in a given section is the same as the number of ends per unit width required in the weaver’s beam for producing a fabric with a given color pattern and specification. The length of each section is generally equal to the length of the warp required in a weaver’s beam plus due allowance for the waste in the process. One end of the warping drum is conical shaped, as shown in Fig. 4.15. This is necessary for providing support to the outside ends of the first section to prevent the yarns from sloughing off at the end of the drum.

The leading end of each section is attached to the drum such that the edge of the section is placed exactly on the nose of the conical portion of the drum or by the nose formed due to winding of the previous section, as shown in Fig. 4.16. During the process of winding a section on the drum, a slow continuous traverse is imparted to the section of warp being wound. After the initial few turns of the warping drum, a lease thread is inserted in each section.
with the help of a leasing device. This is necessary for maintaining the correct order of the warp ends as required by the multicolored pattern. These one-and-one leases inserted during warping are helpful during drawing-in of warp ends in the harnesses of the loom.

After completing the warping operation, the full sheet of warp built on a warping drum contains the exact number of ends and width of warp required on the weaver’s beam. This warp sheet is then rewound on a weaver’s beam ready for weaving if the yarns do not require sizing. The yarns that require sizing are also processed exactly in a similar manner, but additional split strings are inserted during one-and-one leasing. These split strings are later replaced during slashing by split rods [10]. The beam prepared on such sectional warpers can be conveniently sized on a slasher without much loss in time because the introduction of one-and-one leases ensures perfect arrangement of all warp threads according to the pattern set during warping, and the counting and arrangement of threads in the expansion comb of the slasher are no longer required [10].
The productivity of the indirect system may turn out to be much lower in comparison to the direct warping system; however, the overall production costs from winding to the gaiting-up of a beam on the loom for the indirect warping system can be lower depending on the complexity of the pattern and length of the fabric being produced [10]. In the direct system of warping, the cost is directly in proportion to the length of the fabric being produced. As the amount of production needed increases, in terms of the length of fabric, the cost of the direct warping system decreases, and it tends to level off when the optimal operating conditions are reached. Nevertheless, in the indirect system the costs are reasonably constant irrespective of the warping length being produced [10].

4.4 SIZING

The primary purpose of sizing is to produce warp yarns that will weave satisfactorily without suffering any consequential damage due to abrasion with the moving parts of the loom. The other objective, though not very common in modern practice, is to impart special properties to the fabric, such as weight, feel, softness, and handle. However, the aforementioned primary objective is of paramount technical significance and is discussed in detail herein.

During the process of weaving, warp yarns are subjected to considerable tension together with an abrasive action. A warp yarn, during its passage from the weaver’s beam to the fell of the cloth, is subjected to intensive abrasion against the whip roll, drop wires, heddle eyes, adjacent heddles, reed wires, and the picking element [12], as shown in Fig. 4.17. The intensity of the abrasive action is especially high for heavy sett fabrics. The warp yarns may break during the process of weaving due to the complex mechanical actions consisting of cyclic extension, abrasion, and bending. To prevent warp yarns from excessive breakage under such weaving conditions, the threads are sized to impart better abrasion resistance and to improve yarn strength. The purpose of sizing is to increase the strength and abrasion resistance of the yarn by encapsulating the yarn with a smooth but tough size film. The coating of the size film around the yarn improves the abrasion resistance and protects the weak places in the yarns from the rigorous actions of the moving loom parts.

The functions of the sizing operation are

1. To lay in the protruding fibers in the body of the yarn and to cover weak places by encapsulating the yarn by a protective coating of the size film. The thickness of the size film coating should be optimized. Too thick a coating will be susceptible to easy size shed-off on the loom.
2. To increase the strength of the spun warp yarn without affecting its extensibility. This is achieved by allowing the penetration of the size into the yarn. The size in the yarn matrix will tend to bind all the fibers together, as shown in Fig. 4.18. The increase in strength due to sizing is normally expected to be about 10 to 15% with respect to the strength of the unsized yarn. Excessive penetration
of the size liquid into the core of the yarn is not desirable because it affects the flexibility of the yarn.

3. To make a weaver's beam with the exact number of warp threads ready for weaving.

Figure 4.19 illustrates various possible conditions that may occur in practice depending upon the properties of the size employed. This emphasizes the importance of an optimal balance between the penetration of the size into the yarn and providing a protective coating around the yarn, as shown in Fig. 4.19d. The flow properties of the size liquid and the application temperature have important effects on the distribution of the size within the yarn structure. More size at the periphery of the yarn will tend to shed off on the loom under the applied forces because the size is not well anchored on the fibers. Too much penetration, as shown in Fig. 4.19a, may leave too little size around the yarn surface to protect it against the abrasive action. To rectify such a condition, a higher size add-on is required to provide the required protective surface coating [13].

### 4.4.1 Sizing–Weaving Curve

A typical sizing–weaving curve is as shown in Fig. 4.20. Initially the warp breaks decrease with the increase in size add-on level. This is due to the associated increase in yarn strength and reduction in yarn hairiness. The coating of the protective size film around the yarn provides improved resistance
Fig. 4.19  Schematics showing size distribution: (a) too much penetration, no surface coating; (b) too much penetration, more size added to provide surface coating; (c) too little penetration, no anchoring of yarn structure; (d) optimal distribution. (From Ref. 13.)
to abrasion and also affords adequate protection to the weak places in the yarn. The reduction in warp breakage rate with an increase in size add-on reaches a point beyond which further size add-on will not show any significant improvement in yarn performance on the loom. The weaving efficiency, which is inversely proportional to warp yarn end breakage rate, reaches its peak when the warp breakage rate is at its minimum. The optimal range of size add-on is usually between points A and B as shown in the typical curve in Fig. 4.20. Increasing the size add-on beyond the optimum, in fact, has a detrimental effect on weaving performance since the warp breaks increase. Excessive size add-on leads to an increased penetration of the size, which makes the yarn inflexible. Also, higher size add-on may tend to coat the yarn with a very thick film of size which is not sufficiently anchored to the fibers. Such a thick coating of size film may have a lower extensibility compared to the extensibility of the warp yarn itself. Inflexibility of the yarn and a size film not bound securely have a net effect of size film shedding due to its easy rupturing, thus making the yarn vulnerable to intensive abrasion action and leading to a higher

Fig. 4.20  A typical sizing–weaving curve. (From Ref. 20.)
warp breakage rate. The best weaving efficiency region consistent with optimal size add-on is usually achieved in practice by trial and error. In the next chapter the different methods used for correlating laboratory evaluation and its relationship to actual weaving performance are discussed.

4.4.2 Sizing Machines

The essential components of a sizing machine to slash spun warp yarns may be categorized as follows:

1. Creels—unwinding zone
2. Size boxes—sizing zone
3. Drying cylinders—drying zone
4. Bust rods—splitting zone
5. Head stock—weaver’s beam preparation zone
6. Controls and instrumentations

Figure 4.21 shows a schematic diagram of a typical sizing machine and its essential components.

Warp yarns from warping beam placed in a creel are withdrawn and fed to the size box by a feed roll. The yarns are then impregnated in a size liquor preheated to a desired application temperature. Then the yarns are passed through a pair of rolls, commonly known as squeeze rolls, to squeeze out excessive size before they are subjected to the drying cylinders of the drying zone. This is necessary to minimize the drying energy required to dry the warp yarns. The yarns wet with size solution are passed over and under the heated drying cylinders to dry the sheet of warp yarns to a desired level. The dried yarn sheet is then passed through a series of bust rods in the splitting zone to

![Fig. 4.21 Schematic of sizing operation. (Courtesy of West Point Foundry and Machine Company.)](image-url)
separate the yarns. In the final phase, the separated yarns are passed through a guide comb and wound onto a weaver’s beam. The following sections will deal with each function and component of the sizing machine separately.

Creels—Unwinding Zone

The creel on a modern slasher is available in several different forms. Basically it must be well built and of robust construction, capable of carrying heavy warper’s beams. The primary function of the creel is to allow smooth and steady unwinding of the warp yarn sheet without a side to side swinging of the warper’s beam and without entangling two adjacent warp sheets being unwound. Also, the ends from either side of the warper’s beam should not touch the beam flanges. To prevent the sideways swinging of the beams and allow a smooth unwinding of the warp sheet, modern creels are equipped with ball bearings to support the end shafts of the warper’s beams. This also helps in eliminating unwinding tension variations in the warp sheet [14].

Both fixed and movable (on wheels) types of creels are available. The advantage of the movable creel is that while slashing is in progress from one set of beams, the loading of another set can be done on another stand-by creel, which can be attached to the back of the sizing machine later without loss of much time. Consequently, the next set on the sizing machine can be started with much less down time, thus increasing the slashing efficiency.

The major creel types housing multiple beams are [14]

Over/under
Equitension
Inclined
Vertical stack

Over/Under Creel. In the over/under creel, as the name implies, the warp yarn passes over one beam, under the next beam, again over the next beam, and so on, as shown in Fig. 4.22. This type of creel is most commonly used for slashing spun warp yarns of cotton and synthetic fibers. The threading pattern of warp from the beams in this type of creel varies depending upon the number of size boxes used. For heavy to medium construction fabrics, where two size boxes are used in industrial practice, all top beams in the creel may be threaded over and under and then straight to the first size box, as shown schematically in Fig. 4.23. All bottom beams are threaded over and under and then straight to the second size box [11], as shown in Fig. 4.23.

Equitension Creel. In this type of creel, the warp sheet is withdrawn from the individual beam and is passed over a guide roll mounted on the creel
framework. Thus the yarn sheet from each warper’s beam is drawn individually and passed over a guide roll; it then joins the yarn coming from other beams of the top or bottom tier, respectively, and then passes forward directly to the size box [11], as shown in Fig. 4.24. This type of creel is more useful for lightweight fabrics of open constructions.

**Inclined Creel.** The inclined creel may be either double tier or single tier. Obviously, the single tier creel requires much greater floor space, and two tier creels are therefore more commonly used in the industry. The double tier inclined creel is commonly used for filament warps. As shown in Fig. 4.25, the inclined creel allows a direct path of the yarn from each beam through the hook reed to the size box.

**Vertical Creel.** This type of creel is most suitable where a large number of warper’s beams are used. This creel allows the operator easy access to all the warper’s beams. The beams are supported on vertical stands in three decks in several modules, as shown in Fig. 4.26. The passage between each pair of beams...
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modules allows the operator to easily mend a break or correct a problem in a warp yarn leaving the warper's beam [11].

Warping Beam Braking Systems. These systems are required for preventing the over-running of the beams, especially during the reduction in speed of the slasher at the time of a break or during the doffing of the weaver's beam. Also, the braking device allows control of yarn tension between the size box and the creel during the normal constant speed operation. The most commonly used braking system is the "rope and belt" device in which the braking force is applied by means of a rope wrapped around the warper's beam head or by a belt wrapped around a drum or a grooved pulley attached to the beam [11], as shown in Fig. 4.27. Usually the drum or grooved pulley containing ball bearings is attached to both ends of the warping beam shaft so as to ensure free rotation during the normal working of the slasher. The braking force is applied by hanging deadweights that must be decreased man-

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ually as the beam diameter decreases to maintain a uniform yarn tension from start to finish of the warping beams. The deadweight system is substituted by pneumatic cylinders in the pneumatic braking system. The pneumatic pressure in such cylinders on the individual warping beam can be integrated into a central regulator accessible to the operator. The centralized pneumatic braking system, integrated with the sizing machine drive controller, is very efficient because it applies a higher braking force only when the slasher is decelerated. This prevents the application of excessive tension during the normal working of the slasher [14]. A more precise system is the automatic pneumatic braking system in which a sensor is placed between the creel and the size box for measuring the tension in the whole warp sheet. The desired tension in the warp sheet is preadjusted by the operator depending upon the yarn type, yarn count, and style of the fabric being produced. The air pressure in the pneumatic cylinders is automatically adjusted in proportion to the tension fluctuations registered during acceleration or deceleration, and also from start to finish of the warper’s beams. This system assures a constant unwinding tension of the warp yarns from the warp beams for the entire sizing process, with minimal operator intervention [15].

Size Boxes—Sizing Zone

The size box and all parts that remain in contact with the size solution are made of stainless steel to prevent corrosion. The shape of the size box from the bottom is contoured with no sharp ends. The size liquor in the size box
is normally heated by steam supplied through a steam coil placed at the bottom of the size box. The steaming coils placed in the size box should ensure uniform heating of the size liquor in the entire size box. The type and the design of the coil vary depending upon the size box manufacturer. The entry of the high pressure steam in the size box also creates a turbulence which results in the agitation of the size liquor. This is favorable in the case of a starch-based size used for sizing spun yarns because the agitation prevents gelling and scumming of the size near the corners. For filament slashing, a size box with direct heating coils is not desirable as the agitation of the size liquor may disturb the filaments. Also, the bottom of the size box should have an outlet to the effluent disposal system so that the size box can be completely drained when cleaning is required [16].

The configuration of size boxes is quite diverse and they are available in a variety of different forms depending upon the sizing machine manufacturer. However, the basic function of all size boxes is to impregnate the warp sheet

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**Fig. 4.27** Rope or belt braking system. (From Ref. 11.)
in the size liquor at a predetermined application temperature and to squeeze out the excess size liquor before the yarn sheet reaches the drying zone. Most slashers are equipped with a single sizing box having two pairs of squeezing rolls and an immersion roll. Figure 4.28 shows a typical size box. A sheet of warp yarn is drawn from the warper’s beams and fed to the size box over a pair of guide rolls with a slack rod or tension roll riding on the warp between the two guide rolls. The sheet of yarn is immersed in a size solution by one or two immersion roll(s). The immersion roll is normally movable. It is mounted on the size box with a rack and pinion mechanism so that it can be freely lowered and raised. The amount of size that will be picked up by the yarns will depend upon the depth of the immersion roll and the level of size liquor in the size box. At a given constant size level in the box, the lower the position of the immersion roll, the greater the pick-up of the size by the yarns, as it allows a longer time for the yarns to remain in the size liquor and vice versa. The yarn sheet with wet size on it then passes through one or two pairs of squeezing rolls, as shown in Fig. 4.28.

The purpose of the squeeze rolls is to remove the excess size liquid from the yarns. For filament yarn sizing a single squeeze size box is usually used; however, in case of spun cotton and synthetic yarns where higher size addition is required, double squeeze size boxes are normally preferred [10]. The bottom roll in a pair of squeeze rolls is made up of stainless steel and the top roll is made from cast iron material covered with rubber. The top roll is usually

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**Fig. 4.28** Schematics of size box. (From Ref. 16.)
under pressure in addition to its own weight of around 180 to 250 kg. The pressure is usually applied by compressed air operating on pneumatic cylinders or pneumatic diaphragms [10]. In modern slashers, the trend is to use a high squeezing pressure to save energy in drying and to make it possible to use higher concentrations of the size liquor to obtain the predetermined size add-on. In high pressure squeezing, the squeeze roll loading is up to approximately 9000 kg (20,000 lb), which is about 15 times the loading used in a conventional size box [18]. In high pressure squeezing, the quantity of water evaporating during the drying process will be lower, thereby allowing not only savings in drying energy, but also an increase in sizing machine productivity [17]. The drawback of the high pressure squeezing is that the top squeeze rolls deflect or bend when loaded at such high pressure. This results in a nip size variation across the width of the roll, as shown in Fig. 4.29. An uneven nip zone width causes a variation of squeezing pressure across the roll width, resulting in variation in size add-on from the selvedge to the center of the warp sheet [18]. For narrow size boxes (< 1.4-m width of yarn sheet) West Point Co. research [18] has found that the variation in size add-on due to top roll bending is not significant. Nevertheless, in the case of wider size boxes corrective action
incorporating "crowned" squeeze rolls should be used to obtain a uniform nip width. A crowned squeeze roll is produced by grinding the rubber cover top roll to a slightly larger diameter in the center than at the ends. This compensates for the possible bending of the top roll while under high pressure and provides a reasonably uniform nip width and squeezing pressure across the entire width of the roll [18].

A double squeeze size box with twin rolls is also used for slashing light and heavy warp sett spun yarns. The twin immersion rolls allow both sides of the yarns to be exposed to the size mixture, thus ensuring uniform coating and penetration of the size liquor. Both squeeze rolls are equipped with independent loading and lifting controls. This provides flexibility to the slashing operator in using either one or both rolls depending upon the requirement [14]. A size box having double roller, double immersion with high pressure squeezing, as shown in Fig. 4.30, is also used [19]. In such a size box, one set of immersion and squeeze rolls is followed by another set of immersion and squeeze rolls. A recent development is the Equi-Squeeze Size Box, shown in Fig. 4.31. In this system the top squeeze roll position is adjustable. A unique bracket and loading system allows the positioning of the roll to the rear 15 or 30 degrees off the top center position, as shown in Fig. 4.31. By moving the roll to the rear, the adherence of yarns to the roll as they leave the squeezing nip is minimized.

![Fig. 4.30](image)

**Fig. 4.30** Schematic of double squeeze rollers, double immersion with high pressure squeezing. (1) Driven dry feed rollers; (2) guide roller; (3) immersion roller; (4) rubber-covered squeeze roller; (5) finishing roller; (6) size level float switch; (7) size circulating pump. (Courtesy of Platt Sizing.)
Drying Cylinders—Drying Zone

There are two principal types of drying methods used, namely,

1. Cylinder, or can, dryers
2. Hot air, or convection, dryers

*Cylinder Dryers.* These are most widely used as they are the most energy efficient. The cans or cylinders are about 75 cm in diameter and are used in a multiple unit containing a series of five, seven, nine, or eleven cylinders, usually arranged in two tiers to save floor space. The maximal working pressure of steam in these cylinders is about 4.92 kg/cm² (70 psi). The cylinders are made of stainless steel. These cylinders are mounted on ball bearings and driven positively by a chain and sprocket. This eliminates undue tensioning of the yarns while they are dried. The cylinders are also coated with nonstick coating, e.g. Teflon®, for preventing the size and yarns from sticking while the warp is partially dried. Usually the first three cylinders from the front are coated with Teflon in any sizing machine containing five, seven, and nine cylinder systems. For an eleven-cylinder drying system, usually the first four cylinders are coated with Teflon. In the case of filament sizing, usually all cylinders are coated with Teflon.

The cylinders in a drying section are usually arranged either horizontally or vertically. The horizontal system (Fig. 4.21) is generally used because it
allows easy access to the cylinders for threading and mending a break, whereas the vertical system is useful in cases where floor space is limited and when more cylinders are required because a greater number of size boxes are used [14]. The horizontal system of drying cylinders usually consists of seven, nine, or eleven cylinders, depending upon whether one or two size boxes are used. The number of drying cylinders required in a typical slasher will be decided by the density of the warp and the slashing speed that is used. For a higher number of warps and faster slashing speeds, a greater number of drying cylinders will be required. With faster slashing operation, the time available for the warp yarns to be dried will be less, and therefore a high heat transfer rate is required. On a multicylinder machine, in practice, it is desirable to increase the drying temperature during the first phases of drying and to decrease it during the final phases. However, too high of a drying temperature is detrimental to the quality of the sized warp and also too much penetration of size will take place. Typically the temperature range from 80 to 105°C is used in practice [1].

**Convection Drying.** In this system, hot air is used as a drying medium instead of the steam used in cylinder drying. The heated air is passed through the drying chamber. The warp yarn through its passage in the drying chamber comes into contact with the heated air circulation, as shown in Fig. 4.32. The air is heated either by electric coil or steam [14]. The advantage of the hot air convection drying system is that the whole yarn surface is subjected to a uniform drying temperature in contrast to cylinder drying where only a part of the yarn surface is in contact with a hot cylinder. The surface of the yarn in contact with the hot cylinder is likely to be overdried. Cylinder drying is therefore expected to result in uneven drying, with a resultant uneven distribution and migration of size in the yarn [20]. Modern multiple-cylinder drying systems overcome this drawback by subjecting both the top and bottom sides of the yarns to drying by allowing the yarns to pass over and below the hot cylinders, resulting in progressive and uniform drying.

**Infrared and Microwave Drying.** Other forms of drying methods, though not yet widely used in practice for sizing, are infrared drying and microwave drying systems. These systems aim to conserve energy through the efficient and cost-effective use of drying energy to replace conventional steam-based conductive drying. Infrared drying energy can be sourced either electrically or from gas. In an electric system, a series of infrared lamps with reflectors are mounted above and/or below the warp yarn sheet to be dried. The cost of electricity-based infrared drying is usually higher than that of conventional steam-based conductive drying. Gas-based infrared energy can
be achieved by heating refractory materials to incandescence. This drying energy is similar to hot air drying based on the convection principle. The heat produced due to the combustion of gases is also circulated. The yarn can be passed through a number of infrared-radiating gas burners for drying.

Microwave radiation is an inexpensive form of energy generation widely used in many industrial practices. Microwave energy can be obtained easily without causing pollution and therefore receives attention for the drying of textiles where large amounts of energy are consumed. The major problem of the conventional form of microwave energy radiation is the lack of uniform heating, resulting in randomly occurring hotspots which cause overheating in some areas and underheating in others. This problem has been corrected recently by the introduction of appropriately designed "waveguides" systems where microwave energy is transmitted back and forth across the material. This improvement in uniformity of distribution in microwave radiation has opened up new opportunities for its use in textile drying applications. Industrial microwave systems designed for specific purposes are now available which can be retrofitted to the existing conventional fossil fuel burning ovens or drying chambers that can be used as pre- or post-dryers. The use of microwave drying in sizing is in an early stage of development and has yet to replace the conventional drying methods based on conduction and convection.

Lease Rods—Splitting Zone

The function of the lease rods in the splitting zone is to separate the individual yarns which are stuck together because of the drying of the size film in the
drying section. To achieve this, a series of lease or bust rods, with one large diameter busting rod, are used, as shown in Fig. 4.33. The lease rods are generally chromium-plated hollow cylindrical bars flattened at both ends to be placed firmly in the brackets. The number of lease rods used is determined by the number of warper’s beams being used in the creel. The yarn sheet emerging from the drying section is divided into two sections by one large lease rod, as shown in Fig. 4.33, and each section is further subdivided into two subsections by successive lease rods. The pattern of dividing by lease

Fig. 4.33  Schematics of splitting zone. (From Ref. 1.)
rods in the splitting section is usually kept similar to the pattern of combining the sheet in the unwinding section, which helps in maintaining the order of the warp sheet, thus facilitating the subsequent drawing-in operation [1]. Also, the leasing-in of the sized yarns to the weaver’s beam is facilitated by inserting leases in the top few layers of the warp. Even under normal operating conditions, the splitting zone imposes tension in the warp by offering resistance to the forward movement of the dried warp sheet. However, under stable running conditions, the tension imposed on the warp sheet is not affected significantly [21].

Head Stock

The head stock is a take-up unit supporting the weaver’s beam and necessary drive gears. The drive equipment imparts necessary beaming tension for compact and straight winding of the warp yarn on the weaver’s beam. The configuration of the head stock is available in a variety of widths and styles. The width of the head stock is determined by the width of the weaver’s beam and the number of weaver’s beams being wound side by side. Usually head stocks are available which allow winding on a single beam, two beams side by side, and two beams positioned vertically or half beams run in center [14]. Double beam head ends with vertical arrangement are primarily used for towel, gauze, and leno warps, which contain so few warps that winding on only one beam may either lead to the warp being overdried or else the full drying efficiency of the cylinder surfaces not being used [10].

A typical head stock is shown in Fig. 4.34. Irrespective of the configuration, the head stock is equipped with a positively driven roll, commonly known as the delivery roll or draw roll. The cork and rubber covered draw roll is placed between two heavy chrome-plated nip rolls, as shown in Fig. 4.35, to assure that the yarn sheet being drawn is wrapped well around the draw roll [14]. The delivery roll moves at a constant speed for any sizing machine, and the speed of the weaver’s beam is adjusted to impart the necessary winding tension. This poses a problem of driving the weaver’s beam at a constant tension from start to finish of the beam, because the surface speed of the beam keeps increasing as the diameter of the beam increases, and consequently the winding tension also increases. This requires that the driving arrangement of the weaver’s beam must incorporate a proportional reduction in the rotational speed of the weaver’s beam to assure winding at a constant surface speed. On most modern sizing machines this is automatically controlled. Depending upon the type of arrangement used, the head stock driving system may be grouped as controlled tension beam drive, DC multimotor drive, or digital drive [14].
The arrangement and the principle used vary from machine to machine and the techniques employed by various manufacturers differ considerably, although the objectives remain the same.

**Controlled Tension Beam Drive.** This system is the most accurate; is reliable, easy, and inexpensive to maintain; and is used widely. The drive is purely mechanical and utilizes a pneumatically loaded clutch to transfer the input torque to a positive infinitely variable (PIV) speed variator. In this system, the position of the pulleys in transmission is adjusted by comparing the revolutions of the clutch input shaft to the output shaft. With the increasing beam diameter the torque required to drive the beam also increases; however, the revolution of the beam should decrease to keep the surface speed constant, so the slippage across the clutch should be increased. This will lead to a reduction in the clutch output speed at the constant input speed. The automatic adjustment of speed and torque thus continues until the beam is full. While placing the new empty beam, the operator is required to reset the system to the proper ratio of barrel to full beam diameter [14]. In this type of system, normally a single DC motor drive is used for the whole sizing machine.
Multimotor Drive. This system uses two DC motors, one for driving all components of the sizing machine, except the beam, and the other exclusively for driving the beam. The motor driving the beam provides constant winding tension as the beam diameter increases. This system is very simple mechanically but very complicated electrically. This system does not require resetting before beginning the new beam [14].

Digital Drive. This system comprises an electrical analog to the mechanical line shaft drive. The components of the sizing machine such as head end, dryer section and size box, etc., are driven by an individual motor. The digital system used for regulating the speed is most accurate [14].

Controls and Instrumentation

There are a variety of controls available on modern sizing machines. The essential functions of all these controls are to provide optimal quality of warp at a minimal cost. The controls usually act on the basis of information provided by the particular sensors placed on the machine. Figure 4.36 is a sketch of a typical two-size box slasher with locations of various sensors and controls. The most important of these are summarized here [22]:

1. Automatic tension control. In the direction of the yarn path, from the creel to the weaver’s beam at the head stock, controls are placed to monitor tension and effectively regulate the speed of the sizing machine. The controls are placed in the creel to maintain uniform unwinding of the warp beams in the creel, in the size box for a smooth drive of the dry feed rolls, in the drying section to drive cylinders, and in the head stock to drive the weaver’s beam.
Fig. 4.36  Sensors and controls on a typical two-size box slasher. (From Ref. 22.)
2. Automatic size box level regulator, with a warning indicator for low size level or overflow.
3. Electronic stretch indicators and controllers with digital display for yarn elongation. Excessive yarn elongation (stretch) resulting from the applied tension is detrimental to the quality performance of the warp during weaving. The loss in elongation results in an increase in warp breaks on the loom. Surface speed sensors, mechanical or electronic, in direct contact with the warp sheet are placed from the creel to the front roll in each zone. The automatic controls adjust the size box roll speeds to maintain a constant stretch.
4. Electronic moisture detectors, used to regulate the slashing speed automatically or steam pressure in the drying cylinders.
5. Steam pressure controllers in the cylinders which may be interfaced to drive the controller to reduce the steam pressure during the slow or creep speed operation.
6. Temperature controls for the drying cylinders which can be used for maintaining accurate temperature and effective condensate removal.
7. Squeeze roll pressure release system designed to decrease the squeezing pressure when operating the machine at creep speed or maintaining proportional pressure with respect to the operating speed of the sizing machine.
8. Size liquor filtration and circulation system designed to filter out yarn waste and fibers (wild yarns and short fibers) found in the sizing system.
9. Creel braking systems to decelerate the warper’s beams effectively, thereby preventing over-run and maintaining the unwinding tension at a constant speed operation.
10. Microprocessor controls interfaced to a computer for effective management of the operating variables of the sizing machine.
11. Wet pick-up measurement and size add-on control. In this device, microwave energy which is absorbed by water is used to continuously measure the wet pick-up immediately after the yarn sheet leaves the size box. The on-line refractometer monitors the size solids in the size mix. The size add-on, which is the product of the wet pick-up and size solids in the size mixture, is automatically calculated by the microprocessor. The correction in the size add-on is made by automatically adjusting the squeeze roll pressure to keep the add-on practically constant throughout the sizing operation [22].
12. On-line size encapsulation measurement. Size encapsulation is the measure that defines the degree of reduction of the yarn hairiness due to sizing. One on-line yarn hairiness sensor is placed on the unsized and the other on the sized yarn sheet. The difference between the two, expressed as percentage, is the measure of size encapsulation [22].

Effect of Sizing Machine Parameters

The different zones of sizing machines—namely, creel, size box, drying, and head end—have to be controlled effectively for producing a good loom or size beam. Although the design and configuration of the sizing machine have some influence, the effect of different sizing parameters on the quality of size beam in general will be considered in this section. The quality of sizing will have a profound effect on the weaving efficiency and the quality of the woven fabric. Since modern shuttleless looms are running at four to ten times faster than the speed of the conventional shuttle loom, effective sizing—by exercising all the necessary controls on the sizing parameters from creel to head end—is important.

**Creel Zone.** The warping beams are the heart of the creel zone for ensuring effective unwinding of the warp. Therefore, the physical quality of the beams must be good. The edges should be smooth and free of burrs so that the warp ends do not cling to the edges during the process of unwinding. This may cause the warp yarn to break or be damaged due to abrasion. The mill should ensure that the warp beams are cleaned and polished at regular intervals. Also, the distance between the flanges of the beams should be constant and these flanges must be at right angles to the barrel. This must be measured before warping so that it does not create a problem when beams are delivered to the sizing section. The quality of warping on the beams should be good, with no cross-ends nor buried or embossed ends at the edges near the flanges. The density of the warping beam should be as uniform as possible to ensure uniform unwinding during sizing. The warping tension must be controlled and beam density (hardness) must be measured with a suitable pressure gauge (e.g., durometer). Warping beam preparation data such as slack selvedges, broken ends, laps, and cross-ends must be recorded and supplied to the sizing machine operator to enable effective control and correction of various problems.

On the sizing machine, the warping beams must be aligned properly in the creel. The distance between the front end of the creel to the back of the size box must be fixed on both sides to avoid slack or tight ends on the
selvedges. The beam journals should be adequately tight, and bearings should work freely to ensure proper tension is maintained. The effect of the braking system has been described previously in this section. The control of yarn stretch between the back of the creel and the size box is critical. It should be as low as possible but should not exceed 0.4 to 0.8%, and it should be checked frequently.

Size Box. The major features of modern size boxes were discussed previously in this section. Positive feeding of yarns from the creel to the size box is necessary for ensuring a minimal stretch in the creel zone. The purpose of the size box is to allow the immersion of the yarns in the size box for a uniform and thorough penetration of the size and coating of the surface of the yarn. The following sizing variables should be checked and controlled where necessary:

- Viscosity of the size solution
- Sizing machine speed
- Size add-on levels
- Concentration of the size mixture
- Volume of the size box (both quantity and size level)
- Threading arrangements
- Condition of squeeze rolls
- Squeezing pressure
- Hardness of squeeze rolls
- Diameter of squeeze rolls
- Number of size boxes
- Yarn count and size box warp density per unit space

Size viscosity is dependent on the concentration of the size and the application temperature in the size box. Viscosity influences the size pick-up and consequently the size add-on of the yarn being sized. The continuous heat losses in the size box are caused by the incoming warp sheet, which is at a lower temperature; convection and radiation losses from the surface of the size to the atmosphere; and conduction losses of the size box itself. Unless the heat is uniformly applied to replenish the loss, the size solution will be cooled and a resultant increase in the viscosity is unavoidable. Heating of the size in the box is usually done by injecting steam into the size mixture. The quality of steam, therefore, is important. Excessive moisture in the steam will dilute the size due to condensation, thereby reducing the effective solid content of the size mixture. This, in turn, lowers the viscosity and affects the size pick-up and size add-on of the yarn being sized.
Squeeze roll configuration, thickness and hardness of covering, surface finishes, roll diameter, speed of the sizing machine, and squeezing pressure are a few important parameters which affect the sizing quality. A wide variety of size box configurations is available to fulfill the specific needs of various constructions and styles of fabrics for a particular mill.

Roll hardness of the rubber-covered squeeze roll influences the level of size add-on of the yarn. The suitability of the squeeze roll is dependent upon the particular sizing application (style and construction of fabric, spun or filament yarns, blend of spun yarn, yarn counts, etc.) and the sizing chemical being used (e.g., starch, PVA, acrylics, auxiliaries etc.). Harder rolls enable a sharper nip and lower pressure than softer rolls, thereby squeezing more size from the yarn and resulting in a lower pick-up. A soft roll makes a flatter nip at the same squeeze pressure so resultant size pick-ups are higher. As the thickness of the rubber covering the squeeze roll decreases, the nip becomes sharper causing the size pick-up to decrease. The prolonged exposure to high heat and constant use tend to harden the rolls and can cause permanent deformation of the coverings of the squeeze roll, which affects sizing due to uneven squeezing, lapping on rolls due to broken ends, and build-up of size on rolls. Periodic buffing of the squeeze rolls should take place, and the rolls should be re-covered when necessary. An impression of the nip should be made periodically and the record should be maintained. All settings, such as temperature, pressure, switches, and monitors, should function well at all times to ensure good quality of sizing.

The size box level determines the contact time between the yarn and size mixture. If the size level in the box is low, the yarn contact time will be shorter and vice versa. With shorter contact time, the size may not penetrate into the yarn, and the coating of the yarn may not be adequate. Ultimately, a low size level in the size box influences the size add-on, size coating, film characteristics, and control of yarn hairiness, besides affecting other properties. Devices to monitor and control the size level should be installed to eliminate the adverse effect of differences in size level on sizing.

The control of the yarn stretch between size box and drying zone is also important. Yarns being wet in the size box tend to elongate depending upon the fiber and yarn characteristics. Appropriate devices should be utilized to monitor the stretch. Space between yarns in the size box is an important criterion to ensure sufficient penetration by and adequate encapsulation of the size. This cannot occur if the yarns are too close together (i.e., crowded). This crowding of yarns in the size box creates a problem, particularly with spun yarns where the protruding fibers of adjacent yarns become entangled and cemented together. Consequently, higher energy may be required during split-
ting after drying. This will also increase yarn breakage during sizing, increase yarn hairiness and clinging on the loom, increase yarn breakage during weaving, and increase size shedding on loom. Too small spacing between yarns will also result in matting and entanglement, and this is especially acute in hairy yarns having long protruding fiber ends. To reduce this problem, the spreading of yarns further apart must be done to increase spacing between them. The distribution of the yarns in the size box may be expressed as percent yarn occupation:

$$\text{percent occupation} = \frac{\text{number of ends in the sizing sett}}{\left( \frac{\text{number of threads per cm at 100\% occupation}}{\text{distance between flanges of warp beam in cm}} \right)} \times 100$$

The number of threads at 100\% occupancy can be calculated from Table 4.2. The distance between the flanges of the warping beam provides the information on the total working space in the size box since it represents the width of the warp sheet. The actual number of ends is the total number of yarns in the fabric style being sized. The normal percent occupancy is about 50\% for yarns sized for shuttle looms and about 60 to 80\% for yarns sized for air-jet weaving. Another parameter used for expressing the yarn spacing in the size box is equivalent yarn diameter (EYD). If the space between adjacent yarns in the size box is equal to 1 yarn diameter, the EYD is 1, which corresponds to a size box occupation of 50\%. Similarly, yarn spaced 2, 3, and 4 diameters apart would have EYD of 2, 3, and 4, respectively, which correspond to percent yarn occupations of 33, 25, and 20\%, respectively. Spun yarns normally require an EYD of 1.1 to 1.5.

**Drying.** About 75 to 80\% of the total energy used in sizing is for drying the warp sheet. The water in the warp sheet is evaporated by converting it into steam that can be readily removed. Out of the three methods of heat transfer, namely, conduction, convection, and radiation, the conduction method is most commonly used, where multicylinder drying is employed. The mechanism of cylinder drying is explained in Fig. 4.37. The heat of vaporization of the superheated steam transfers to the wet yarn through the walls of the drying cylinder. The amount of water to be evaporated from the wet yarn depends upon the size add-on levels and the solid content of the size. This relationship is graphically presented in Fig. 4.38. For example, a yarn sized at 12\% add-on with 8\% solid content in the size box requires 1.38 kg of water to be removed through evaporation for each kilogram of yarn being sized.
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The drying configuration employed depends upon the number of size boxes used, number of yarns in the sett, wet splitting, percent yarn spacing or EYD employed, number of drying cylinders available, size add-on level, solid content of the size mixture, etc. If only one size box is used, the yarn sheet is generally split in two and each sheet is dried on a separate set of drying cylinders and then combined again for final drying. By increasing the spacing between the yarns, the cylinders are not overloaded and the yarns actually dry faster, and this allows increase in sizing speed. If two size boxes are employed, there will be four sheets of wet warp, each dried separately before combining them for the final drying. Yarns sized using the high pressure squeezing technique require much less drying energy (fewer cylinders); additionally higher sizing speeds can be employed because they contain less water.

The rate of evaporation (drying rate) and the threading of yarns through the cylinders are critical for uniform drying. The temperature of the first drying cylinder is normally set at the lowest possible temperature so that sticking of yarns on the cylinder is avoided. Such sticking causes a rough yarn surface which tends to increase shedding of size both on the sizing machine and on the loom during weaving. Moreover, sticking of yarns to the cylinder increases
hairiness of yarns as the fibers are pulled from the yarn bundle during transfer to the next cylinder. After the first cylinder, the temperature is gradually increased to ensure thorough drying. If possible, the last drying cylinder should be set relatively cool to prevent false moisture regains and to control tension variations. Most sizing machines are fitted with Teflon-coated drying cylinders to minimize the sticking of the yarns. These coatings must be safeguarded and should be free of scratches or worn surfaces. Too high temperature of the drying cylinders should be avoided as it tends to cause the size to migrate due to sudden conversion of water into steam. The size is blown away from the yarn when in contact with very hot cylinders, causing an inadequate coverage of the yarn due to a lack of encapsulation or else excessive size on some yarns.
Fig. 4.38 Water evaporation requirements versus percent size add-on and percent size solids in size box. (Courtesy of DuPont Co.)
The yarn with an inadequate size coating will break during weaving while the yarn with excessive size will cause shed-off on loom.

**Yarn Stretch.** The most critical issue in sizing is to control the yarn stretch. As yarns pass through the long path from creel to head stock, the tension applied in the process will tend to elongate it. If this elongation is not controlled, the deformation so introduced will be permanently set in the yarn. The control of yarn elongation (stretch) between the squeezing rolls of the size box and the first drying cylinder is critical, since the wet yarns under high heat undergo stretching even at low tensions. This must be controlled by proper selection of the drive system, such as digital or variable speed differential transmission, between the size box and the drying unit.

The tension develops when the yarn is passed through the drying cylinders for ensuring proper drying. The surface speeds of all drying cylinders should be controlled, and if they are uniform, no stretch will develop in the drying zone. Despite good control, the variable speed transmission employed is susceptible to some output variation resulting from the variation in input speeds and loads. This results in a variation in tension, particularly in the wet warp sheet and during periods of acceleration and deceleration of sizing speeds. The newer sizing machines are fitted with better controls and mechanisms to control stretch more precisely.

The number of drying cylinders required to dry the yarns—based on the drying loads—can be determined from the data of wet pick-up (WPU), solid content of the size, speed of the sizing machine, number of ends in the sett, and yarn count. The following calculations represent a typical example:

\[
\text{wet pick-up} = \frac{\text{weight of sizing solution (kg)}}{\text{weight of unsized yarn (kg)}}
\]

\[
= \frac{\text{size add-on to yarn (%)} \times \text{solids in sizing solution (%)}}{100}
\]

\[
\text{drying load} = \frac{\text{sizing speed (m/min) \times total ends \times WPU \times (100 - \% solids in solution)}}{1000 \times 1000 \times 100} \times \text{yarn count (tex)}
\]

The drying load is expressed in kilograms of water evaporated per minute. For example, a sizing machine is operated at a speed of 73.2 m/min, there are 6000 ends in the sett, 8% is the solid content in the solution, 10% is the size add-on, and the yarn count is 22.7 tex. Then the calculation is
Winding, Warping, and Sizing

\[ \text{WPU} = \frac{10}{8} = 1.25 \text{ kg of solution per kg of yarn} \]

\[
\text{drying load} = \frac{73.2 \times 6000 \times 1.25 \times (100 - 8)}{1000 \times 1000 \times 100} \times 22.7
\]

\[ = 11.46 \text{ kg of water evaporated per minute} \]

Thus it will require six drying cylinders for two-shed drying.

The above example provides an idea of the minimum number of drying cylinders for predrying; spreading of warp yarns over as many drying cylinders as available will result in the best drying of the warp, with adequate encapsulation, control of hairiness, and size penetration.

**Head Stock.** The properly dried warp ends coming out from the drying zone must be handled well by separating individual ends and be wound on the weaver’s beam at uniform tension. If the ends are not separated well, the size film is damaged when the yarns pass through the lease rods. The size coating on the yarn surface is damaged and the yarns become vulnerable to breaks on the loom during weaving. If the spacing between the yarns is adequately set, there is no entanglement of the fibers of two adjacent yarns, which prevents damage to the size films. The proper splitting of yarns at the first leasing rod is an indication of proper sizing. A low splitting force indicates that the yarn hairiness will not be increased due to splitting.

The bust rods (lease rods) should be of large diameter and well polished to prevent the damage to the warp sheet. The yarn sheets should be evenly split between the lease rods such that the individual sheets represent the warping beam from which they came. This minimizes the yarn tension and size shedding in the splitting zone. The lease rods should be adjusted to ensure uniform spacing and leveled warp sheets to ensure that they do not touch each other while entering the front comb.

The density and height of the comb wires should be sufficient to ensure uniform winding of the warp on the weaver’s beam. Uneven spacing between the dents and the crossed ends should be avoided to ensure a uniform distribution of the warp sheet. A traversing V or slant comb reed is used to help in providing an even distribution of the warp yarns and for avoiding abrasion between the yarns, which causes size shedding. To avoid abrasion and size shedding the yarns should never touch the bottom of the comb. It is recommended that the spread of the warp sheet exiting the drying cylinders should be the same as the distance between the flanges of the weaver’s beam on which the warp is wound. If the distance between the flanges of the weaver’s beam is higher, then the yarns are drawn at an angle which produces undue
Chapter 4

stresses and strains, which may result in size shedding, yarn breaks, and attendant problems during weaving.

The winding of the warp on the weaver’s beam is done at a constant speed by means of a precision mechanism. The winding tension and uniformity of the ends should be controlled. The yarn should be drawn by the delivery roller and presented straight to the weaver’s beam. The press rolls on the beam should be clean and smooth to ensure correct pressure and beaming tension. If too high a pressure is used, then the beam density will be too high and yarn slackening may occur during winding; while too soft a pressure will result in a very soft weaver’s beam, which will cause problems during weaving. As the beam diameter increases, the surface speed also increases if the rotational speed is not decreased proportionately. This will exert high winding tension, which is detrimental. In modern precision winding mechanisms, the revolutions of the beam are reduced to keep the surface speed constant.

4.5 SINGLE-END SIZING SYSTEMS

Single-end sizing systems are widely used for sizing a wide variety of multifilament yarns, such as zero twist flat, textured, and low twisted fine denier yarns. Modern single-end sizing machines operate at extremely high speeds of up to 500 m/min. The sizing system is very versatile and it has simplified the yarn passage to produce high quality sizing beams. The single-end sizing systems consist of a creel and a warper, beam-to-beam sizing of the warper beams, and a beamer to assemble sized section beams into a weaver’s beam. Figure 4.39 illustrates the single-end sizing system.

![Beam to Beam System](image)

**Fig. 4.39** Single-end sizing systems. (Courtesy of Tsudakoma Corporation, Japan.)
About 800 to 1500 supply packages can be placed in the creel, and the ends delivered from these packages are wound onto a large warper’s beam on a warping machine at uniform tension. The broken ends or filaments in a supply package can be repaired or removed during this process to ensure a defect-free warper’s beam. The warper’s beam is placed on the supply stand at the back of the sizing machine. The yarns are sized by impregnating them in the sizing solution and then dried and wound onto a sectional beam on the beam-to-beam sizing machine. Figure 4.40 shows a schematic of the beam-to-beam sizing machine. The yarn is fed to the sizing section by a positively driven feed roller and the squeezing roller. A high pressure squeezing of 15 kN is used to ensure adequate squeeze and reduction in subsequent drying load. The squeezing pressure is automatically controlled in accordance with the sizing speed. The sizing machine comprises both cylinder drying and hot air chamber drying. The cylinder drying acts as a predrying step, with the number of drying cylinders varying from three to seven depending upon the yarn type and sizing speed. The hot air drying chambers enable the contactless drying of the sized yarn to ensure undisturbed size coating and smooth yarn surfaces without adversely affecting the yarn or its properties. The drying temperatures in the chambers can be adjusted to between 150 and 160°C for high-speed operations and to between 120 and 130°C for low-speed operations. Since the warper’s beam thus prepared is free of yarn defects, the sizing machine generally runs without interruptions, therefore making it feasible to operate at a high production speed and efficiency with very little downtime. The yarns are sized, dried, and wound onto a sectional warper’s beam at a distance of almost 1 mm apart, thus eliminating crowding during sizing and intermingling during subsequent unwinding. The required number of section beams are placed on the beam creel of the beamer so as to assemble a weaver’s beam. The versatility of this system allows it to be used as a nonsizing system by skipping the sizing process, making it particularly suitable for high-twisted filament yarns. Warper’s beams are prepared on a warper, and waxing or oiling, if required, is applied during the process. Such unsized section beams can then be assembled on a beamer into a weaver’s beam. Alternatively, the system can also be used as a creel to the beam sizing system, where the yarns delivered from the packages mounted in the creel can be directly sized, dried, and wound straight onto a section beam. The sized section beams are then placed on the beam creel of a beamer to wind onto a weaver’s beam. This system is suitable for high quality filament yarn packages containing a minimum number of yarn defects, and in such cases the system ensures a high level of performance and quality preparation of beams.
4.6 DRAW-WARPING AND SIZING

It is necessary that thermoplastic yarns (fibers) should be drawn to provide the necessary molecular orientation to achieve desired physical and mechanical properties. The production of drawn thermoplastic yarns and fibers can be accomplished in several ways. However, requirements of the subsequent fabric-forming process normally dictate the type of yarn production method which is best suited for a particular yarn and package performance [23]. The use of partially oriented yarn (POY) is increasing because of the relatively long shelf-life, ease of transportation and handling, and the fact that it can be produced in relatively large quantities at low cost. Fabrics made from such POY yarns will have a poor dye uptake and strength; therefore, it is necessary that they are fully drawn before the fabric formation stage. In conventional production methods the spun POY yarns are drawn and heat set on texturizing machines or produced in a flat (untwisted and untextured) filament state before subjecting to warping operation. This method is known as spinning–drawing–warping. In this method of processing POY yarns, it is necessary to handle each feeder package individually, and therefore uniform tension and temperature control for each end become critically important. Even slight differences in tension and temperature from end to end will result in different yarn properties such as tenacity and elongation [24]. Moreover, uneven drawing between two packages will cause differences in dye uptake when the fabric is formed. In order to alleviate some of the drawbacks of processing POY yarns by this conventional method and to improve the conversion process for efficiency and quality, new methods have been recently reported [25,26]. The new processes of draw-warping or draw-beaming and draw-sizing now enable producers to use POY feedstock to produce a fully drawn warping beam and sizing beam in a single step, yielding better quality preparation at higher production speeds and lower operating costs [25].

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4.6.1 Draw-Warping or Draw-Beaming

This process produces sectional or warp beams from undrawn or partially oriented filament yarn by combining drawing and warping in a single process step, thus eliminating the separate step of draw-twisting altogether. This single step process is cost effective and also produces excellent quality by rendering a very uniform dye uptake, attributed to simultaneous drawing and heat setting of the entire yarn sheet. Moreover, since the feeder packages are very large, several sets are produced under identical processing conditions.

The combined unit for simultaneous draw-warping, as shown in Fig 4.41, consists of the following [27]:

1. **Creeel.** It has a capacity to hold up to 1500 packages. It can be either a buggy type, rotary, or magazine type consisting of all package sizes and different types of yarns. It also contains oil-dampened yarn tension compensators to ensure uniform unwinding tensions on all individual ends in the yarn sheet.

2. **Drawing unit.** This unit consists of seven cantilevered godets with a hot plate for processing polyester yarns, as shown in Fig. 4.42. The unit provides the required force for uniform drawing of the sheet of yarn ends. The housing of the draw unit is designed as a rugged construction of welded heavy grade sheet metal. The seven godets are also welded and are supported on cantilevered shafts in

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**Fig. 4.41** Draw-warping line. (Courtesy of Liba Maschinenfabrik GmBH, Germany.)

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self-aligning roller bearings [24]. All godets are chromium plated to prevent abrasive damage. The drive to the unit consists of two thyristor-controlled DC motors for the godet groups 1–3 and 4–7, reducing gears, and flat belts for the two godet groups through a common electric supply. Drawing is accomplished between godets 3 and 4 by the different speeds of the two godet groups. The ratio is preset at a predetermined level and maintained with high precision by a digital controller under all operating conditions. Because of their helical inner structure, the heated/cooled godets work according to the counterflow principle and therefore have a high degree of surface temperature uniformity [24]. For processing, godets 2 and 3 are heated and godet 4 is cooled. A hot plate is used between these godets to heat set the yarn sheet. The hot plate swivels away from the yarn sheet when the line stops so as to prevent overheating of the yarn ends. Processing of nylon is generally done with unheated godets and without the hot plate in the draw zone. For processing delicate yarns, godet 3 can be equipped with shock heating/cooling for a quick temperature change. Rubber-coated nip rolls are used at the entry and exit points of the draw unit.
3. **Tangle reed.** In the tangle reed, each yarn end is individually entangled by means of compressed air to produce sufficient cohesion for subsequent processes. The integrated groups of tangle jets are located in two swivel-mounted manifolds. One group of jets accommodates numerous single jets. Each group can be removed separately. These groups of jets can be operated selectively for entangling only the required number of yarn ends.

4. **Yarn inspector.** An optoelectric yarn inspector, either in a single or dual channel design, is used for detecting broken ends. These are equipped with infinitely adjustable sensitivity.

5. **Relaxation zone or godet trio.** When processing nylon, it is important that controlled shrinkage reduction takes place at a low yarn tension. To achieve this, a hot plate with high heat flow density similar to that in the draw unit is used. Controlled shrinkage is achieved through differences in speed between the draw unit and the godet trio. The underfeed of the trio in relation to the draw unit is adjusted according to the process requirements. The center godet of the trio can be cooled by water in order to reduce the heat absorbed by the yarn sheet from the hot plate.

6. **Oiling device.** It contains an oiling roll, with its speed infinitely adjustable for a wide range of applications. The application of oil improves the running properties of the yarn in subsequent processes, such as warp knitting, sizing, and weaving. When the warper is stopped, a special mechanism to lift the yarn sheet away from the oiling roll can also be equipped to prevent excessive application of oil.

7. **Warper.** The warper, similar to the warper for spun and filament yarns, can handle the section beams having flange diameters that are commercially used. Optionally, it can also handle dual beams simultaneously. The warper is driven by a DC motor electronically connected with the entire line. The expansion reed is equipped with a motor drive to laterally position the yarn sheet and adjust the yarn sheet width, as well as with interchangeable chromium needle reeds. All monitoring devices and switches for the entire line for setting, operating, and controlling the electric and hydraulic components are located in one operating panel at the warper and are easily accessible and convenient to handle. Temperatures, speeds, and speed ratios are preset and monitored. The monitoring devices indicate the working order of the entire line as well as any malfunctioning in individual components. The hydraulic system in the warper head stock...
facilitates mounting and doffing of the beams, engaging the drive coupling, and operating the press roll to enable quick beam doffing [27].

4.6.2 Draw-Sizing

The process of draw-sizing combines the steps of drawing, warping, and sizing in a single step. The sectional beams with individually sized yarn ends can be produced from partially oriented yarns. The sized section beams are in turn combined into weaving beams on an assembling machine. The processes are very cost effective and produce an outstanding product quality [26]. The draw-sizing line consists of a combination of a draw-warping unit with the single-end sizing machine and a creel and a separate beam assembler. With this combination, filament yarns can be quickly and efficiently draw-sized at speeds up to 500 m/min. [25]. In a single-end sizing machine, up to 1100 ends can be sized and wound on a section beam and then subsequently assembled to make a weaver’s beam on an assembling line, as shown in Fig. 4.43. The essential components of creel and draw units of a draw-sizing line are similar to those described for a draw-warping line. After wet intermingling in the drawing zone, the oil-free wet warp sheet enters the sizing bath under optimal tension for size pick-up. Size enters between the intermingling nodes and thus cements all monofilaments together. A conditioning reed leads the wet sized warp sheet to the drying zone, consisting of a series of steam heated cylinders (rolls) or containing radiofrequency dryers which conserve energy. The moisture content of the yarns is reduced from close to 60% down to 10% at exit from the dryers. An enclosed steam-heated Teflon-coated hot roll dryer performs the final drying to 1% moisture content, relaxation and heat setting, bringing the boiling water shrinkage down to a 1% level. Finally, the warp sheet is wound onto beams of 200-cm maximum width and 100-cm flange diameter. Sizing can either be incorporated in the warp-drawing process as in the warping–drawing–sizing line, or warp-drawing can be performed on a warping-drawing machine at a relatively high speed, followed by off-line beam-to-beam sizing. The off-line process produces inferior quality preparation because the crowding of warp threads in a relatively narrow pitch results in more filament damage, more yarn breaks, and less uniform size pick-up [25]. Also, the integrated on-line process requires one less step and therefore reduced material handling, resulting in better process economics. The advantages of WDS systems are

1. Improved dye uptake and levelness because of the drawing of the entire warp sheet under isothermal conditions.
Fig. 4.43  Schematics of warping–drawing–sizing line. (Courtesy of Barmag-Tsudakoma, Japan.)
2. The rates of breakage due to drawing can be significantly reduced, thus minimizing slubs due to piecing.
3. The system produces very level and uniform beams, and consumption of sizing agents is also reduced.
4. This system produces very uniform warp shrinkage. If required, the shrinkage can also be minimized.

4.7 SIZING OF DIFFERENT YARNS

Sizing of different types of yarns, such as spun and filament yarns, requires different approaches besides different chemicals. The task is further complicated due to the fact that the speed and weft insertion technique of the weaving machine, environmental laws, construction and weave of the fabrics, type of fiber, yarn structure in case of spun yarn and textured or flat filament in the case of continuous filament are a few factors that influence the sizing parameters. Table 4.3 summarizes the factors which influence the sizing parameters.

The difference in the mechanism involved in spun and filament sizing is shown in Fig. 4.44. For spun yarns, the size must bind the protruding and surface fibers to the yarn matrix by laying them down and encapsulating them with a protective coating of appropriate sizing chemicals. Because the filament yarns are regular and smooth and do not have protruding fibers, they need to be spot-bonded by the size to prevent the fraying of individual filaments. In general, multifilament continuous filament yarns are stronger, and an improvement of strength due to sizing is not required.

4.7.1 Sizing of Ring and Open-End Spun Yarn

The yarn structure produced by two different yarn systems, namely, ring and open-end, are quite different [28–30], as discussed in Chapter 2. The open-end yarns are

| Table 4.3  Factors Influencing Sizing Parameters |
|-----------------|-------------------------------------------------|
| Type of yarn, spun or filament |
| Spun yarn parameters such as twist, count, and fiber blend |
| Spinning system, i.e., ring, rotor, air-jet, compact, etc. |
| Type of weaving machine, i.e. shuttle, projectile, rapier, air-jet, water-jet, multiphase, etc. |
| Type of fiber, natural or manmade |
| Fiber blend |
| Construction and weave of fabric |
| Environmental laws |
About 20 to 30% lower in hairiness
Relatively porous and have an open surface structure
About 10 to 20% weaker in tensile strength and less elastic at similar twist levels
About 20% bulkier (larger diameters)
Lower in abrasion resistance

These differences in properties of open-end spun yarns require them to be sized in different ways as well. In general, higher size add-on will be required for open-end spun yarns to compensate for their inherently lower tensile strength. Because of the bulkier and porous nature of open-end spun yarns,
the viscosity of the size formulations should be higher to control excessive penetration of size, thereby preventing the yarns becoming too stiff. Generally, open-end yarns will require more precise tension control at the unwinding zone and at the size boxes. The application of the size for open-end yarn should be at a lower temperature than that normally used for ring-spun yarns, which have a more compact structure. As size formulations with higher viscosity and lower application temperature are used, open-end spun yarns will have a thicker coating of size on their surface. This normally poses a problem in splitting of fibers after drying. Therefore, wet splitting and wet separation of the sheet are recommended by using large diameter splitting rods. Because the size add-on required for open-end yarns is generally higher, sometimes a “false” drying phenomenon occurs. The surface of the yarn appears dry while the core remains wet. Therefore, the moisture content of the dried yarns leaving the slasher should be set at least one percentage point below that used for the equivalent ring-spun yarns. The temperatures of the drying cylinders, sizing machine speeds, and calibration of moisture indicators must be controlled carefully to prevent the problem of under- or overdrying of open-end yarns.

Fig. 4.45  Mechanism of filament peeling that results in loom stop. (From Ref. 31.)
4.7.2 Sizing of Filament Yarns

Multifilament yarns are continuous with no hairiness but contain occasionally some broken filaments which may cause problems during weaving [31,32]. Such filaments may have broken during spinning and winding or during the preparatory weaving processes of the mills. The broken filaments can create problems during weaving by entangling in loom parts, causing them to “peel back” until a ball is formed, which ultimately results in a break in the yarn and resultant loom stoppages, as shown in Fig. 4.45. Therefore, point bonding of filaments with size as shown in Fig. 4.46, is an important objective, which requires size with high adhesion and good film strength [31,32]. The requirement of a protective coating on filaments is far lower because of spin finishes that the spinner applies during production. These spin finishes and lubricants applied during sizing result in improved abrasion resistance. The size add-on required for filament sizing typically varies from 4 to 6% as opposed to 10 to 15% in the case of spun yarns. The concentration of the size and add-on depend upon the following factors:

- Yarn denier—lower deniers (finer yarns) have higher surface areas and therefore require more size.
- Construction of fabrics—the higher the number of warps per unit space, the higher the size requirement.
- Type of weave—plain weave fabrics are more difficult to weave due to a greater number of interlacements compared to weaves with long floats such as satin.
- The loom type, for example, shuttle or shuttleless, and weaving conditions influence the type and amount of size to be applied. The use of a water-jet loom also influences the characteristics of the size selected. The size should be water soluble during application but should be water insoluble when dried, so that when the pick is inserted by the water jet the size is not removed.

Fig. 4.46 Concept of point bonding for the filament sizing. (From Ref. 31.)
Type of sizing machine—conventional, predryer type or single-end sizing; each has different application procedures and constraints.

The size considerations for filament yarns, in terms of fiber type and loom type, are shown in Table 4.4 [31]. The suitability of ingredients for filament sizing and the application procedures are discussed and reviewed in the literature [31–35]. Size requirements for filament yarns are summarized by Hall [31] as follows:

- The size solution must wet-out and penetrate the filament bundle. This may not be an inherent attribute of the basic size since it can be achieved through the use of compatible binders and additives, such as emulsifiers and wetting agents.
- The viscosity of the size solution must be low enough to allow for good penetration into the filament bundle.
- The size must have good adhesion to the particular filament type being sized, as shown in Table 4.4.
- The sizing agent must have quick drying without a delayed set or producing a tacky surface.

<table>
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<th>Size</th>
<th>Fiber</th>
<th>Type of loom</th>
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<td></td>
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<td>Shuttle</td>
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<tr>
<td>Dispersable polyester</td>
<td>Polyester</td>
<td>Suitable</td>
</tr>
<tr>
<td>Polyacrylates (esters)</td>
<td>Sodium</td>
<td>Suitable</td>
</tr>
<tr>
<td></td>
<td>Ammonium</td>
<td>Suitable</td>
</tr>
<tr>
<td>Polyacrylic acid</td>
<td>Polyacrylates (esters)</td>
<td>Suitable</td>
</tr>
<tr>
<td>Polyvinyl alcohol</td>
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<td>Suitable</td>
</tr>
<tr>
<td></td>
<td>Ammonium</td>
<td>Suitable</td>
</tr>
<tr>
<td></td>
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<td>Suitable</td>
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<td>Suitable</td>
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<tr>
<td></td>
<td>nylon*, acetate, polyester</td>
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</tr>
<tr>
<td></td>
<td>Ammonium</td>
<td>Suitable</td>
</tr>
<tr>
<td></td>
<td>Polyvinyl acetate</td>
<td>Sodium</td>
</tr>
</tbody>
</table>

* Fabrics requiring a neutral pH.

Source: Ref. 31.
The size should produce an elastic and flexible film which matches the elasticity and flexibility that the yarns have to withstand during weaving.
The size should be antistatic or should not contribute toward static build-up.
The size shedding on the loom should be minimized so that deposition of size on heddles, reeds, and other loom parts are avoided or minimized.
The size film properties should be insensitive to changes in humidity conditions. Ideally, the size should be brittle when bone dry on the sizing machine so as to achieve separation of individual yarns at the splitting rods, but when the moisture is equilibrated in the weaving room at high humidity the size should be tough and flexible.
The size should be easily removable during desizing.
The size should not be detrimental to the yarn, processing equipment, or human health.
The size should be easy to prepare without the need of special equipment or costly controls.
The size properties should not be affected by the type of producer spin finish used.

4.8 PREWETTING OF SPUN YARNS

The concept of prewetting spun yarns with hot water before impregnating them with size solution is not new, but it has received considerable attention in recent years [36,37]. Prewetting, in essence, is a washing process which improves the specific adhesive force of the size on the surface of warp yarns. The effect of prewetting was tested on 100% cotton, polyester/cotton blended and 100% polyester ring, and rotor-spun yarns [38]. The principle of prewetting spun yarns before sizing is shown schematically in Fig. 4.47. Depending upon the application range and operation, two basic technologies are used commercially, namely,

Prewetting in a separate compartment with two immersions and two squeezes
Combined prewetting and sizing

In a conventional two–size box sizing machine, the first size box may be used for prewetting yarns with hot water. A temperature as high as ~90°C is used to ensure adequate washing out of pectin in the case of cotton yarns. The unsized yarn coming from the warp beams is passed through the first size box containing hot water. Generally, a double immersion, double squeezing system containing two sets of immersion rolls and a pair of squeeze rolls is used, as shown schemati-
Fig. 4.47  Schematic showing prewetting concept in a conventional two box sizing machine. (From Ref. 38.)

cally in Fig. 4.47. Industrial practice has proved that such a system yields the best results [36]. This intensive wetting and washing enables the hot water to penetrate the warp yarns adequately, and the resulting washing action is optimized. The hot water partially dissolves the waxes, dust, and other material loosely held by the fibers. The first squeezing action holds back the dirt and also expels the air from the yarns so that more water is absorbed during the second immersion. The longer dwell time in the wetting compartment permits the increase in sizing speeds even for coarser yarns. Generally, high pressure squeezing of up to 10,000 daN is required to ensure adequate prewetting and to avoid dilution of the size in the size box [36–38]. The wet warp sheet emerging from the prewetting box is fed to a second size box containing the sizing solution. The process after prewetting remains as normally followed in conventional sizing. In the other commercially available system the prewetting and sizing compartments are combined in a single unit; nevertheless the principle employed remains the same.

The improvement in surface adhesion of the size to the yarn takes place because the outer surface of the yarns is wetted with size, whereas the yarn core, already wet with water due to prewetting, prevents the excessive penetration of the size. Such improved surface coating and lesser penetration due to prewetting allows the size add-on to be reduced by up to 30 to 50% depending upon the sett of the fabric and the type of loom on which it is woven. Figures 4.48 and 4.49 show the cross sections of 20 tex cotton ring-spun yarn conventionally sized and prewetted for wet-on-wet sizing, respectively. Better adhesion of the size to the yarn surfaces increases the warp yarn tensile strength by 15 to 20% and also reduces the hairiness of the yarns, which in turn improves weaveability due to lower end breaks on the loom resulting from reduced
clinging tendency during weaving. The reduction in size add-on results in direct cost savings due to reduced consumption of sizing ingredients and also the resultant decrease in effluent loads. It is well known that sizing is responsible for 50 to 70% of total effluent pollution [37]. The estimated savings due to reduced size consumption per machine, with a typical production of about 2500 tons/year, is in the range of US$5000 to US$150,000 depending upon the sett of fabric, sizing chemicals, and yarn characteristics.
REFERENCES


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38. Wunderlich, W.; Stegmaier, T.; Trauter, J. Fundamentals of pre-wetting staple fiber yarns; Melliand Int, March 2002; Vol. 8, 43–45.
PERFORMANCE OF Sized YARNS

5.1 INTRODUCTION

The ideal and most reliable evaluation of sized yarn performance can be made during the actual weaving operation. The process of evaluating sized yarns, sizing ingredients, and various size formulations by an actual weaving trial, albeit not impossible, is time consuming, risky, and prohibitively expensive. In research, where a quick and reliable estimation is required, some other means of assessment and criteria ultimately linked to weaveability will have to be developed. The criteria used should yield maximal and reliable information, yet should be sufficiently quick to assess [1]. To assess the efficiency of a variety of size formulations and the effect of slashing variables under a wide range of weaving conditions, it is imperative that a laboratory evaluation system is established [2–7]. This chapter discusses the importance of the laboratory evaluation of sized yarns and its correlation to weaveability.

The factors that affect the weaveability of warp yarns are diverse and numerous. Table 5.1 shows the dependence of weaveability on sized warps [8]. The consideration of the sizing process, in terms of processing the warp on the loom at maximal efficiency, is a “macro aspect.” On the other hand, the consideration and control of thousands of warp yarns on the beam precisely during the process of weaving involves a “micro aspect” of sizing [8]. Even one yarn going out of its place or one broken end causes stoppage of the weaving process, and the mending of such a broken warp end results in imperfection in the cloth. The micro aspect of the sizing process requires an under-
standing of the stresses and the abrasive action that the warp yarns have to withstand during weaving, the nature of imperfections, such as thick and thin places in an unsized yarn, and the characteristics of sizing ingredients and the size add-on level that protects the weak places in a yarn.

5.2 CRITERIA OF ASSESSMENT

Various criteria have been used in characterizing warp yarn performance, which include the objective assessment of yarn properties before and after slashing. The criteria used may be broadly categorized in the following groups:

1. Tensile strength and elongation
2. Cohesiveness and adhesion of size film
3. Abrasion resistance of sized yarns
4. Fatigue and abrasion of sized yarns (under cyclic loading in tension, bending, and shear)

5.2.1 Tensile Strength and Elongation

Earlier attempts to assess weaveability were directed toward the assessment of the tensile strength and elongation at break of yarns before and after sizing. The increase in tensile strength was taken as a criterion to correlate with weaveability [9–11]. As expected, this approach has not shown consistent correlation with actual weaving performance since the actual tension experienced by a yarn during weaving rarely exceeds 20% of the breaking strength of a yarn [8,10,11]. Even unsized yarns in many instances have at least this minimum requirement of strength and elongation at break. Another approach used to assess the performance of sizing materials has been to apply sizing ingredients, such as starches, to desized cloth and then test the strength, elongation, stiffness, smoothness, and crushability of the resulting fabrics [12–14].

5.2.2 Cohesiveness and Adhesion of Sized Films

In this criterion the physical and mechanical properties of size films have been studied [15–18]. To determine the cohesiveness of the size film, a thin film of size is cast and evaluated for strength, elongation at break, stiffness, and tackiness properties. The results are usually normalized by using the weight or thickness of the specimen to facilitate comparison between size films made from different ingredients and size formulations. Faasen and van Harten [10] prepared size films by pouring sizing solutions on a flat methacrylate plate.
Table 5.1 Dependence of Weaveability on Sized Warp

<table>
<thead>
<tr>
<th>Frequency of warp breaks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition of sized warp</td>
</tr>
<tr>
<td>Condition of unsized warp</td>
</tr>
<tr>
<td>Construction of fabric</td>
</tr>
<tr>
<td>Quality of warp yarn</td>
</tr>
</tbody>
</table>

Influence of weaving:

- Climate of weaving room
- Loom type
- Condition of loom
- Settings on loom
- Speed of loom
- Warp tension

Fabric construction:

- Quality of personnel
Effect of sizing

- Suitability, quality of size and additives
- Type, amount, uniformity of size application
- Degree of heat, mechanical demands during sizing
- Slashing warp defects: such as stuck ends, missing or crossed ends

- Pressure, condition of squeeze rollers
- Speed of sizing machine
- Size condition: such as viscosity, temperature, concentration, degree of starch degradation, etc.

Source: Ref. 8.
The methacrylate plate used was found to be the most suitable as the films could be easily peeled off. The films were carefully dried in an oven at approximately 40°C. The 10-mm-wide film strips were then conditioned at 20°C and at various relative humidities for several days. The tensile testing of the size films at a gauge length of 100 mm was carried out on an electronic dynamometer operating on the principle of constant rate of extension. Table 5.2 shows the results of the experiments on various size films performed at different relative humidities [10]. In general, on increasing the relative humidity from 45 to 65%, the strength of the starch products increased, whereas those of sodium alginate and sodium carboxymethyl cellulose (SCMC) decreased. However, increasing the relative humidity from 65 to 85% reduced the strength of all size films. The extension of films made from sodium alginate and starch ether increases significantly with an increase in relative humidity from 65 to 85%, as shown in Table 5.2. Films of SCMC (B) and starch ether become sticky at a relative humidity of 85% and show a tendency to flow. Such products are, therefore, unsuitable for use in a weaving room where relative humidities are generally in the vicinity of 85%. Potato starch, oxidized potato starch, and a mixture of potato starch and sodium alginate are reasonably stable toward changes in relative humidity. However, it is hard to visualize that the studies on size films alone will yield adequate correlation with weavability since the measurements are made exclusively on size without the “reinforcing” action of the yarns or fibers [19].

Compatibility of the size with the textile materials, in other words the “adhesive power” of the size to substrate, has been evaluated by sizing a roving and then determining its tensile strength [19–21]. The adhesive power is then defined as a ratio of the tensile strength at a gauge length \( l \) to the tensile strength at zero gauge length:

\[
\text{adhesive power} = \frac{\text{tensile strength of sized roving at gauge length,} \ l}{\text{tensile strength of sized roving at zero gauge length}}
\]

A typical relationship between adhesive power versus size add-on is shown in Fig. 5.1; a “good” sized roving can be distinguished from the roving that is “badly” sized. The adhesive power of the well-sized roving increases linearly with an increase in add-on of up to about 5%, beyond which the slashed roving yields. Such studies provide useful guidelines regarding the relative adhesive characteristics of different size ingredients with different types of fibers. Figure 5.2 shows a typical stress–strain diagram of a sized roving at a gauge length \( l \). King et al. [19] have used the criterion of roving strength in establishing the differences between sizing formulations, as shown in Figs.
Table 5.2  Mechanical Properties of Size Films

<table>
<thead>
<tr>
<th>Sizing ingredient</th>
<th>45% RH</th>
<th></th>
<th>65% RH</th>
<th></th>
<th>85% RH</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength (kg/mm²)</td>
<td>Breaking extension (%)</td>
<td>Strength (kg/mm²)</td>
<td>Breaking extension (%)</td>
<td>Strength (kg/mm²)</td>
<td>Breaking extension (%)</td>
</tr>
<tr>
<td>Potato starch</td>
<td>2.4</td>
<td>3.3</td>
<td>3.5</td>
<td>2.0</td>
<td>2.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Oxidized potato starch</td>
<td>3.2</td>
<td>4.2</td>
<td>4.1</td>
<td>2.0</td>
<td>3.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Starch ether</td>
<td>1.2</td>
<td>3.8</td>
<td>2.1</td>
<td>1.8</td>
<td>0.4</td>
<td>29.9</td>
</tr>
<tr>
<td>Sodium alginate</td>
<td>2.7</td>
<td>7.7</td>
<td>2.3</td>
<td>5.9</td>
<td>2.5</td>
<td>16.5</td>
</tr>
<tr>
<td>Potato starch + sodium alginate (3:1)</td>
<td>3.6</td>
<td>5.9</td>
<td>3.3</td>
<td>3.7</td>
<td>2.8</td>
<td>3.6</td>
</tr>
<tr>
<td>SCMC (A)</td>
<td>9.8</td>
<td>11.5</td>
<td>6.0</td>
<td>15.0</td>
<td>3.7</td>
<td>17.2</td>
</tr>
<tr>
<td>SCMC (B)</td>
<td>3.9</td>
<td>31.5</td>
<td>3.3</td>
<td>32.0</td>
<td>1.6</td>
<td>86.0</td>
</tr>
</tbody>
</table>

*Note:* SCMC: sodium carboxymethyl cellulose.

*Source:* Ref. 10.
Fig. 5.1 Adhesive power of size versus size add-on. (From Ref. 21.)

5.3 to 5.8. They used six different hanks of roving. The broken lines in all these figures indicate the respective property of the unsized roving. The solid lines indicate the strength of the respective rovings at various size formulations. For example, in Fig. 5.3, the application of a 2% solution of starch (Clinco 15) resulted in an increase in strength of the roving from 90 gf to 570 gf (curve E); the addition of a similar quantity of Methocel (100 cps) gave a strength of 1440 gf (Fig. 5.4, curve Q). On the other hand, the differences in ultimate elongations of the rovings treated with the above sizing agents are small, as shown in Figs. 5.5 and 5.6. Similarly, the bending lengths are about the same, as shown in Figs. 5.7 and 5.8. Figure 5.9 shows the relationship between tensile strength and size content for a 1000 tex (0.6 Ne) cotton roving [10]. The strength of the unsized roving was 0.2 kg (1.96 N) at a gauge length of 100 mm. These rovings were impregnated in sizing solutions at approximately 90°C, squeezed, and dried at room temperature. Before testing, the samples were conditioned at 20°C and 65% relative humidity. From Fig. 5.9 it appears that, for all sizing agents, a maximum strength of approximately 9 kgf (88.3 N) is attained, which is equivalent to the fiber-bundle strength of the unsized roving [10]. Sodium carboxymethyl cellulose, having good adhesive power, attains this maximum strength at about 3% add-on, whereas those with inferior
adhesive power, for example, potato starch, require a higher size add-on (~ 7%).

The relative differences in the reinforcing abilities of different sizes obtained by such a roving technique, though useful for preliminary screening of different sizing ingredients and size mixtures, are not expected to correlate well with weaveability for obvious reasons. The linear density, fiber arrangement and structure, size add-on, and other sizing parameters in such relatively low twisted rovings are different to those found in actual staple warp yarns subjected to weaving. Besides, the idea of measuring the mere tensile strength of rovings and yarns does not provide effective criteria of estimating weaveability, since no gross differences may be observed between the strength, elongation, or flexibility (of rovings and yarns) before and after treatment with different sizes. Moreover, different weaving efficiencies may be realized with yarns sized with different size mixtures, indicating that the average strength, elongation, and flexibility of most yarns are relatively less important [19].

Fig. 5.2 Stress–strain curve of sized rovings at I gauge length. (From Ref. 21.)
Fig. 5.3  Breaking strength of sized rovings. (A) 2% Clinco 15 + Elvanol 72–51; (B) 2% Clinco 15 + Nopc 1111; (C) 2% Clinco 15 + Onyxsan HSB or 2% Clinco 15 + Onyxsan S50; (D) 2% Stymer S + Nopc 1111; (E) Clinco 15; (F) 25% Stymer S + 75% Elvanol 72–51; (G) Elvanol 72–51; (H) 50% Stymer S + 50% Elvanol 72–51; (I) 75% Stymer S + 25% Elvanol 72–51; (J) Stymer S; (K) Merlon SP; (L) Merlon BR; (M) 0.5% Nopc 1111 + Stymer S. (From Ref. 19.)
Fig. 5.4  Breaking strength of sized rovings. (N) 2% Cellulose WP-10 + glycerine; (O) 2% gelatin + Nopco 111; (P) 2% Cellulose WP-10 + Carbowax PF-45; (Q) Methocel, 100 cps; (R) gelatin; (S) 25% Sorbitol + Cellulose WP-10; (T) Cellulose WP-10; (U) Methocel, 15 cps; (V) 100% Sorbitol + Cellulose WP-10; (W) 2% Cellulose WP-10 + sorbitol; (X) Carbowax PF-45. (From Ref. 19.)

5.2.3 Abrasion Resistance

The discussion so far has pertained to the strength and elongation of sized yarns, and no account has been taken of the abrasion resistance of sized yarns. It is known that during weaving the yarns experience the abrasive action of the moving loom parts such as heddle eyes, reeds, whip rolls, and picking elements. Several different criteria of assessing abrasion resistance of sized yarns...
Fig. 5.5  Ultimate elongation of sized rovings. (A) 2% Clinco 15 + Elvanol 72–51; (B) 2% Clinco 15 + Nopc 1111; (C) 2% Clinco 15 + Onyxan HSB or 2% Clinco 15 + Onyxan S50; (D) 2% Stymer S + Nopc 1111; (E) Clinco 15; (F) 25% Stymer S + 75% Elvanol 72–51; (G) Elvanol 72–51; (H) 50% Stymer S + 50% Elvanol 72–51; (I) 75% Stymer S + 25% Elvanol 72–51; (J) Stymer S; (K) Merlon SP; (L) Merlon BR; (M) 0.5% Nopc 1111 + Stymer S. (From Ref. 19.)

and unsized yarns have been adopted by a number of research workers [9,22–25]. The comparative improvement in abrasion resistance and strength of the sized yarns due to slashing have been used to correlate with the weaveability [9,22–25]. Owen and Oxley [22] and Owen [23] subjected unsized yarns and yarns sized with various formulations to torsional oscillating stresses on a specially constructed oscillating stress tester [23]. The yarns were sub-
Fig. 5.6  Ultimate elongation of sized rovings. (N) 2% Cellulosize WP-10 + Glycerine; (O) 2% Gelatin + Nopco 111; (P) 2% Cellulosize WP-10 + Carbowax PF-45; (Q) Methocel, 100 cps; (R) Gelatin; (S) 25% Sorbitol + Cellulosize WP-10; (T) Cellulosize WP-10; (U) Methocel, 15 cps; (V) 100% Sorbitol + Cellulosize WP-10; (W) 2% Cellulosize WP-10 + sorbitol; (X) Carbowax PF-45. (From Ref. 19.)

jected to a fixed number of oscillations, and the results were then expressed in terms of percentage of survivors as shown in Fig. 5.10. The sized yarns clearly performed better than the unsized yarns at all stress levels. Owen [23] used this technique to investigate the effect of sizing from the point of view of resistance to repeated tension variations, similar to those which occur in warp yarns during weaving. Owen and Locke [26] modified the earlier oscillating stress tester [22,23] by incorporating the abrasion element consisting of
Fig. 5.7  Bending behavior of sized rovings. (A) 2% Clinco 15 + Elvanol 72–51; (B) 2% Clinco 15 + Nopco 1111; (C) 2% Clinco 15 + Onyxsan HSB or 2% Clinco 15 + Onyxsan S50; (D) 2% Stymer S + Nopco 1111; (E) Clinco 15; (F) 25% Stymer S + 75% Elvanol 72–51; (G) Elvanol 72–51; (H) 50% Stymer S + 50% Elvanol 72–51; (I) 75% Stymer S + 25% Elvanol 72–51; (J) Stymer S; (K) Merlon SP; (L) Merlon BR; (M) 0.5% Nopco 1111 + Stymer S. (From Ref. 19.)
Fig. 5.8 Bending behavior of sized rovings. (N) 2% Cellulosize WP-10 + Glycerine; (O) 2% Gelatin + Nopco 111; (P) 2% Cellulosize WP-10 + Carbowax PF-45; (Q) Methocel, 100 cps; (R) Gelatin; (S) 25% Sorbitol + Cellulosize WP-10; (T) Cellulosize WP-10; (U) Methocel, 15 cps; (V) 100% Sorbitol + Cellulosize WP-10; (W) 2% Cellulosize WP-10 + sorbitol; (X) Carbowax PF-45. (From Ref. 19.)

three rows of case-hardened steel pegs, as shown in Fig. 5.11. Yarns hanging from the jaws just touch the pegs in the top and bottom rows, and the middle pegs can be traversed sideways to deflect the yarns around by a desired amount. In a test, the yarn hanging from the jaws passes to one side of the corresponding top and bottom pegs and around the opposite side of the displaced middle
Fig. 5.9  Relation between tensile strength and size add-on of a 0.6 Ne (1000 tex) sized cotton roving. (From Ref. 10.)

Fig. 5.10  Effect of Torsional Oscillating Stress on Yarns. (A) Unsized; (B) sized with maize starch. Load: 129.6 gf; Speed: 120 rpm. (From Ref. 23.)
Oscillating stresses abrasion tester. (From Ref. 26.)

The shaft was rotated by a belt driven from a small electromotor to provide abrasion to yarns at the point of contact. Using these modified equipment, Owen and Locke [26] subjected yarns to a fixed number of abrasion cycles and measured the breaking strength of such abraded yarns. The results, as shown in Table 5.3, were expressed in terms of percent deterioration in the breaking load, calculated as follows:

\[
\text{deterioration}(\%) = \frac{\text{mean strength of yarn after abrasion} - \text{mean strength of yarn before abrasion}}{\text{mean strength of yarn before abrasion}} \times 100
\]

They also estimated the resistance of yarns to abrasion in terms of the number of rubs required to break all the specimens in a sample. Typical results of the experimental evaluations are shown in Fig. 5.12 for two experiments, D1 and D3, performed at different times but under identical conditions. Because of the arbitrary nature of this test, Owen and Locke [26] concluded that the possibility of predicting yarn performance during weaving was not feasible; however, a comparison of good and bad warp yarns, and of differently sized yarns, could be meaningfully undertaken. Besides the oscillating stresses, the laboratory apparatus did not simulate any other major forces that the yarns experience during weaving.
Table 5.3 Effect of Abrasion Resistance on Breaking Tenacity of Yarn as Measured on Oscillating Stress Machine

<table>
<thead>
<tr>
<th>Test</th>
<th>Number of rubs</th>
<th>Treatment</th>
<th>Number of breaks in abrasion experiment</th>
<th>Mean breaking load (MBL)</th>
<th>Probable error of MBL</th>
<th>Deterioration (%)</th>
<th>Probable error of % deterioration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>Unrubbed</td>
<td>—</td>
<td>9.630</td>
<td>0.0918</td>
<td>6.81</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rubbed</td>
<td>2</td>
<td>8.974</td>
<td>0.0913</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>Unrubbed</td>
<td>—</td>
<td>9.556</td>
<td>0.0884</td>
<td>5.03</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rubbed</td>
<td>0</td>
<td>9.075</td>
<td>0.0827</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>Unrubbed</td>
<td>—</td>
<td>9.503</td>
<td>0.0892</td>
<td>8.09</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rubbed</td>
<td>4</td>
<td>8.734</td>
<td>0.0838</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1a</td>
<td>1000</td>
<td>Unrubbed</td>
<td>—</td>
<td>9.533</td>
<td>0.0830</td>
<td>8.04</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rubbed</td>
<td>0</td>
<td>8.767</td>
<td>0.0900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3000</td>
<td>Unrubbed</td>
<td>—</td>
<td>10.013</td>
<td>0.0927</td>
<td>6.61</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rubbed</td>
<td>4</td>
<td>9.351</td>
<td>0.0929</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>Unrubbed</td>
<td>—</td>
<td>9.720</td>
<td>0.0922</td>
<td>2.53</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rubbed</td>
<td>0</td>
<td>9.474</td>
<td>0.0887</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1500</td>
<td>Unrubbed</td>
<td>—</td>
<td>9.883</td>
<td>0.0933</td>
<td>5.76</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rubbed</td>
<td>2</td>
<td>9.314</td>
<td>0.0960</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6a</td>
<td>1500</td>
<td>Unrubbed</td>
<td>—</td>
<td>8.873</td>
<td>0.1028</td>
<td>8.64</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rubbed</td>
<td>3</td>
<td>8.106</td>
<td>0.0810</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>2000</td>
<td>Unrubbed</td>
<td>—</td>
<td>9.107</td>
<td>0.0947</td>
<td>6.09</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rubbed</td>
<td>2</td>
<td>8.552</td>
<td>0.0825</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: Speed: 120 rpm. Yarns: 5 Ne (118 tex). Number of specimens in each test: 140. Length of specimen: 225 mm (9 in.). Load: 44.7 g.

*Source: Ref. 26.*

Loom-Action Abrader

In order to find a substitute for full-scale weaving trial—still the most effective method of determining warp yarn performance—earlier researchers have analyzed all the major forces that a yarn undergoes during weaving [27]. Ramirez and Vidosic [27] evaluated the tension variations on a single end for one complete cycle of weaving and also assessed the frictional effects of various loom parts causing longitudinal and lateral abrasion. On the basis of such an experiment, these authors built a laboratory prototype of a loom-action abrader, as shown in Fig. 5.13. Four positions of the harnesses, shown in the figure, were designed to simulate the loom stresses and abrasion that warp yarns
experience on a loom. The forward and backward movement of the reed imposed lateral abrasion on the yarns being tested. The number of cycles required to break the yarns was used as a criterion to characterize the performance of the sized yarns, as shown in Table 5.4. The 22s Ne (26.84 tex) yarns sized with light, medium, and heavy sizing compounds showed statistically significant differences in their mean number of cycles to break as measured on the loom-action type abrader [27]. A similar approach to the loom-action type abrader [27] was taken by Mehta and Shah [28], who fabricated a dummy loom identical in principle to that used by Ramirez and Vidosic [27]. Instead of a single yarn as tested by Ramirez and Vidosic, Mehta and Shah used a sheet of 250
Fig. 5.13  Laboratory abrader with harnesses in four positions. Pins 1 to 4 are fixed; W indicates equal hanging weights. (From Ref. 27.)

to 300 stationary ends of sized warp. The yarns were threaded through a set of heddles and a reed similar to that used on a standard loom. The number of breaks obtained from large-scale weaving trials for the same six samples were compared to those obtained on the dummy loom along with their tensile properties, as shown in Table 5.5. Mehta and Shah [28] calculated rank correlation coefficients between the large-scale weaving trials, tensile strength, breaking elongation, and the data obtained on the dummy loom (Table 5.5). A rank correlation coefficient of 1 was found between breakage rate on the dummy loom and large-scale weaving trials, whereas the correlations obtained with tensile strength and breaking elongation were statistically insignificant. Both the loom-action type abrader [27] and the dummy loom [28] have their own

Table 5.4  Data Obtained on Loom-Action Abrader

<table>
<thead>
<tr>
<th>Sizing material</th>
<th>Mean number of cycles to break</th>
<th>Standard deviation from mean (%)</th>
<th>Average tensile strength (gf)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>554</td>
<td>13.5</td>
<td>360</td>
<td>4.9</td>
</tr>
<tr>
<td>Medium</td>
<td>651</td>
<td>9.2</td>
<td>340</td>
<td>4.8</td>
</tr>
<tr>
<td>Heavy</td>
<td>762</td>
<td>15.4</td>
<td>345</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Source: Ref. 27.
Table 5.5  Warp Breakages and Tensile Properties of Sized Yarns

<table>
<thead>
<tr>
<th>Sizing treatment</th>
<th>Breaks per 10,000 picks in actual weaving trial</th>
<th>Breaks per 10,000 abrasion on dummy looms</th>
<th>Mean breaking strength (gf)</th>
<th>Mean breaking extension (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>5.7</td>
<td>269.3</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>2.7</td>
<td>7.8</td>
<td>286.3</td>
<td>3.6</td>
</tr>
<tr>
<td>7</td>
<td>3.8</td>
<td>9.5</td>
<td>292.0</td>
<td>4.3</td>
</tr>
<tr>
<td>21</td>
<td>2.2</td>
<td>6.7</td>
<td>311.9</td>
<td>4.9</td>
</tr>
<tr>
<td>4</td>
<td>3.2</td>
<td>9.4</td>
<td>263.7</td>
<td>5.4</td>
</tr>
<tr>
<td>5</td>
<td>7.2</td>
<td>16.1</td>
<td>263.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Rank correlation against large-scale weaving trial</td>
<td>—</td>
<td>1</td>
<td>+0.38</td>
<td>+0.14</td>
</tr>
</tbody>
</table>

Source: Ref. 28.

limitations. The former can test only one yarn, whereas the latter uses a sheet of 250 to 300 yarns but ignores the forward movement of the warp yarns which happens on the loom when the weft thread is subjected to beat-up, resulting in sustained abrasion. Moreover, the dummy loom process is also time consuming; 250 to 300 warp yarns have to be threaded through the heddle eyes and dents of the reed. Obviously, the change to a fresh sample is cumbersome and economically expensive on the dummy loom [28]. Radhakrishnan et al. [29], using this dummy loom [28], measured the tensile properties of sized and unsized yarns before and after sustained abrasion for a fixed number of strokes. The plots of frequency distributions of strength and extension at break for both unsized and sized yarns on a laboratory slasher indicate a pronounced flattening of the distribution for sized yarns subjected to abrasive action, as shown in Fig. 5.14. For laboratory sized yarns, the frequency distribution was found to be bimodal, and this they attributed to a new population of considerably weaker yarns due to sustained abrasive action. Similar experiments repeated on mill sized yarns did not show a pronounced bimodality in the strength of the sized abraded yarns, as shown in Fig. 5.15. However, the considerable flattening of the distribution curve was still visible, which indicated the creation of new weak places [29]. Using a similar technique of assessing tensile strength distribution of sized yarns before and after sustained exposure to abrasive action on a dummy loom [28], Radhakrishnan et al. [29] reported the effect of size add-on on the abrasion resistance of yarns, as shown
Fig. 5.14 Abrasion resistance of laboratory-sized yarns. (From Ref. 29.)

in Fig. 5.16. Four sets of 100 ends, with 8.8, 7.9, 5.7, and 3.2% size add-on abraded separately for 20,000 cycles on the dummy loom [28], produced 20, 19, 25, and 100 breaks, respectively. A plot of the strength distributions of the survivors, as shown in Fig. 5.16, showed that the characteristic flattening effect increased as the amount of size on the yarn decreased. The authors argued that the bunching of the strength distribution curves of unabraded sized yarns, as shown in Fig. 5.16, did not indicate the superiority of any particular size add-on; however, the strength distribution curves of abraded yarns did indicate differences. Radhakrishnan et al. [29] also evaluated the relationship between the tensile strength distribution of sized yarns that survived the abrasion on the dummy loom [28] and the actual number of weaving breaks, which is shown in Fig. 5.17. The strength of survivors after subjecting yarns to 20,000
Fig. 5.15  Abrasion resistance of mill-sized yarns. (From Ref. 29.)

abrasion cycles on the dummy loom [28] was plotted in the form of cumulative frequency distributions and was compared with the warp breakage rates per 10,000 picks, as shown in parenthesis in Fig. 5.17. The order of ranking of the extreme left tails of these distributions compared well with the order of ranking of the actual weaving breakage rates.

The sustained abrasion of sized yarns for a prolonged period on the dummy loom [28] created very weak places even though the size film on the yarn provided the needed protection to the core of the yarn. The early rupture and rub-off of the size film exposed the bare yarn surface to the rigorous abrasive action of the heddles and reed of the dummy loom, causing frayed, untwisted, weak places or complete rupture. The places where the applied size adhered cohesively afforded full protection to the yarn or created only a slight
Fig. 5.16  Effect of size percentage on abrasion resistance. Yarns containing less size develop more weak places when subjected to the same amount of attrition in the dummy loom. However, before abrasion has taken place, their tensile strength distributions are much the same. Note particularly the case of the 3.2% size, which gave no survivors after abrasion. (From Ref. 29.)

weakening of the yarn during the course of the abrasive action. When the size film was very irregular, the tendency for local flaking became pronounced, causing superposition of strong and weak places leading to two distinct modes in the bimodal distribution, as shown in Fig. 5.14 [29].

To substitute a large-scale weaving trial by a reliable estimate of weave-ability in the laboratory, Ranganathan and Verma [4] fabricated the SRI Weavability Evaluator by incorporating all the features necessary to simulate forces

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Fig. 5.17 Comparison of different sizes. The yarns E, K, G, and H were sized in four different ways from the same gray lot. They were evaluated by drawing the cumulative frequency curves of strength after attrition in the dummy loom. The position of the extreme left tail of these curves rank the yarn in the same order as the relative warp breakage rates, which are indicated in brackets in the chart. (From Ref. 29.)

acting on a loom. The results of a comparative evaluation between large-scale weaving trials and the laboratory estimate on the SRI Weavability Evaluations are presented in Table 5.6. The laboratory data consistently overestimated the breakage rates for all trials. A similar approach was used to develop the TRS technique for size evaluation [5]. The TRS technique incorporated three steps of operations performed sequentially that consisted of a primary screening phase, a full-scale laboratory evaluation, and an extended mill-scale confirmation trial. The technique, though yielding a high confidence level in predicting the sized yarn performance, was lengthy, time consuming, and expensive to adopt.

Fatigue and Abrasion

So far, no consistent correlation between weaveability and the standard laboratory evaluation of sized yarns in terms of tensile strength/elongation [9–11], elasticity [24], abrasion resistance [4,23,25–29], or adhesion and cohesion of size films [19–21] has been established. This may be due to the fact that
Chapter 5

### Table 5.6
Comparison of Warp Breakage Rates in the Mill Trials and That Obtained on the SRI Weavability Evaluator

<table>
<thead>
<tr>
<th>Warp yarn</th>
<th>Breakages in mill</th>
<th>Breakages in SRI laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total number of picks observed</td>
<td>Average breaks per 10,000 picks</td>
</tr>
<tr>
<td>80s</td>
<td>$2 \times 10^5$</td>
<td>1.0</td>
</tr>
<tr>
<td>34s</td>
<td>$2 \times 10^5$</td>
<td>2.1</td>
</tr>
<tr>
<td>18s</td>
<td>$2 \times 10^5$</td>
<td>3.47</td>
</tr>
</tbody>
</table>

*Source: Ref. 4.*

during the actual weaving process the warp yarns are subjected to cyclic stresses that are complex in nature; these include cyclic tensile, bending, and torsional stresses. The resistance of a yarn to such repeated stresses, called fatigue strength, was considered by Faasen and van Harten [10,11] and by Owen and Oxley [22]. Figure 5.18 shows a plot of the relation between the size content, the static strength, and the fatigue strength of a warp yarn. The fatigue strength of the unsized yarn is only 40% of the static strength. Even

![Fig. 5.18](image)

*Fig. 5.18* Effect of size add-on on static and fatigue strength. (From Ref. 10.)
Performance of Sized Yarns

with a very low amount of size, less than 0.5%, the fatigue strength of the sized yarn equals the static strength of the unsized yarn. Upward of size content of 1%, the fatigue strength and the static strength increase linearly with an increase in size content; however, the fatigue strength is around 80% of the static strength [10]. Faasen and van Harten [10,11], however, suggested that “since the weaving tension, in general, is no more than 20% of the static strength of the unsized yarns, neither the static strength nor the fatigue strength is an important factor in the assessment of the properties of sized yarns. It is, therefore, necessary to find other criteria to determine the weaveability of sized yarn.”

The actual weaving process is far more complex than what is envisaged in laboratory evaluations. The warp yarn is subjected to complex mechanical actions consisting of cyclic extension, abrasion, and pseudotwisting – untwisting due to extension and bending. The warp yarns under the state of dynamic loading on a loom have to withstand cyclic stresses imposed due to the lifting of heddles, flexure and buckling in the heddle eyes, and frictional forces arising due to the abrasion of yarns with heddle eyes, reed wires, whip roll, drop wires, and the picking element [10,11,30–32]. It is also obvious that maximum chaffing takes place in the heddles because a force normal to the heddle eye is set up due to the deflection of the yarn and its movement in a plane perpendicular to the plane of the eye, which in turn intensifies the rubbing action [32]. The forward displacement of warp yarns during beat-up and the extension of the yarns during shedding should be accounted for as the reed and the pick being moved to the fell of the cloth exert a rubbing action on the warp yarns. In shuttle looms, the bottom part of the shed frequently rubs against the sley board, and also the shuttle abrades the warp yarns during its traverse both in the longitudinal and the transverse directions. The abrasive action is further intensified by the sett of the cloth being woven; increase in warp and weft density increases abrasion and the resultant warp yarn tension [32]. The combined effect of all these complex deformations causes the yarns to become more hairy, and if sizing is not done adequately the resultant hairiness causes the yarns to entangle and break during the weaving action. It is extremely difficult to quantify this aspect of warp breakage and to establish a correlation between laboratory measurements and actual warp yarn performance. The yarn breakage due to hairiness needs to be studied extensively if any further understanding of the warp yarn performance during weaving is to be properly accounted for.

Zolotarevskii [32] studied the effect of abrasion and repeated extension on unsized and sized yarn. He showed that repeated extension without abrasion had no effect on yarn strength, as shown in Table 5.7, while even partial
Table 5.7 Effect of Repeated Extension on Warp Yarn Strength

<table>
<thead>
<tr>
<th></th>
<th>Breaking strength of sized yarn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>gf</td>
</tr>
<tr>
<td>From warp beam</td>
<td>277.1</td>
</tr>
<tr>
<td>Warp-beam to pulsator</td>
<td>277.0</td>
</tr>
<tr>
<td>Warp-beam to abrader</td>
<td>253.8</td>
</tr>
<tr>
<td>Warp-beam to pulsator to abrader</td>
<td>239.3</td>
</tr>
<tr>
<td>Extracted from fabric</td>
<td>258.2</td>
</tr>
</tbody>
</table>

Source: Ref. 32.

Abrasion caused a decrease in strength by 8.3%. The partial abrasion of yarns following the process of repeated extension loading on a Borodovskii pulsator [33] resulted in a decrease in strength of the warp yarn by 13.6%. This implied that the repeated extension by itself (below the endurance limit) did not impair yarn strength but almost doubled the loss in strength when repeated extension and abrasion were combined. Zolotarevskii [32] concluded “repeated extension has an indirect but highly adverse effect, in that it decreases the resistance of warp yarn to abrasion. During weaving, the loss in strength of the warp yarn is caused by abrasion only.” However, Zolotarevskii did not examine the effect of subjecting the warp yarn to both fatigue and abrasion simultaneously. Milovidov [34] performed cyclic tension tests on a Borodovskii pulsator [33] at 350 cycles/min on unsized yarns having preset relative deformations of 0.75, 1.0, and 2.0% and sized yarns at 1.0% extension. He reported that sizing improved the yarn endurance to cyclic loading, defined as the number of cycles to break. The increase in endurance strength was far greater than the increase in breaking strength. He further subjected three yarns spun at different twist levels to the endurance test and compared them to the end-breakage rate on ten looms recorded over a period of 3 months. The results are summarized in Table 5.8. The results show that the yarns with the highest endurance and twist have the lowest end-breakage rate, even though their breaking strength is the lowest. The yarn having the lowest twist shows the highest end-breakage rate despite its highest tensile strength. Milovidov [34] calculated the coefficient of correlation, $r$, between the end-breakage rate on the looms and the endurance of the sized warp yarns ($r = -0.890$), breaking strength of sized warp yarn ($r = -0.36$), and the extension of the sized warp yarn ($r = -0.72$).
### Table 5.8  Relation Between End-Breakage Rate and Endurance, Breaking Strength, and Elongation at Break of Sized Warp Yarn

<table>
<thead>
<tr>
<th>Twist variant</th>
<th>Coefficient of twist (α of the warp yarn)</th>
<th>Total length tested (m)</th>
<th>End breaks per zone</th>
<th>End breaks per meter of cloth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Between backrest and heald shaft</td>
<td>Between heald shaft and reed (in back position)</td>
</tr>
<tr>
<td>3</td>
<td>123</td>
<td>170</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>170</td>
<td>23</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>165</td>
<td>170</td>
<td>14</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test variants</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indices</td>
<td>Unsized</td>
<td>Sized</td>
<td>Unsized</td>
</tr>
<tr>
<td>Actual count (tex)</td>
<td>54.1</td>
<td>52.1</td>
<td>52.2</td>
</tr>
<tr>
<td>Breaking strength of single yarn (g)</td>
<td>202 ± 8</td>
<td>249 ± 7</td>
<td>218 ± 9</td>
</tr>
<tr>
<td>Breaking extension (%)</td>
<td>4.4</td>
<td>3.7</td>
<td>4.7</td>
</tr>
<tr>
<td>CV of breaking strength (g)</td>
<td>14.4</td>
<td>10.2</td>
<td>14.5</td>
</tr>
<tr>
<td>Endurance under cyclic extension (cycles to failure)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unsized yarn</td>
<td>1325 ± 368</td>
<td>2316 ± 805</td>
<td>3347 ± 504</td>
</tr>
<tr>
<td>Sized warp</td>
<td>1653 ± 606</td>
<td>3019 ± 253</td>
<td>5070 ± 270</td>
</tr>
<tr>
<td>End breaks in spinning per 1000 spindle/hour</td>
<td>140</td>
<td>—</td>
<td>111</td>
</tr>
</tbody>
</table>

Source: Ref. 34.

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Davydov et al. [35] studied the residual strength of cotton yarn of 18.5 tex at a constant cyclic speed, base loads, and sample lengths but at different numbers of cycles. The results obtained indicated that the cyclic extension produces changes in the initial pattern of yarn strength distribution. The changes in the yarn section which resulted from repeated extension vary with the yarn sections. The largest changes occur in the ‘‘weaker’’ sections where the probability of yarn rupture steadily increases. In the ‘‘strong’’ sections of the yarn, the repeated extension produces practically no variations in the yarn strength [35].

Fatigue

The repeated loading and unloading of a material under small stresses (whether in repeated uniaxial, bending, or shear) often causes cumulative extension, which decreases its resistance to failure despite the stress intensity being well below the ultimate strength under static load. Such a phenomenon is commonly known as fatigue. The initiation and propagation of such cumulative fatigue damage is hard to detect in practice, and generally there is no prior indication of the impending failure [36]. It appears, therefore, that the yielding of warp yarn during weaving is perhaps independent of the yarn strength and abrasion resistance of the individual yarns but depends on the gradually diminishing resistance of the material attributable to the cumulative damage inflicted due to tensile fatigue under relatively small forces (well below the breaking point applied under a static load) combined with abrasion [34,37,38]. The studies on fatigue resistance of staple and multifilament yarns are of great importance as fatigue affects the processing performance, for example, the behavior of sized yarns during weaving and that of multifilament yarns in automobile tires.

The assessment of fatigue damage under cyclic tensile and bending forces accompanied by abrasion may be made according to the following three criteria [37]:

1. *Failure*, in which the yarn is subjected to fatigue until it fails under cumulative damage. The results obtained, usually in terms of fatigue cycles, are expressed as fatigue lifetime or survival time. In this criterion only information about lifetime is available; the rate at which the yarn performance deteriorates with the increasing intensity of fatigue is not known. Obviously predicting the impending failure is not possible by this method.

2. *Loss in mechanical properties*, where the yarn is subjected to a known number of cycles prior to its fatigue lifetime and the results are expressed in terms of loss in some mechanical properties, usually
tensile. If the yarn is subjected to a known number of cycles in a progressively increasing order and the loss in mechanical properties is estimated at each such step, then the rate of fatigue damage can be assessed. The rate of fatigue damage yields useful information about practically unacceptable levels of deterioration in yarn properties. The yarn, though not broken, may have poor residual properties after a certain number of fatigue cycles. Such a yarn with decreased resistance may be prone to potential failure.

3. **Visual damage.** The previous two criteria are objective in nature, whereas this method of assessing fatigue yields only qualitative information about the pattern and extent of fatigue damage inflicted on the fine structure of the yarn. The fiber damage resulting due to fatigue can be visualized to understand the fatigue resistance of different types of fibers.

**Reutlinger Webtester**

To alleviate the attendant risks and cost of time consuming weaving trials, therefore, an instrument that can simulate all the important stresses occurring during weaving should be selected. The Sulzer-Ruti Webtester, similar in principle to that designed by the Institute of Textile Technology, in Reutlingen [39,40] is shown in Fig. 5.19. This apparatus simulates all the most important stresses to which the yarns are subjected during weaving. The important weaving forces and the manner in which they are simulated on the webtester are described in Table 5.9 [41]. The base or pretension on the webtester simulates the static warp tension on the loom, which is applied by hanging predetermined deadweights while mounting the specimens. The extent of the sinusoidal motion of the yarn clamp determines the strain amplitude, which simulates the cyclic extension imposed due to the lifting of the heddles. The abrasion on the yarn due to the rubbing with heddles and reed is simulated by the abrasion element consisting of pins. The yarn bending and buckling in the heddle eyes are simulated by deflecting the specimens around the abrasion pin. The speed of fatiguing on the webtester, expressed as cycles per minute, simulates the speed of weaving. The intensity of the various forces listed in Table 5.9 can be varied within a realistic range in various combinations to simulate practical conditions similar to those that occur on a loom.

The webtester is connected to a microprocessor to which all signals are fed after the corresponding analog/digital conversion. The measured data are cyclically sampled and processed continuously. The data on calculated properties such as breaking strength, breaking extension, and work of rupture are available at the end of the test in addition to other statistical calculations.
Fig. 5.19  Reutlingen Webtester. (Courtesy of ITV Denkendorf.)

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Table 5.9  Weaving Stresses and Analogous Simulation on the Webtester

<table>
<thead>
<tr>
<th>Forces during weaving</th>
<th>Analogous forces on the webtester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static warp yarn tension in center of the shed</td>
<td>Initial stressing force by application of weights while mounting specimens</td>
</tr>
<tr>
<td>Cyclic extension through lifting of healds</td>
<td>Cyclic extension through sinusoidal motion of yarn clamps in axial direction</td>
</tr>
<tr>
<td>Abrasion on yarn due to healds and reed</td>
<td>Axial abrasion through abrasion element consisting of pins</td>
</tr>
<tr>
<td>Bending and buckling in heald eyes</td>
<td>Bending and buckling around abrasion pins</td>
</tr>
<tr>
<td>The level of tension is maintained by warp-beam regulator</td>
<td>The initial base tension is measured in the test and maintained constant during the test</td>
</tr>
</tbody>
</table>

Source: Ref. 41.

A line diagram of a set of yarn specimens mounted on a webtester is shown in Fig. 5.20. On the webtester, 15 yarn specimens, each 50 cm long, are mounted under constant base tension between two clamps. One clamp is fixed and the other clamp is movable horizontally in the plane of the mounted specimens to impose predetermined cyclic extensions simultaneously to all 15 yarn specimens. The yarns are deflected around stationary abrasion pins made of brass or any other material at a fixed setting. There are two sets of pins on the webtester: two square pins are mounted on a fixed plate and the center pin—circular in cross section—is mounted on a movable plate so as to adjust the penetration of the pin to a desired level of bending and abrasion intensity. Figure 5.21 shows the schematic of the abrasion pin configuration on a Sulzer-Ruti Webtester [42]. The yarn samples are then subjected to cyclic extension at a predetermined speed. With the progressively increasing fatigue action, the yarn breaks and the number of cycles at break are recorded by the microprocessor. The breakage of any one of the 15 specimens necessitates that the total base tension under which the remaining specimens are mounted must be reduced accordingly by an appropriate amount so as to maintain a constant base tension throughout testing. This is automatically achieved by the microprocessor on the Sulzer-Ruti Webtester as the rupture of the specimen is recorded. The test is usually continued until 10 out of the 15 yarn samples have ruptured. It is important to note that due to the imposed cyclic tensile fatigue on the yarn samples some yarns elongate and develop slack. Such slackened yarns exhibiting negligible tension no longer experience the cyclic...
fatigue and abrasion action. Under practical weaving conditions, such slackened yarns have no serviceability, and therefore during fatigue testing such an occurrence is classified as a pseudobreak. The yarns are then manually removed, with the cycles at which the yarns slackened being recorded. On a recent Reutlinger Weaving Tester, photoelectric devices are fitted to monitor the slub formation due to abrasion and slackening of yarns due to fatigue. The signals from photoelectric sensors are transmitted to the microprocessor for automatic registration of slub formation and slackening of the yarns during the test.

To understand the rate of fatigue damage in yarns, it is necessary to know the fatigue lifetime of the yarn based on the failure criterion. The rate of fatigue damage can be conveniently estimated by subjecting yarns for a known number of fatigue cycles on a time-scale of zero to the maximal value of the fatigue lifetime determined on the basis of failure. Then the fatigue results can be represented in terms of loss in some important yarn property, for example, tensile strength. Anandjiwala and Goswami [37] have reported a study in which they subjected staple yarns to fatigue cycles equal to 25, 50, 75, and 100% of their fatigue lifetimes estimated on the basis of failure. The yarns that survived the imposed fatigue were collected and mounted on
a black board. These survivors were in turn broken on an Instron tensile testing machine at a gauge length of 25 cm. At least 30 such survivors were collected at each level of fatigue. The yarns were mounted between the jaws of an Instron tensile tester such that the abraded portion remained in the center. The results were then expressed in terms of tenacity and elongation at break. For visual observation of fatigue damage inflicted, the yarns were observed with a scanning electron microscope.

Analysis of Fatigue Results

The discussion presented in the following sections on analysis of fatigue is primarily based on numerous studies carried out by various authors [39–42,45,49–55,57–61,63–67] whose work is referenced in the text when quoted. The earlier attempts to characterize fatigue performance of various materials, including textiles, were made in terms of average, median, or logarithmic lifetimes [39–41,43–45]. Following these early experimental findings, statistical development in the area of extreme value theory [46] and its application to fatigue phenomenon of various metals was first reported by Weibull [47]. Following the developments in engineering materials, research workers in textiles have shown that the cyclic fatigue behavior of fibers [48–52], yarns [53–58], tire cords [59–61], and fabrics [62] generally follow the third asymp-
totic distribution of extreme value theory [46], commonly termed the Weibull distribution. However, research findings are inconsistent, especially concerning the fatigue performance of fibers and yarns, in predicting the performance of sized yarns during weaving. The problem is in the understanding of the exact nature of the distribution and how it can help in discerning the mechanism of fatigue performance of fibers and yarns.

Prevorsek and Lyons [52] have identified both unimodal and bimodal distributions for acrylic fibers. They have shown that the distribution changes from unimodal to bimodal with the increase in stroke from 2.0 to 4.1% at 250 cycles/min [52]. For nylon and polyester fibers, they have confirmed that the unimodal pattern of the distribution is well suited with only some exceptions [51,52]. The controversy of observing unimodal and bimodal distributions for the tensile fatigue behavior of yarns have been extensively reported and discussed by various researchers [57,58,63–68]. The earlier studies of the tensile fatigue of yarns have reported bimodal distributions of fatigue lifetimes [63]; however, later studies have shown the preponderance of a unimodal Weibull distribution [56,57,64]. This poses a formidable problem in understanding the mechanism of yarn failure under cyclic tensile loading since the mechanism involved in bimodal behavior is inherently different to that in a unimodal Weibull distribution.

**Failure Criterion.** Trauter and his coworkers [39–41] utilized the Reutlinger Webtester to measure the number of cycles to break when yarns were subjected to abrasion and fatigue. They continued testing until 9 out of 15 specimens were broken or slackened as per the method described in the previous section. They replicated the test four times, giving a total 60 yarn specimens tested. They recorded number of cycles at break for first nine breaks and for four replications, as shown in Table 5.10. From this test they obtained mean values ST(1) to ST(9), as shown in Table 5.10, and transferred them on to a semi-logarithmic plot, as shown in Fig. 5.22. This produces either a straight line or nonlinear curve which can be converted into two straight lines. This plot on a semi-logarithmic scale was designated as a “life characteristic curve,” and it was used to characterize the abrasion resistance of the yarns tested. The authors further simplified the analysis by considering the number of cycles at break for the first and sixth yarn break, denoted by ST(1) and ST(6), respectively. By using this simplified analysis, Trauter and his coworkers [39–41] explored the effects of the test conditions and sizing parameters.

The fatigue lifetimes of all 150 specimens of 20 tex, 50/50 cotton/polyester ring-spun yarns that failed are shown in Fig. 5.23 by Anandjiwala and
### Table 5.10  Typical Test Results on the Webtester

<table>
<thead>
<tr>
<th>Sequence of yarn break</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trail 3</th>
<th>Trail 4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>522</td>
<td>480</td>
<td>515</td>
<td>532</td>
<td>ST(1) = 512</td>
</tr>
<tr>
<td>2</td>
<td>735</td>
<td>678</td>
<td>702</td>
<td>723</td>
<td>ST(2) = 709</td>
</tr>
<tr>
<td>3</td>
<td>975</td>
<td>1041</td>
<td>1023</td>
<td>988</td>
<td>ST(3) = 1006</td>
</tr>
<tr>
<td>4</td>
<td>1093</td>
<td>1131</td>
<td>1082</td>
<td>1145</td>
<td>ST(4) = 1113</td>
</tr>
<tr>
<td>5</td>
<td>1188</td>
<td>1255</td>
<td>1209</td>
<td>1153</td>
<td>ST(5) = 1201</td>
</tr>
<tr>
<td>6</td>
<td>1301</td>
<td>1452</td>
<td>1435</td>
<td>1409</td>
<td>ST(6) = 1399</td>
</tr>
<tr>
<td>7</td>
<td>1478</td>
<td>1402</td>
<td>1532</td>
<td>1522</td>
<td>ST(7) = 1483</td>
</tr>
<tr>
<td>8</td>
<td>1631</td>
<td>1693</td>
<td>1732</td>
<td>1746</td>
<td>ST(8) = 1701</td>
</tr>
<tr>
<td>9</td>
<td>1742</td>
<td>1780</td>
<td>1861</td>
<td>1832</td>
<td>ST(9) = 1804</td>
</tr>
<tr>
<td>Yarn elongation ΔL (mm)</td>
<td>1.54</td>
<td>1.36</td>
<td>1.61</td>
<td>1.45</td>
<td>1.49</td>
</tr>
</tbody>
</table>

**Note:** ST(1) and ST(6) represent the abrasion characteristics (number of cycles for the first and sixth yarn breaks).

**Source:** Ref. 39.

Goswami [37]. The range of the number of cycles at break varies from a minimum of 1903 to a maximum of 4076, the calculated average lifetime being 3055.8 cycles, with a standard deviation of 568.9 cycles. A histogram of the data is plotted in Fig. 5.24 [37]. The distribution obtained is far from normal in nature. Representing such widely scattered data in terms of average lifetimes will not exactly characterize the complete phenomenon of fatigue.

The problem of analyzing such nonnormal asymmetric distributions that occur in fatigue experiments has been considered and discussed at length by several authors [45–47] under the broad spectrum of extreme value statistics. Based on such extreme value statistics, some researchers have fitted various statistical distributions, such as the first asymptotic, the log-normal and the third asymptotic distribution (commonly known as Weibull) [46,47]. Barella [63–65], Prevorsek et al. [45], and Picciotto and Hersh [57] have shown that the fatigue behavior of yarns under cyclic extension accompanied by abrasion resistance follows the three parameter Weibull distribution, with some exceptions. However, these authors have reported somewhat inconclusive results in terms of the unimodal and bimodal pattern of distribution.

The Weibull distribution of the extreme value theory is given by

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where $P(x)$ is the probability that the yarn will survive $x$ cycles; $x_o$ is the lower bound of the distribution, known as minimum lifetime, that all specimens are expected to survive; $v$ is the characteristic extreme lifetime; and $k$ is a scalar parameter that determines the shape of the distribution. Among several different methods of estimating Weibull parameters [46,47], it has been shown by Picciotto and Hersh [57] that the linear regression technique produces the most plausible results. Consequently, the Weibull distribution may be expressed in a more convenient linear form by double logarithmic transformation of Eq. (5.1) to give

$$\ln \left\{ -\ln [P(x)] \right\} = y = k \cdot \ln (x - x_o) - k \cdot \ln (v - x_o)$$  \hspace{1cm} (5.2)
Fig. 5.23  Diagram of typical fatigue behavior based on failure criterion. (From Ref. 37.)

Fig. 5.24  Histogram representing typical fatigue results based on failure criterion. (From Ref. 37.)
The survival probability may be estimated by using a standard computational program [69] which uses the method of maximum likelihood as described by Kalbfleisch and Prentice [70]. Figure 5.25 shows the probability of survival plotted against the number of cycles at break, which is similar to that plotted by other authors [44,46,47,64]. The estimation of Weibull parameters $x_o$, $\nu$, and $k$, for a given $N$ experimental observations, can be conveniently carried out by defining a function $S$ such that

$$S(x_o, \nu, k) = \sum_{i=1}^{N} (y_i - y_{ic})^2$$

where the subscript $c$ indicates the computed values for some approximate initial guesses of $x_o$, $\nu$, and $k$. When $S$ becomes zero, separate residue is also zero. The problem of changing the initial guesses until $S$, which is a function of these guesses, reaches a minimum value (ideally zero) can be solved by a standard function minimizing technique [71]. A computer program was prepared for fitting the Eq. (5.2) and to estimate all three parameters for given experimental results [37]. A typical fit based on Eq. (5.2) for the data plotted

![Typical plot of number of cycles to break versus probability of survival.](From Ref. 37.)
in Figs. 5.23 and 5.25 is shown in Fig. 5.26. The estimated parameters of the Weibull distribution are \( x_0 = -0.054, \nu = 3289.014, \) and \( k = 6.3724, \) with coefficient of determination \((r^2)\) of 0.999 [37].

**Rate of Fatigue Damage Criterion.** The rate of fatigue damage in fibers and yarns has been ignored by various research workers [50,51,57,64]. The idea of fatigue lifetimes only on the basis of failure criterion, discussed in the previous section, is hardly enough to characterize the complete fatigue behavior of yarns and its anticipated effect on weaveability, since the characteristic lifetimes calculated by fitting the Weibull distribution are sometimes far higher than the actual tensile fatigue cycles imposed on looms [42]. Even the mean lifetimes used as a criterion to describe the fatigue failure of yarns [44] is also often several times higher than the actual level of tensile fatigue experienced by yarns during weaving. This implies that the reported breaks of such yarns during actual weaving perhaps occur well before the imposed fatigue attains the value equal to its characteristic lifetime. Therefore, the understanding of the progressive deterioration of important yarn properties, for example, tensile strength, at increasing fatigue level may yield useful information about the possibility of potential failure. This may in turn contribute toward estimating

![Typical fit of three-parameter Weibull distribution to experimental results.](Fig. 5.26)
the capacity of the material to sustain failure and the phenomenon of impending failure which is otherwise not very well understood.

Figure 5.27 shows a typical graph of loss in tenacity and elongation at break with increasing fatigue. Values of tenacity and elongation at break marked at 0% of the characteristic lifetime indicate the properties of yarns before being subjected to fatigue. In general, as the fatigue level is increased in steps of 25, 50, 75, and 100% of the characteristic fatigue lifetimes, the tenacity and elongation at break decrease. The extent of change in tenacity

![Graph of typical fatigue results based on rate of damage criterion.](image)

**Fig. 5.27** Plot of typical fatigue results based on rate of damage criterion. (From Ref. 37.)
Performance of Sized Yarns

and elongation at break for each level of fatigue is calculated and given in Table 5.11. In this particular test, the deterioration of the yarn properties is relatively small up to the imposed fatigue cycles below 50% of characteristic lifetime, as shown in Fig. 5.27 and Table 5.11. However, at fatigue cycles between 50 and 75% of the characteristic lifetime, the loss in tenacity and elongation at break is almost twice the amount suffered up to 50% of characteristic lifetime; beyond fatigue cycles equal to 75% of the characteristic lifetime there is a precipitous and profound loss in tenacity and elongation at break. The survivors, after experiencing fatigue cycles equivalent to their characteristic lifetimes, i.e., 100% level, have a residual tenacity and elongation at break equal to only 30 and 55%, respectively, of their respective values before being subjected to any fatigue. Such sudden losses in tenacity and elongation at break beyond fatigue cycles equal to 75% of characteristic lifetime perhaps indicate the possibility of potential failure of yarns on the loom if the yarns experience a fatigue level of similar magnitude and the actual tension imposed during weaving exceeds the residual tenacity. The progressively increasing deterioration of the tensile properties with the increasing fatigue level may explain why the same yarns sized at a particular add-on and from the same ingredients under identical slashing conditions behave differently on different types of looms. The yarns which work satisfactorily on automatic shuttle looms may perhaps fail to work satisfactorily on high-speed shuttleless weaving machines.

Visual Damage Criterion. This criterion of evaluating fatigue damage, though subjective in nature, yields useful information regarding microstructural damage of yarns which occurs during the course of fatiguing. The survivors of yarns obtained after subjecting to known intensity and level of fatigue

<table>
<thead>
<tr>
<th>Percentage of characteristic lifetime</th>
<th>Tenacity at break (cN/tex)</th>
<th>Elongation at break (%)</th>
<th>Loss in tenacity (%)</th>
<th>Loss in elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18.66</td>
<td>8.32</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>25</td>
<td>17.14</td>
<td>7.90</td>
<td>8.14</td>
<td>5.05</td>
</tr>
<tr>
<td>50</td>
<td>16.11</td>
<td>7.62</td>
<td>13.66</td>
<td>8.41</td>
</tr>
<tr>
<td>75</td>
<td>13.42</td>
<td>7.12</td>
<td>28.11</td>
<td>14.42</td>
</tr>
<tr>
<td>100</td>
<td>5.55</td>
<td>4.61</td>
<td>70.26</td>
<td>44.59</td>
</tr>
</tbody>
</table>

Source: Ref. 37.

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accompanied by abrasion action were collected and mounted on a stub for scanning electron microscope studies. A typical SEM photograph of a portion of sized ring spun yarn subjected to abrasion and fatigue (450 cycles/min, 0.5% strain amplitude, 3 cN/tex pretension and 2.5 mm abrasion pin position) is shown in Fig. 5.28. The photograph shows a complete and partial rupture of some of the fibers caused by intensive abrasion action. The severity of the damage inflicted on the fibers under cumulative tensile fatigue, however, was influenced by the intensity and level of fatigue and abrasive actions and the properties of fibers, such as tensile, frictional, bending, and the nature of spin finish in the case of synthetic fibers. This type of visual study may be used in understanding the relative differences in fatigue behavior of similar yarns spun on different spinning systems.

Effect of Webtester-Related Parameters on Fatigue Behavior

Anandjiwala and Goswami [37] reported experimental work on 20 tex sized ring and open-end spun yarns using the webtester and the following parameters: 450 cycles/min, 2.5 mm abrasion pin deflection, 3 cN/tex base tension, and 0.5% strain amplitude. To isolate the effect of each parameter, the parameter under investigation was systematically varied by keeping all other parameters constant. Since this study was not intended for comparison of fatigue resistance of ring and open-end spun yarns, the separate results were given

Fig. 5.28  SEM photomicrograph representing visual fatigue damage. (From Ref. 37.)
for the different yarn types. The trends and results obtained were, however, consistent for both yarn types.

**Effect of Base Tension.** The results of the effect of base tension on the fatigue behavior of ring-spun yarns from the above-mentioned study [37] are shown in Fig. 5.29. The characteristic lifetime linearly decreased with an increase in the base tension at which the yarns were mounted on the webtester as expected. There is an almost five times reduction in characteristic lifetimes when the base tension is increased from 2 to 5 cN/tex. The straight line fitted by regression analysis is shown by the solid line in Fig. 5.29. The slope and intercept of this fitted straight line are $-818.38$ and $4387$, respectively, with a correlation coefficient ($r$) equal to $-0.98$. However, no clear trend was noticed between base tension and the scalar parameter determining the shape of the Weibull distribution. This is due to the fact that consideration of only characteristic lifetime does not give the entire picture of the distribution of lifetime that normally occurs. Therefore, it is always much more informative to observe the effect in terms of complete distributions at all base tension levels. Figure 5.30 shows the fitted Weibull distribution for the yarn tested at

![Fig. 5.29](image-url)  
**Fig. 5.29** Effect of base tension on fatigue behavior of open-end spun yarn. (△) Characteristic lifetime; (——) fitted straight line; (×) scalar parameter. (From Ref. 37.)
all base tension levels shown in Fig. 5.29. From Fig. 5.30 it is apparent that the entire distribution for any particular base tension level shifts toward the left, which indicates a reduction in fatigue resistance. This is consistent with what is shown in Fig. 5.29.

Scanning electron micrographs of two ruptured ends of a yarn fatigued at the same number of cycles but at various base tensions are shown in Plates 5.1–5.4. The plates denoted by A and B are photomicrographs of the same yarn at lower (27×) and higher (100×) magnifications, respectively. It is obvious from Plates 5.1A–5.4A that the progressive deterioration of the yarn increases as the base tension is increased from 2 to 5 cN/tex. With the increase in base tension more fibers fray out at the ruptured yarn ends, perhaps because of higher intensity of abrasion. The photomicrographs taken at higher magnification reveal the partial and complete rupture, peeling-off, curling, and severe surface damage of some of the fibers, particularly at higher base tension levels. The failure of the yarn is caused by the mixed mode of fatigue and abrasion actions. The isolation of the effect of simple fatigue and simple abrasion on the rupture of the yarns was not considered by the authors [37] because their formative research work was primarily intended for understanding the yarn fatigue and its effect on the performance of yarns during weaving. Yarns are
Plate 5.1  SEM photomicrograph of open-end spun yarn fatigued at a speed of 450 cycles/min, base tension of 2 cN/tex, strain amplitude of 0.5% and abrasion pin deflection of 3.0 mm, magnification (A) 27× and (B) 100×. (From Ref. 37.)

always subjected to combined actions of abrasion and cyclic extension fatigue on a loom, and the webtester simulates all the major forces that occur [32,33].

Trauter et al. [39] found similar results in their experiments on the effect of pretension on the abrasion resistance of 20 tex cotton yarn, fatigued at a strain amplitude of 0.5% and abrasion pin position of 3.0 mm, as shown in Fig. 5.31. They estimated the abrasion resistance for first and sixth breaks, denoted as ST(1) and ST(6), respectively, at base tensions of 5, 10, 20, and
Plate 5.2  SEM photomicrograph of open-end spun yarn fatigued at a speed of 450 cycles/min, base tension of 3 cN/tex, strain amplitude of 0.5% and abrasion pin deflection of 3.0 mm, magnification (A) 27× and (B) 100×. (From Ref. 37.)

30 cN (0.25, 0.5, 1.0, and 1.5 cN/tex), as shown in Fig. 5.31. In general, the abrasion resistance decreased with an increase in base tension, as shown in Fig. 5.31.

An increase in the base tension at which the yarn specimens are mounted on the webtester at a constant deflection of abrasion pin results in an increase in the transverse pressure between the yarn and the abrasion pin, which in turn results in an increase in intensity of abrasion. A high intensity of abrasive
action, which is associated with higher tension, obviously will cause an accelerated deterioration of the yarn properties. It may be argued that the higher base tension may tend to increase the consolidation of the fibers in a yarn, which should result in a better tensile resistance; however, the increased severity of the abrasion action perhaps overshadows the consolidation effect. The net effect of these two opposing actions appears to result in decreased fatigue resistance.
Plate 5.4  SEM photomicrograph of open-end spun yarn fatigued at a speed of 450 cycles/min, base tension of 5 cN/tex, strain amplitude of 0.5% and abrasion pin deflection of 3.0 mm, magnification (A) 27× and (B) 100×. (From Ref. 37.)

Effect of Abrasion Pin Position. The results of the same study [37] reported the effect of abrasion pin position on the characteristic lifetime and scalar parameter of the Weibull distribution for ring-spun yarns, and the results are shown in Fig. 5.32. With an increase in abrasion pin position from 1.5 to 2.0 mm the fall in fatigue resistance of the yarns is very pronounced, as is obvious from Fig. 5.32. Beyond a 2.0-mm abrasion pin deflection, the fatigue resistance of the yarn progressively decreases until it reaches a value of 516
cycles at 5.0 mm. The increase in abrasion pin deflection on the webtester geometrically increases the contact angle of the test yarn around the circular pin, as shown in Fig. 5.33. This results in increased frictional forces between the yarn and the abrasion pin. The increase in yarn tension is a consequence of an increase in the deflection of the abrasion pin. The combined effect of these two actions tends to decrease the fatigue resistance of the yarn. The trend of changes in scalar parameter with respect to increased deflection pin position is not clear from Fig. 5.32. Figure 5.34 shows the fitted Weibull distribution for the yarns tested at different abrasion pin positions. Though the slope of individual lines varies slightly, the trend of the entire distribution shifting toward the left—meaning decreasing fatigue resistance—is clearly noticeable.

Trauter et al. [39] also studied the effect of abrasion intensity on the abrasion resistance of 20 tex cotton yarn, tested at a strain amplitude of 0.5% and a base tension of 10 cN (0.5 cN/tex), as shown in Fig. 5.35. They estimated

![Fig. 5.31](image) Effect of base tension on abrasion resistance characteristics. (From Ref. 39.)
Fig. 5.32  Effect of abrasion pin position on fatigue behavior of ring-spun yarn. (○) Characteristic lifetime; (×) scalar parameter. (From Ref. 37.)

Fig. 5.33  Geometry of abrasion pin on the webtester. (From Ref. 37.)
the abrasion resistance for the first and sixth breaks, denoted as ST(1) and ST(6), respectively, at an abrasion pin penetration of 2.5, 3.0, 3.5, and 4.0 mm, as shown in Fig. 5.35. The abrasion resistance generally decreased with an increase in the abrasion pin penetration, as shown in Fig. 5.35.

Besides the deflection, the characteristics of the abrasion pin in terms of its surface roughness, material, size, and shape may also affect the fatigue resistance. Very rough surfaces will tend to reduce the fatigue resistance of the yarn, whereas very smooth surfaces such as glass may enhance the fatigue resistance because of the decreased abrasion resulting from the lower frictional coefficient. Similarly, abrasion pins with triangular or square cross sections may tend to increase the abrasive action due to sharp corners in comparison to polished round cross sections, resulting in rapid deterioration of the yarn. A polished brass pin having circular cross section with a 6-mm diameter was used but the effect of pin characteristics was not explored in this work [37].

**Effect of Speed of Fatiguing.** Figure 5.36 shows the effect of speed of fatiguing on the characteristic lifetime and scalar parameter of the Weibull distribution for the ring spun yarns [37]. With an increase in speed of fatiguing, in general, the characteristic lifetime decreases; however, the scatter observed is somewhat larger. The straight line fitted by the regression method is shown
by a solid line in Fig. 5.36. The slope and intercept of this straight line are $-1.94$ and $3584.5$, respectively, with a correlation coefficient ($r$) equal to $-0.72$, which is rather poor. The effect of increasing the fatigue speed on scalar parameter is not very clear, as seen in Fig. 5.36. Because of the wide scatter observed in the scalar parameter, and to some extent also in characteristic lifetime, the plotting of the entire Weibull distribution at each speed level has turned out to be somewhat difficult.
Scanning electron photomicrographs of two ends of a ruptured yarn are shown in Plates 5.5, 5.2, and 5.6 tested at 350, 450, and 550 cycles/min respectively. The plates denoted by A and B are the photomicrographs of the same yarn at lower (27×) and higher (100×) magnifications, respectively. At a low speed of fatiguing (350 cycles/min) the fibers were partially pulled away from the yarn matrix with one end still remaining in the yarn. The fibers are partially displaced from the surface of the yarn and coiled around adjacent fibers. The yarn rupture is principally a result of the abrasive action of the pin. At higher speeds of fatiguing, the resultant damage to the yarn is more severe because of the rapidity of the combined actions of abrasion and extension fatigue. The photographs taken at higher magnification show partial and complete breakage, peeling-off, surface damage due to abrasion, and curling-off of some fibers.

Effect of Strain Amplitude. Figure 5.37 shows the effect of change in strain amplitude on the characteristic lifetime and scalar parameter of the Weibull distribution for ring spun yarns, as reported in the same study [37]. The increase in strain amplitude, in general, tends to decrease the characteristic lifetime of the yarns. At constant speed of fatiguing, the strain amplitude
determines the amount by which the yarn is extended on every cycle: the higher the strain amplitude, the greater is the cyclic extension, resulting in a higher intensity of fatigue action. The regression line is shown by the solid line in Fig. 5.37. The slope and the intercept of this fitted straight line are $-2001.3$ and $2836$, respectively, with a correlation coefficient ($r$) equal to $-0.93$. However, there appeared to be no noticeable relationship between

Plate 5.5 SEM photomicrograph of open-end spun yarn fatigued at a speed of 350 cycles/min, base tension of 3 cN/tex, strain amplitude of 0.5% and abrasion pin deflection of 3.0 mm, magnification (A) 27× and (B) 100×. (From Ref. 37.)
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Plate 5.6 SEM photomicrograph of open-end spun yarn fatigued at a speed of 550 cycles/min, base tension of 3 cN/tex, strain amplitude of 0.5% and abrasion pin deflection of 3.0 mm, magnification (A) 27× and (B) 100×. (From Ref. 37.)

scalar parameter and strain amplitude. Figure 5.38 shows the composite plot of the fitted Weibull distribution for all strain amplitude levels.

Trauter et al. [39] also studied the effect of strain amplitude on the abrasion resistance of 14.3 and 20 tex cotton yarns fatigued at a pretension of 10 cN and pin penetration of 3 mm, as shown in Fig. 5.39. They again estimated the abrasion resistance for the first and sixth breaks, denoted as

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Fig. 5.37 Effect of strain amplitude on fatigue behavior of ring-spun yarn. (•) Characteristic lifetime; (——) fitted straight line; (×) scalar parameter. (From Ref. 37.)

ST(1) and ST(6), respectively, at strain amplitudes of 0.3, 0.5, 0.8, and 1.1%, as shown in Fig. 5.39. The abrasion resistance generally decreased with an increase in strain amplitude, as shown in the figure.

The reduction in fatigue resistance of the yarn with increasing strain amplitude is attributed to the development of permanent “set” in the yarn when subjected to a cyclical elongation of higher magnitude. The cyclical extension of the yarn beyond its yield point results in a residual elongation, which gradually increases under cumulative fatiguing process; consequently, the yarn either exhibits actual rupture because it weakens or it develops slack which may be classified as a pseudobreak.

Practical Applications

The realistic practical applications of fatigue/abrasion behavior of sized yarns as evaluated on the Sulzer-Ruti Webtester in the laboratory may be directed to assess the efficiency of various size formulations applied at various add-on levels, the efficiency of different size types and their mixtures, the performance behavior of various yarn types, and the optimization of processing variables on a slasher, even without conducting costly and time-consuming in-plant...
Fig. 5.38  Weibull distribution fit representing effect of strain amplitude at 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8% for ring-spun yarn. (From Ref. 37.)

Fig. 5.39  Effect of strain amplitude on abrasion resistance characteristics. (From Ref. 39.)
weaving trials. However, the confidence level of using the technique to assess fatigue/abrasion failure of sized yarns developed by Anandjiwala and Goswami [37] and several other authors [39–42,57,58,63–68] depends upon the positive correlation between the laboratory evaluation on the webtester and the actual weaving trials on the loom. Indeed, the task is enormous, because for setting up such correlation a large amount of experimental work is required to be conducted on different types of yarns, different size types, different size formulations, and on different types of looms. The research work leading to establish basic principles and a methodology to link the laboratory evaluation of fatigue/abrasion behavior as measured on the webtester to that on a loom is a step in the right direction. The following is a discussion of the methodology established and the analysis technique developed to assess the laboratory evaluation of fatigue based on failure criteria that can be advantageously used in practical situations.

Figure 5.40 shows the effect of size mixtures on a 20 tex, 50/50 cotton/polyester open-end yarn sized at 9% nominal size add-on level. The entire Weibull distribution fitted to the experimental results of fatigue measured on the webtester [39,40] for the same yarn sized with Recipe C (70% PVA + 22% starch + 8% wax) and Recipe A (50% PVA + 42% starch + 8% wax) is plotted using the technique developed by the authors [37]. The rightward shift of the entire distribution indicates improvement in the fatigue resistance of the yarns. The fatigue resistance of the unsized yarns, as expected, is poor. The effect of size application manifests itself in the improvement in fatigue resistance due to the cementing action of the fibers in the yarn and enhancement in abrasion resistance. Figure 5.40 shows the usefulness of the laboratory technique employed in showing that the yarn sized with Recipe C performs distinctly better than that sized with Recipe A. Such initial laboratory trials help in assessing various size mixtures without conducting the time-intensive and costly in-plant trials.

Figure 5.41 shows the relative fatigue performance of 20 tex, 50/50 cotton/polyester ring and open-end spun yarns sized at 9% nominal size add-on with the size mixture containing 70% PVA + 22% starch + 8% wax. The distinct rightward shift of the entire distribution of the fatigue behavior of the open-end spun yarn indicates comparatively better resistance than that of the ring-spun yarn. This is attributed to the relative differences in the structure of the yarns spun on different spinning systems. Perhaps, the open-end yarn with a relatively open yarn structure facilitates better penetration and migration of size mixture resulting in a better cementing action of fibers in the yarn core. The ring-spun yarn with a compact twist geometry does not allow substantial size penetration and migration. Perhaps more size is deposited
Fig. 5.40  Effect of size mixtures on fatigue behavior of 20 tex, 50/50 cotton/polyester open-end yarn, Recipe A: 50% PVA + 42% starch + 8% wax; Recipe C: 70% PVA + 22% starch + 8% wax. (From Ref. 37.)

Fig. 5.41  Relative fatigue performance of 20 tex, 50/50 cotton/polyester ring- and open-end spun yarns sized at 9% add-on level of 70% PVA + 22% starch + 8% wax mixture. (From Ref. 37.)
on the surface of the ring-spun yarn, resulting in easy size shed-off due to the applied abrasion during testing on the webtester. This interesting feature of the same size mixtures applied to different yarn types under identical processing and testing conditions can be easily estimated using the laboratory technique. Such laboratory studies help in optimizing size mixture, add-on level, and processing conditions for yarns spun on different spinning systems.

Trauter et al. [39] used the webtester to study the effect of size add-on (degree of sizing) on the abrasion resistance of yarns. They prepared a “life characteristics curve” of the yarn at different size add-on levels, as shown on the left-hand side of Fig. 5.42. Then they plotted the abrasion characteristics ST(1) and ST(6) of the life characteristics curve against the degree of sizing on a semi-logarithmic scale, as shown on the right-hand side of Fig. 5.42, to characterize the abrasion resistance. The abrasion resistance increases with an increase in size add-on. The abrasion characteristics of the yarns “sized” with water only also lie on this graph, shown by the arrow at 0% size add-on, which represents the lower limit of the abrasion resistance of the warp yarns.

A sizing recipe that requires less size add-on to achieve the same abrasion characteristics can be regarded as more effective. Trauter et al. [39] studied the efficiency of two different size recipes by means of abrasion characteristics,

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**Fig. 5.42** Effect of size add-on on life characteristics and abrasion resistance of yarn. (From Ref. 39.)

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denoted by ST(1) and ST(6) in their analysis of tests conducted on the webtester. They sized the same yarn with two different size recipes, denoted by Recipe A and Recipe B, at different levels of add-on on a pilot sizing plant at Reutlingen. The abrasion characteristics were measured and plots were prepared for both sizing recipes, as shown in Fig. 5.43. To develop standards for comparison purposes, the authors measured the abrasion characteristics, ST(1)* and ST(6)*, on the webtester of the same yarns with the same size recipes but sized on industrial sizing machines. As shown in Fig. 5.43, at the same level of abrasion characteristics (e.g., ST(1)* = 530 cycles and ST(6)* = 1050 cycles) of the industrially sized warp yarns, the size add-on required for Recipe A is almost 16.3%, whereas for Recipe B only 9.8% is required. This implies that Recipe B is more effective than Recipe A as a lower size add-on is required to achieve the same abrasion resistance. Trauter et al. [39] also made a comparison for a 16.7 tex, 65/35 polyester/cotton blended yarn, sized with different sizing agents using similar methodology. Table 5.12 shows the minimum size add-on required to achieve the standard abrasion characteristics of ST(1)* = 380 and ST(6)* = 850.

Trauter et al. [39,72,73] also attempted to develop a correlation between the abrasion characteristic ST(6) and the warp yarn breakages on the loom. The warp samples (30 tex, 100% cotton and 30 tex 67/33 polyester/cotton) sized in the mills under normal conditions were tested for abrasion characteristics ST(6) on the webtester and correlated with the actual warp breaks during weaving, as shown in Fig. 5.44. The authors claimed that it was possible to predict the actual performance of warp yarns during weaving by testing sam-
Table 5.12 Necessary Size Add-On to Achieve Standard Abrasion Characteristics

<table>
<thead>
<tr>
<th>Tested sizing agent</th>
<th>Necessary size add-on (%)</th>
<th>Equivalent quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch</td>
<td>18.2</td>
<td>1</td>
</tr>
<tr>
<td>PVA</td>
<td>6.0</td>
<td>0.33</td>
</tr>
<tr>
<td>Polyacrylate</td>
<td>7.9</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Note: For ST(1)* = 380 and ST(6)* = 850 cycles.
Source: Ref. 39.

plexes on the webtester for assessing the life characteristic curve and abrasion characteristics ST(6). The results reported by Trauter et al. [39] were limited to only a few trials; however, they reported a confidence level of more than 80% based on their experience.

The methodology introduced in this section provides information about the usefulness of the webtester for assessing the weaving performance of sized warp yarns in the laboratory. The mills can attempt a variety of sizing- and yarn-related measurements by using the webtester and prepare their own data which can be used with considerable confidence.

Fig. 5.44 Correlation between abrasion characteristics and warp break during weaving. (From Ref. 39.)
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