Part III

Quality and other issues

12
Testing cotton yarns and fabrics

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12.1 Introduction

In this highly competitive global market, the survival of a textile company will greatly depend upon its ability to meet demanding quality specifications through optimised manufacturing and testing regimes, within acceptable price and delivery time frames. Textile testing forms an essential link in the quality assurance and quality control chain and may be divided broadly into two major types, namely subjective and objective, Slater[1,2] having reviewed both. This chapter deals largely with the objective or instrument testing of yarn and fabric physical and related properties inasmuch as they relate to their subsequent performance.

Clearly, the intended application of the yarn or fabric is critical in determining which properties, and therefore tests, are important. For example, for fabric to be used in children's nightwear, flammability (e.g. the Limiting Oxygen Index – LOI) would be of paramount importance, whereas for fabrics to be used in parachutes, bursting and tear strength, impact resistance and air permeability would be critically important. Nevertheless, generic or general testing of yarns and fabrics is often carried out irrespective of their end-use so as to ensure consistency in the yarn and fabric and to detect any changes suggesting possible production problems. Ultimately, wearer (field) trials would provide the most reliable measure of actual performance, but these are expensive, time consuming and difficult to organise and design in such a way that meaningful and accurate results are obtained.

In carrying out any tests it is important to as far as possible use accepted test methods ensuring that the correct sampling, sample preparation and handling, atmospheric conditions (e.g. 20 °C ±2 °C and 65% ± 2% RH), conditioning time and instrument calibration are adhered to. ASTM D3777 deals with the writing of specifications for textiles. Standards test method organisations include:

- AATCC (American Association of Textile Chemists and Colorists)
- ASTM (American Society for Testing of Materials)

- BSI (British Standards Institution)
- BIS (Bureau of Indian Standards)
- DIN (Deutsche Industrie Norm) German National Standards
- EN (European Norm)
- ISO (International Standards Organization)
- JIS (Japanese Industrial Standards)

It should be noted that BS, EN and DIN standards now largely use ISO designations.

Ideally, there should be a written pre-agreement between the buyer (customer) and seller (supplier) as to the test method and specifications to be adhered to, thereby avoiding potential ambiguity and dispute. This should also preferably include agreement as to which independent/arbitration testing house or laboratory should be used in the event of claims and disputes. In addition, and at the very least, there should be available for comparative testing purposes, either a reference or 'benchmark' yarn/fabric sample, possibly the yarn/fabric sample on the basis of which the purchase was agreed upon, or a similar yarn/fabric sample from the same source, previously used and found to be acceptable. For more in-depth treatment of yarn and fabric testing and quality related aspects, the reader is referred to various textbooks and reviews (see section 12.4).

12.2 Yarn testing

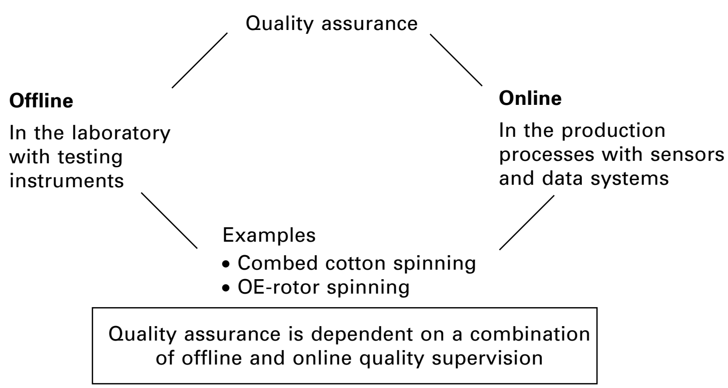
12.2.1 Introduction

The yarn represents the final outcome of the fibre processing or yarn manufacturing part of the fibre to fabric textile pipeline. Prior to the yarn it is still possible, within certain limits, to take corrective action should problems or mistakes have occurred during the earlier processing stages. Once the yarn has formed, any corrective action is limited to yarn clearing (i.e. removal of gross or unwanted faults), uptwisting and singeing. The properties of the yarn largely determine subsequent fabric manufacturing performance and efficiency (also sewing performance) as well as the properties, aesthetic and functional, of the fabric and end-product. Yarn quality control, and the associated testing of those yarn properties which determine the yarn quality, are therefore crucial in ensuring that the yarn meets the requirements of the subsequent fabric manufacturing stages as well as of the fabric and end product. Preferably the process should be one of quality assurance and total quality management (TQM) rather than quality control only, so that the yarn meets the necessary quality requirements cost-effectively without the need for any corrective action or excessive rejects or waste. A further important reason for the accurate measurement of yarn properties is that the yarn often changes hands, i.e., is sold and therefore subject to buyer–seller contractual agreement and specifications, as well as potential claims. The results obtained can be compared with international by accepted 'norms' or 'benchmark' values, such as Uster® Statistics and Yarn Hairiness Grades [http://www.cogetex.ch/Services/Sujets/Uster/GraphsYQ.html]

The testing or monitoring of yarn properties (Fig. 12.1) can take place either on-line during spinning (e.g. rotor and air-jet spinning) and winding, or more commonly off-line, such as measuring the yarn evenness and tensile properties, or both. It is conceivable that in years to come, on-line monitoring will become the norm, even to the extent that the yarn tensile properties (e.g. breaking strength and elongation), which are virtually impossible to measure non-destructively on a continuous on-line basis, could be deduced from the relevant measured fibre properties and those yarn properties, such as twist, linear density and evenness, which can be measured on-line.

Integrated (comprehensive) and automatic yarn testing is increasingly becoming the norm, certain instruments often combining capacitance and optical technologies, simultaneously measuring properties, such as yarn mass (linear density) unevenness (irregularity), imperfections (thin and thick places and neps), hairiness and its variations, diameter and diameter unevenness, density (derived), shape, relative and absolute count (linear density) and neps classified according to type (i.e. fibrous neps, trash and dust). Such systems also produce variance length curves and yarn quality profiles and direct comparison with standard or benchmark values, yarn specifications and customer values. Some comprehensive integrated 'dynamic' yarn systems 'dynamically' measure strength, weak places, elongation, shrinkage, friction, abrasion, linting, faults, entanglements, diameter, hairiness, etc.

This section deals with the testing of those yarn properties commonly specified or used, individually or collectively, as a measure of yarn quality, the correct sampling procedures being critical (ASTM D2258). Yarn properties,



12.1 Method of applying quality assurance (source: Uster Technologies).

such as twist liveliness (residual torque) and stiffness, although of some importance, are not widely tested and will therefore be referred to only in passing.

12.2.2 Count (linear density)

Count (linear density) is a fundamental structural parameter of a yarn, and the average count and its variations are of paramount importance in virtually all facets of textile performance and specifications, undue variations in yarn count, or off-specification count, leading to problems in terms of fabric mass and barré, and often to claims. Traditionally, the average yarn count (linear density) and its variation (CV) are determined by weighing a number 100 m lengths of yarn (e.g. ASTM D861, ASTM D1059, ASTM D1907, ASTM D2260, BS2010, BS2865, ISO 1144, DIN 53830, part 1). Linear density (count) variations (CV), based upon the weighing of 100 m lengths, of less than 2% are generally considered acceptable. Ideally, 20 to 30 × 100 metre lengths of yarn, preferably each coming from a different yarn bobbin or package, should be tested. The count of cotton yarn can be expressed in any one of the following three systems:

1. Tex count (linear density): weight in grams of 1000 m of yarn (i.e. mg/m or g/km)
2. Cotton count (Ne): number of 840 yd lengths in a pound
3. Metric count (Nm): number of 1000 m lengths of yarn in one kilogram. The conversion from one system to the other is as follows:

$$\text{tex} = \frac{590.6}{\text{Ne}} = \frac{1000}{\text{Nm}} \qquad 12.1$$

Today 'relative count' and count deviations, from the nominal (or set) value, can also be determined on optical or capacitance type instruments (DIN 53817, part 2), even on-line, although in the case of the latter, it could be influenced by variations in the fibre type (dielectric constant) and moisture content within the test length.

12.2.3 Twist

Twist is one of the fundamental constructional parameters for yarns. Average twist levels and twist variations are reflected in the yarn tensile properties, thickness, bulk, stiffness and handle. These, in turn, are reflected in the yarn performance during the subsequent fabric manufacturing processes and ultimately in the corresponding fabric properties.

Traditionally, twist was counted manually by the direct twist counting method (ASTM D1423, BS 2085) where the operator would clamp the yarn test length (popularly 25 mm for singles yarn and 500 mm for two-ply yarn) under a pre-determined tension, and then untwist the yarn, using a 'dissecting needle' until all the twist is removed. Today, twist is more commonly measured automatically, using different test methods and techniques, for example, double-untwist-retwist test, untwist-retwist tests described in ASTM D-1422, multiple untwist-retwist and twist-to-break, the test length popularly being 50 cm, typically 100 tests per yarn lot are measured, it also being possible to measure the twist (helix angle optically). The yarn twist is expressed in terms of turns per metre (or turns per centimetre) and the CV of twist in percentage, noting the gauge length. Standard test methods include BS 2864, DIN 53830-4, see also ASTM D1244. Twist results may be assessed using 'norms or standards', such as the Testex Twist Statistics, variation in yarn twist being particularly important. Various instruments and test methods are available for testing yarn twist (e.g. Zweigle Automatic Twist Tester D 302 and Semi-automatic Twist Tester D 314).

It is generally accepted that the twist in yarns of different counts (linear densities) is comparable when the twist factor (and helix angle) is constant, twist factor or multiplier being defined as follows:

1. Tex twist factor = turns/m √tex or alternatively (α_{tex}) = turns/cm √tex
2. Metric twist factor (α_m) = turns/m/√ N_m
3. Cotton count twist factor (α_e) = turns/inch/√N_e

where N_m = metric count and N_e = English cotton count.

Conversion from one unit (system) to the other can be done as follows:

$$\alpha_e = 0.033\ \alpha_m = 0.104\ \alpha_{tex}$$
$$\alpha_{tex} = 0.0316\ \alpha_m = 9.57\ \alpha_e$$
$$\alpha_m = 3.16\ \alpha_{tex} = 30.3\ \alpha_e$$

where α_{tex} = turns/cm $\sqrt{\text{tex}}$

Because of their different structure, notably the presence of wrapper fibres, which cannot be untwisted, rotor (open-end) yarn twist is difficult to measure accurately and specific test methods have been devised for this purpose. The single untwist-retwist method is often applied, giving an indication of yarn structure rather than of real twist *per se.*

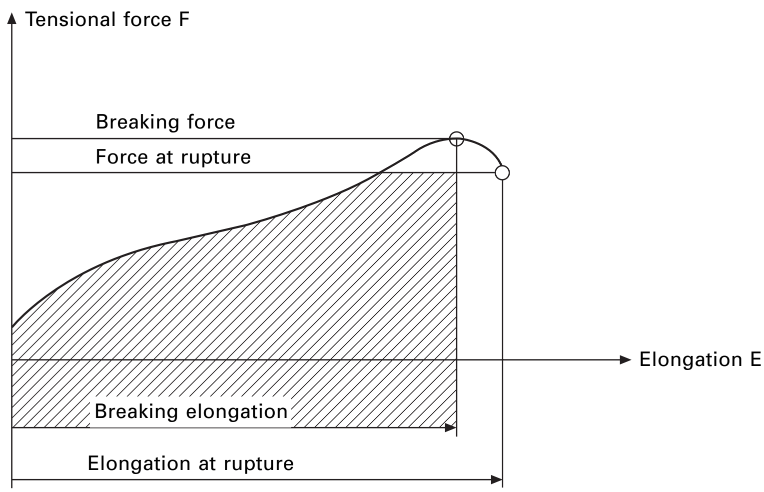
12.2.4 Twist liveliness (torque)

Another fairly important yarn quality parameter is its twist or torque liveliness (residual torque) since this can be reflected in the snarling potential of the yarn and in fabric properties, such as knitted fabric spirality (see ISO 3343). In the main, twist liveliness is related to the twist level and unbalanced twist, and heat setting of the yarn. A low or balanced twist (in the case of plied yarn) will produce a yarn with little, if any, inclination towards twist liveliness. Similarly, good heat setting can reduce, if not eliminate, twist liveliness, even in the case of highly unbalanced twist.

Twist liveliness can be measured by taking a metre of yarn and allowing it to twist around itself by suspending a light weight from the centre of the yarn and bringing the two ends together. Liveliness is then expressed in terms of the number of turns per metre that the yarn twists upon itself. Alternatively, the two ends of a 50 cm length of yarn are clamped under a certain tension and a light weight suspended from the centre of the segment, after which the one clamp is moved slowly towards the other and their distance apart recorded as soon as the yarn begins to snarl.

12.2.5 Tensile properties

The tensile properties of a yarn rank as one of its most important quality characteristics, since they largely determine the efficiency with which the yarn can be converted into fabric as well as the tensile properties of the final product. By tensile properties is normally meant the breaking strength and extension (elongation) at break of the yarn, including their distributions as well as the occurrence of weak places. A distinction can be made between the breaking force (breaking strength), the maximum force registered, and force at rupture, the force registered before the two yarn ends separate (see Fig. 12.2), similarly with elongation. Normally, breaking strength and breaking elongation are measured and reported. Sometimes the strength and extension are combined into a work-to-break (toughness), a measure of the ability of a yarn to do work or absorb energy, expressed in Newton metres or Joules. Actually it is the area under the force-elongation curve, up to the maximum force (Fig. 12.2). Other yarn parameters, such as Young's Modulus, or initial modulus, can also be determined.



12.2 Yarn tension force vs elongation (source: Uster Technologies).

The mean breaking strength is important since it gives an indication of overall yarn strength which will be reflected in the fabric strength and it also provides a measure, though not always a reliable one, of the strength of the weak places. Nevertheless, everyone is familiar with the saying ‘a chain breaks at its weakest link’, indicating that it is the weak places in a yarn and not the average yarn strength, which frequently determine a yarn’s performance, or breakage pattern, during winding, weaving and knitting. It is therefore important to obtain a measure of the isolated weak places in a yarn, in addition to the average strength, since the latter generally does not provide a sufficiently accurate measure of the isolated weak places.

There are a number of different tensile testers on the market, both manual and automatic, and they can broadly be divided into single thread and multi-thread (skein or hank) testers, with the former far more popular and providing a great deal more valuable information than the latter. The single-thread testers provide information on the average or mean strength as well as on the distribution of strength, whereas the multi-thread testers give a more composite picture of strength, with the values being affected by the weaker strands in the skein e.g. ASTM D1578 and BS 6372. The single-thread strength tests also provide values for the yarn extension at break which is very important since it provides a measure of the yarn brittleness, a property sometimes even more important than the breaking strength itself. Various standard test methods are available for testing yarn tensile properties, including BS 1932, DIN 53834, ASTM D2256, ASTM D1578.

Tensile testers can operate according to three different principles (see ASTM D76):

1. Constant rate of yarn extension (the most popular), where the yarn is extended at a constant rate, e.g., Uster® Tensorapid UTR 4, and Tensojet 4, Instron and Premier Tensomaxx 7000.
2. Constant rate of load, where the load on the yarn is increased at a constant rate.
3. Constant rate of traverse, which is a hybrid of the first two but is no longer all that common except in the case of pendulum type multi-thread testing instruments.

Because of the general variability of a staple fibre yarn, it is necessary to carry out a relatively large number of tests so as to obtain a reliable average or mean, about 100 tests per yarn sample generally being the absolute minimum, with 200 to 400 tests preferred, except where a reliable measure of the isolated weak places is also required in which case some 30,000 tests or more may be required, a high correlation being found between isolated weak places (e.g. strength of the P0.01 percentile value) and the number of weft breaks per 100,000 picks. The yarn is generally clamped under a pre-set tension and at a pre-determined gauge length, typically 50 cm. Tests can take place at a certain rate of extension, or at a certain average breaking time (e.g. 20 s) or at very high speeds (e.g. 400 m/min).

An example of a high-speed tensile tester is the Uster® Tensojet 4 (Fig. 12.3), testing at 30,000 breaks per hour (400 m/min), thereby providing an accurate measure of the isolated weak places which play an important role in determining weavability. It is important to remember that the different results obtained from the different types of testers can vary and even the results obtained on the same type of tester will vary, if, for example, the time to break or rate of strain is not kept constant. In general, the following parameters are used to provide an overall picture of the yarn tensile properties:

- mean breaking strength (e.g. cN or gf)
- breaking tenacity (e.g. cN/tex or gf/tex)
- CV of breaking strength (%)
- mean extension (elongation) at break (%)
- CV of extension (%)
- work-to-break (cN.cm or N.m)
- isolated weak places (for example, the percentage of breaks which have a strength and/or elongation below a certain threshold level, such as 4 cN/tex and 2%, respectively).
- skein strength is generally given as the count-strength-product (CSP) which represents the product of the force (e.g. pounds-force or kilograms-force) required to break the skein and the cotton count (Ne) or tex of the yarn.

12.3 Uster® Tensojet (source: Uster Technologies).

To allow the strength of yarns differing in linear density (or count) to be compared and also to provide more universal strength standards, the breaking strength of a yarn is often divided by its linear density (tex) to give what is termed 'tenacity' (e.g. cN/tex) and which is almost, but not entirely, independent of the actual yarn linear density. For quality control purposes, the tensile values obtained for a yarn can be compared with external standards (e.g. Uster® ISO) or internal (in-house) standards. Dynamic and integrated tensile testing, where the running yarn is subjected to a predetermined constant tension, provides a measure of yarn strength, elongation, isolated weak places, friction, abrasion, hairiness and evenness and lint (fly) generation under simulated manufacturing conditions, is also carried out.

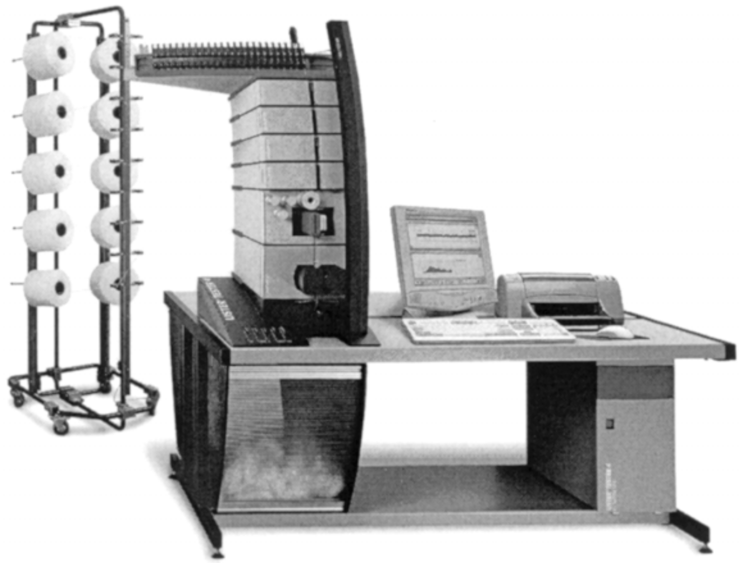
12.2.6 Evenness

Introduction

The terms yarn evenness, unevenness, regularity and irregularity are often used interchangeably and taken to refer to the same yarn characteristic, namely the uniformity or evenness of the yarn mass per unit length (linear density), measured capacitively (ASTM D1425), or of the yarn cross-sectional size or diameter, measured optically. This characteristic is important from two perspectives, namely from an aesthetic or appearance point of view and from a technical or functional (performance) point of view, since unevenness (i.e. thinner or thicker segments) in the yarn cross-section, is commonly associated with variations in the yarn strength and elongation. In practice, yarn evenness is most frequently measured using capacitance, as opposed to optical, techniques which means that it is assessed in terms of changes in segment mass (linear density) rather than in terms of cross-sectional volume (bulk) or diameter, assuming the dielectric properties (notably moisture and fibre blend) of the yarn are constant. Nevertheless, recent evenness testers enable both capacitance and optical measurements to take place simultaneously, sometimes as an option. Examples of modern yarn evenness testers include: Uster® Tester 4-SX (Fig. 12.4) Keisokki KET 80, III/B and Premier iQQU AL1 CENTER. Optical testers include the Zweigle Yarn Detector G 580 (using infra-red light) and the Keisokki Laserspot III Hairiness and Evenness (Diameter) Testing instrument which functions on the principle of Fresnel diffraction of a laser beam.

According to Basu,[3] research has shown that some 42% of the total yarn irregularity is due to the raw material, some 40% due to the condition of the ringframe and 18% due to the roving irregularity. The irregularity (unevenness) added by each processing stage in the yarn manufacturing process is additive, as follows:

$$CV_R = \sqrt{CV_1^2 + CV_2^2} \qquad 12.2$$



12.4 Uster® Tester 4 (source: Uster Technologies).

where CV_R is the resultant irregularity, say of the yarn; CV_1 is the irregularity of the input material (the roving); CV_2 is the irregularity added by the spinning process (ring frame).

Drafting waves introduced into the yarn during spinning have a wavelength of approximately 2.8 times the staple length; while those in the yarn introduced during the roving process will have a wavelength 3.2 × the draft × the staple length. Greater random irregularity or drafting waves in the yarn produce 'cloudiness' in the fabric, as opposed to the patterned (regular) or moiré effect produced by regularly occurring (periodic) irregularity or faults.

In keeping with the conventional approach, the overall yarn evenness characteristics will be grouped and discussed under three headings, namely unevenness (irregularity), imperfections (relatively small and frequent thin and thick places and neps) and faults (grosser and less frequent faults, such as slubs, fly and very long or extreme thin and thick places). For more in-depth treatment of yarn irregularity the reader is referred to various publications.[4]

Unevenness

Enormous strides have been made in the measurement of yarn evenness, both in terms of the speed and the detail of the measurement. Modern evenness testers, which incorporate both capacitance and optical measurement techniques, enable the following yarn properties to be accurately measured, or derived, within one minute:

- mass unevenness (short term (1 to 10 times fibre length)[3], medium term (10 to 100 times fibre length)[3] and long term (more than 100 times fibre length)[3], also spectrograms and variance length curves)
- imperfections (thin and thick places and neps)
- hairiness
- count (linear density), relative and absolute
- diameter
- density
- surface structure
- trash
- dust.

It is also possible to diagnose periodic faults by means of gearing diagrams and ratios, using a database contained in the software of the tester. Furthermore, the appearance of the yarn and its faults, as it would appear on a taper board or in a woven or knitted fabric, may be simulated and evaluated on a screen, and agreed upon quality properties can also be displayed in the form of a pie chart for easy assessment of 'off-quality' properties.

Yarn unevenness (mass unevenness) can be numerically expressed in terms of either the coefficient of variation (CV_m in %) or linear irregularity (U_m in %), commonly measured with an effective 'cut' or measurement length of 8 mm. CV_m (in %) is more commonly reported, being shortened to CV (%).

$$CV(\%) = \frac{s}{\bar{x}} \times 100 \qquad 12.3$$

where s = standard deviation $\bar{x}$; $\bar{x}$ = mean (or average).

For continuous measurement: $CV(\%) = \frac{100}{\bar{x}} \sqrt{1/L} \int_0^L (x_I - \bar{x})^2 \, dl$

$$U(\%) = \frac{100}{\bar{x} L} \int_0^L |x_i - \bar{x}| dl \qquad 12.4$$

dl = an elemental length of material and L is the total length of yarn measured. For completely random variation $CV_m = 1.25\ U_m$

The values obtained can then be compared with the appropriate specifications or standard values (e.g. Uster Statistics at www.cogetex.ch/Services/Sujets/TechSpecs. html).

The limiting (or ideal) irregularity CV_{lim}, of a cotton yarn, derived from Martindale's[5] general equation, in which a completely random arrangement of fibres is assumed, may be calculated as follows:

$$CV_{lim}(\%) = 106/\sqrt{n} \qquad 12.5$$

(although sometimes $CV_{lim}(\%) = 100/\sqrt{n}$ is also used)

$$= 106\sqrt{\frac{F}{\text{tex} \times 1000}} \quad 12.6$$

where F = fibre fineness (in mtex); tex = yarn linear density in mg/m (i.e. tex units); n is the average number of fibres in the yarn cross-section = tex × 1000/F.

From this, the irregularity index I, a measure of the effectiveness with which the spinner has converted the available fibre into a yarn, can be calculated as follows:

$$I = CV_{actual}/CV_{lim} \quad 12.7$$

CV_{actual} being the actual (or measured) irregularity.

Imperfections

Imperfections (i.e. thin and thick places and neps) affect the appearance of the yarn and that of the subsequent fabric, while thin places, generally of higher twist (because of twist running into it), could also represent weak places in the yarn. Imperfections can be measured at different threshold levels, for example:

- Thin places: –30%, –40% and –50% i.e. either 30%, 40% and 50% below the average yarn linear density, or cross-section, more typically – 50% for both ring-spun and rotor-spun yarns.
- Thick places: 35%, 50%, 75% and a 100%, greater than the average yarn linear density, more typically 50% for ring-spun and rotor-spun yarns. These thin and thick places are generally equal in length to the mean fibre length.
- Neps: 140%, 200%, 280% and 400% greater than the average yarn linear density, calculated on the basis of a 1 mm segment length, the maximum length being limited to 4 mm, typically being 200% for ring-spun yarns and 280% for rotor-spun yarns. The neps could be due to the raw material (e.g. immature fibres or vegetable matter) or to processing (e.g. during ginning and carding). It is also possible to optically classify neps as 'process neps' or 'seed coat neps' (trash type).

The frequency of imperfections is normally expressed as the number per 1,000 m. If the number is above 30, the frequency generally follows the normal distribution, while if it is below 30 it follows a Poisson distribution.

Faults

Yarn faults, such as thick places and slubs, are generally due to poor drafting (e.g. a bundle of short fibres not being drafted and travelling into the yarn as a cluster or clump of fibres) or fly being caught in the fibrous strand. In addition to causing a fabric blemish or fault, the more severe yarn thick places and slubs can also cause yarn breakages during fabric manufacturing, either because they generally contain a relatively low twist and are therefore intrinsically weak or if they get caught in yarn guides, e.g., heald eyes, knitting needles and sinkers, etc. It is therefore important in practice to monitor and control yarn faults.

As already mentioned, yarn faults are generally more serious than yarn imperfections, and consist of thick places, slubs and thin places. Whereas imperfections are generally expressed as the number per 1000 metres, the grosser faults as such are expressed per 100,000 m because of their relatively low frequency. The more serious types of yarn faults, termed objectionable faults, generally lead to a fabric defect (or fault) and therefore should be removed by clearing during winding. Very thin places could also lead to either a yarn break during winding or fabric manufacturing or to a thin place (line) in the fabric and should preferably also be removed during clearing. It is commonly stated, however, that a very faulty yarn cannot be transformed into a good quality yarn merely by clearing, as the clearing of excessive faults in the yarn will adversely affect winding efficiency and economics and could produce a yarn with an excessive number of knots or splices which themselves may lead to problems during fabric manufacturing and in the fabric itself. Yarn faults are generally classified according to both their length and cross-section.

As in the case of yarn irregularity and imperfections, yarn faults can be measured and cleared using either optical or capacitance systems. Both are used, although the capacitance systems, such as the Uster® Classimat Quantum, Premier Class *i* and Keisokki Classifault CFT are the most popular. Certain systems, such as the Uster® Classimat Quantum (combining capacitance and optical sensors), also enable foreign fibre classification and measurement of vegetable matter content as well as the simulation of the effects of faults in the yarn and fabric and the determination of yarn count. On-line monitoring and classifying of yarn faults and count deviations on rotor-spining machines is also provided using systems such as Corolab XQ (www.saurer.de).

12.2.7 Diameter

Various instruments optically measure the yarn diameter and its variation, including imperfections and faults (see also previous sections). For example, the two-dimensional optical diameter of yarns is measured on evenness testers, such as the Uster® Tester 4-SX fitted with digital-analog opto-electronic sensors (infra-red) together with a high-resolution line scan camera. Optical yarn diameter unevenness can also be measured, the results not being influenced by the colour of the yarn; the effective measuring (field) length, for example, being 0.3 mm. The results can provide much the same information and can be analysed in much the same way as that for capacitance based yarn mass results.

The shape (roundness) of the yarn can also be determined. From the yarn count and cross-sectional area, the yarn density can be calculated, density depending upon the yarn type and twist. For example, the density of a combed ring-spun yarn is of the order of 0.5 g/cm^3, that of a carded ring-spun yarn of the order of 0.8 g/cm^3 and that of a rotor-spun carded yarn of the order of 0.4 g/cm^3. Yarn diameter can also be monitored on-line during winding. The Zweigle Yarn Detector G580 uses an opto-electronic (infra-red) principle to measure the yarn diameter and its variation, including imperfections and moiré. The Lawson-Hemphill Yarn Analysis Software (YAS) system also measures the yarn diameter, imperfections and faults optically, using a camera (CCD array).

12.2.8 Hairiness

Hairiness normally refers to fibre ends, fibre loops and fibres of varying length (wild fibres) protruding from the surface (or body) of the yarn, frequently as fibre tails. Although hairiness is desirable in certain types of fabrics, notably soft knitteds, brushed fabrics and flannels, it is undesirable in other fabrics, such as shirting. Yarn hairiness affects the fabric surface appearance and properties, including fabric pilling, handle and comfort (thermal insulation). Yarn hairiness also plays an important role in weavability, since the protruding hairs tend to catch on adjacent yarns causing yarn breakages and loom stoppages. It is particularly important in air-jet weaving. In fact, one of the main objectives of sizing is to smooth down the hairs on the yarn, i.e., to reduce yarn hairiness, thereby improving yarn weaving performance. Yarn hairiness positively affects the heat and wear generated when the yarn runs over metal or other surfaces, such as travellers and yarn guides. Variations in yarn hairiness can be particularly problematic, being reflected in variations in fabric surface appearance, and can cause fabric barré and streakiness, it therefore being important that yarn hairiness remains acceptably constant within a certain application and yarn consignment. It is now possible to measure yarn hairiness on-line, for example, on programmable yarn clearers, such as the Uster® Quantum, Yarn Hairiness Grades helping to visualise various levels of hairiness, e.g., (www.Uster.com).

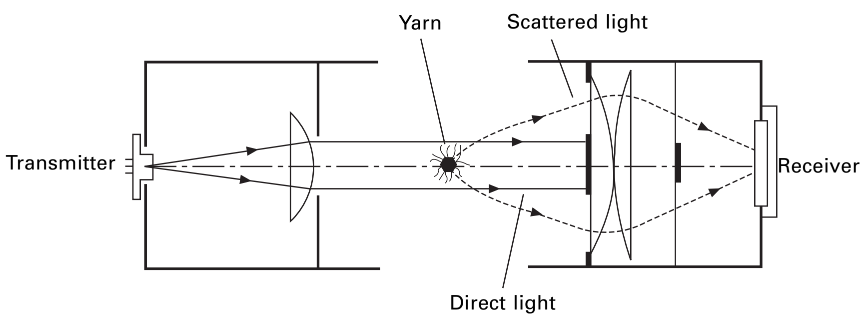
Many different hairiness measuring instruments and test methods (e.g. ASTM D5647), as well as measures of hairiness are used, including a module on the Uster® Tester 4, Shirley Yarn Hairiness Tester and Zweigle G 566 and G 567 Hairiness Tester. In some cases, the number of hairs protruding beyond a certain distance (e.g. 3 mm) from the yarn surface or axis, are measured, while in other cases the overall hairiness of the yarn is measured and expressed as a hairiness index. In the case of the Uster® Tester 4-SX (Fig. 12.5), hairiness is measured over approximately 1 cm lengths of yarn at the same time as the yarn evenness is measured and the results expressed in terms of the hairiness, H, representing the total length of yarn protruding from the yarn surface, for example, a value of 6 for H indicates that the total length of protruding hairs is 6 cm over the distance of 1 cm. Yarn hairiness diagrams, spectrograms, etc., can also be provided, as well as the variation in yarn hairiness, expressed as the standard deviation, sh, or coefficient of variation $CV_H = sh/H \times 100$. The standard deviation, sh, is more commonly used. Barella and co-workers have produced a number of reviews on yarn hairiness.[6]

12.2.9 Yarn appearance

Traditionally, a yarn appearance and grade allocation have been subjectively assigned to yarn wrapped on an inspection or tapered board (blackboard), a number being assigned according to, for example, ASTM standard D-2255, but today this can be done either electronically or by simulation. Electronic grading and simulation systems enable the yarn blackboard or fabric appearance to be simulated using systems such as the Loepfe MillMaster Visual System, Zweigle OASYS® Optical Sensing Unit, YAS Yarn Analysis System of Lawson-Hemphill and Premier CYROS with the appropriate software (see also in section 12.2.6.).

12.2.10 Linting and fly

An important yarn quality parameter is its linting or fly generating propensity during winding, knitting and weaving. If a yarn sheds a great deal of lint and fly, it will contaminate the surrounding atmosphere, creating a health hazard, as well as building up on machine parts, guides, etc., possibly leading to machine damage, stoppages, yarn breakages and the need for frequent cleaning.



12.5 Yarn hairiness measurement (source: Uster Technologies).

Accelerated wear on certain machine components can also result. In addition to this, fly can get caught up in the fabric, forming a blemish which resembles a nep. Fly is generally due to excessive short fibres and possibly weak or damaged fibres in the yarn and to the yarn structure.

An example of an instrument on the market for measuring fly or linting potential is the Zweigle Staff Tester G 556. This instrument also provides a measure of the nepping potential of the yarn, i.e., the tendency for the yarn to form neps (fibre bundles or clusters) when it is abraded during knitting and weaving, since this could be reflected in knitting and weaving performance and the appearance of the fabric. Basically, the yarn is drawn over a knife edge and over itself (it is twisted with itself), and the amount of fly shed over a certain test length is then determined by catching and weighing the fly. Simultaneously, the number of neps is determined as the yarn enters the test zone and as it leaves again, the difference providing a measure of the nepping propensity of the yarn. Fly or linting potential is expressed as a percentage based upon the mass of yarn tested, while nepping potential is expressed as the number of neps per unit length.

12.2.11 Yarn abrasion

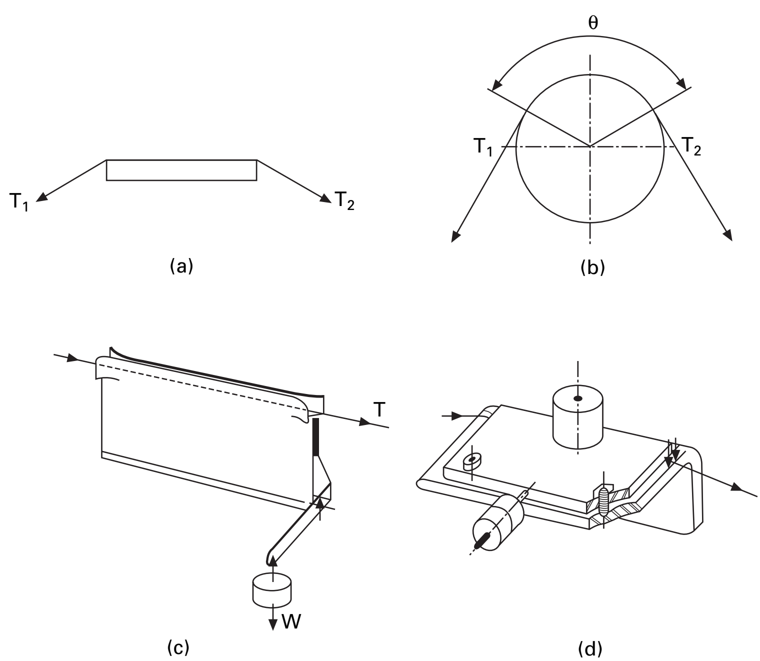
Although yarn abrasion resistance is an important property, particularly from the view of weavability, it is not all that commonly measured, mainly because it is not easy to measure this parameter accurately under conditions which simulate those which the yarn will experience during weaving. Another consideration is that if the yarn is to be sized then it is really the abrasion resistance of the sized yarn which needs to be measured as this would be quite different from that of the unsized yarn, being greatly affected by the type, level and levelness of the size applied. Examples of yarn abrasion testers are on the market, include the Zweigle Staff Tester G 556 and G 552 Abrasion Tester and Reutlingen Weaving Tester G 545, the latter working on the principle that a tensioned yarn web is cyclically abraded and flexed over rods, with the number of cycles required to cause one or more yarns to break or a certain change in the yarn appearance (or neppiness) being noted and used as a measure of the ability of the yarn to withstand abrasion.

12.2.12 Friction

The friction of cotton yarns is mainly important when it comes to machine knitting, particularly when knitting relatively fine yarns on high-speed knitting machines. By and large, two types of yarn friction, or a combination thereof, are measured, namely yarn-to-metal (or occasionally yarn-to-ceramic friction) and yarn-to-yarn (ASTM D3412), since these represent the types of friction mostly encountered in practice. The yarn friction determines the frictional forces and tension developed by the yarn as, for example, it slides over yarn guides, tensioning devices, knitting needles and sinkers, the yarn itself, or other yarns. If the yarn friction is excessive, the tension generated in the yarn could exceed its breaking strength, thereby causing yarn breakages, for example, during winding or knitting. The most effective, and widely used, means for reducing friction is to apply a lubricant, for example, using a solid paraffin wax disc, to the yarn as it is wound onto the package, during winding or during rotor-spinning. Sometimes a lubricant (or softener) is applied to the dye-bath, subsequent to package dyeing, while in some cases an emulsion lubricant is applied during winding, for example, by means of a lick-roller.

Various commercial friction testers and test methods (e.g. ASTM D3108) are available, most of these measuring the tension generated in the yarn as it passes over a cylindrical or flat metal surface, or itself, the yarn-to-metal coefficient of friction (μ) can be estimated by measuring the yarn tension (T_1) prior to the surface and that (T_2) after the surface (Fig. 12.6) using the following classical capstan equation:

$$T_2/T_1 = e^{\mu\Theta} \text{ and } T_2 = T_1 e^{\mu\Theta} \qquad 12.8$$



12.6 Diagrams showing methods of applying tension to yarns: (a) flat plate; (b) capstan; (c) and (d) twin flat plate system (source: P.J. Kruger, *Text. Month*, Feb. 1970).

where Θ = total angle of contact (in radians) between the yarn and the cylinder and e = the base (2.718) of natural (napierian) logarithms. For a gate (flat) type of frictional surface, the relevant equation is:

$$T_2 = T_1 + 2\mu N \qquad 12.9$$

where N is the normal force (pressure) applied to the yarn.

Ideally the coefficient of friction of cotton yarns destined for knitting should be 0.15 (or lower), although the actual value depends to some extent upon the conditions under which it is measured. Examples of commercial friction testers include the Lawson-Hemphill (hand-held, with statistics), Schlafhorst Friction Tester Textechno H. Stein, Zweigle μ-Meter G 532 I, Rothschild F-Meter R-2088 and SAWTRI Yarn Friction Meter (WIRA).

12.2.13 Miscellaneous yarn tests

- Wrapper fibres on rotor-spun yarns (e.g. GAG Yarn Analyser, Engineering College of Aachen).
- Yarn Bulk, e.g., WRONZ Yarn Bulkometer (WIRA).
- Yarn Shrinkage e.g., ASTM D2259-02 and/or AS2001-5-6 'Determination of Dimensional Change of Yarn and Sewing Thread'.

12.3 Fabric testing

12.3.1 Introduction

Fabric properties are determined by the fibre content, yarn and fabric construction and any chemical and mechanical treatment applied to the yarn or fabric.[7] These need to be assessed within the context of the requirements of the specific end-use for which the fabric is destined, within the broad categories of clothing (apparel) textiles, home textiles and industrial (technical) textiles. With respect to clothing, aspects relating to the fabric aesthetics or appearance generally dominate (Table 12.1),[8] while in the case of industrial textiles, technical and performance related properties predominate. Table 12.2 illustrates the diversity of requirements for different applications.[9]

Consumer studies[10] have shown that the main requirement for clothing are ease-of-care performance, elegance (aesthetics) and durability (i.e. acceptable or reasonable wear life). The performance and appeal, or perceived 'quality', of fabrics destined for apparel depend upon a number of mechanical and physical properties, such as handle, resistance to abrasion and pilling, drape, crease recovery, dimensional stability and comfort, the importance of which depends upon the intended end-use and the customer's expectations as well as in the case of apparel, on the customer's wear conditions and garment fit. Wear is the consequence of a number of factors which reduce the

Table 12.1 Fabric properties that are related to tailoring performance, appearance in wear, and handle[8]

Property	Test	Tailoring performance	Wear appearance	Handle
Physical	Thickness	–	–	+
	Mass per unit area	+	+	+
Dimensional	Relaxation	+	+	–
	Shrinkage			
	Hygral expansion	+	+	–
Mechanical	Extensibility	+	+	+
	Bending properties	+	+	+
	Shear properties	+	+	+
Surface	Compression properties	–	–	+
	Friction	–	–	+
	Surface irregularity	–	–	+
Optical	Lustre	–	+	–
Thermal	Conductivity	–	–	+
Performance	Pilling	–	+	–
	Wrinkling	–	+	–
	Surface abrasion	–	+	–

+ Important; – less important.
Source: De Boos, 1997.[8]

serviceability and acceptability of a product, including abrasion, tearing, bending, stretching, rubbing (abrasion), laundering and cleaning (see ASTM D3181).

In practice, mechanical damage or breakdown is generally much more important than chemical damage (including that due to laundering and light) in determining wear life. Generally, the inclusion of one or more laundering cycles together with abrasion and pilling tests improve actual wear prediction, it being important that the tests subject the fabric to relative low and random abrasive forces. Kothari[12] divided fabric properties into six different groups as shown in Table 12.3. Table 12.4[12] provides a more specific example for a shirt.

12.3.2 Wrinkle and crease-recovery

The tendency for a fabric or garment to wrinkle or crease (ASTM D-123) when subjected to sharp folds (bends, creases or wrinkles) under pressure (load) during wear or laundering, is very important from an appearance point of view, also having a bearing on 'ease-of-care' related properties (durable press, easy-care, minimum-iron, etc.) In effect, it is not so much the ability of the fabric to withstand creasing or wrinkling that is important, but its ability to regain its original shape and smooth appearance, from such creases

Table 12.2 Some examples of special parameters for different end-uses of fabrics/garments[9]

Item	Special requirements
Garments for Australia	Improved light fastness, UV protection
Swimwear/beachwear	Chlorinated water/seawater fastness, colourfastness to light.
Towels and napkins	Absorbency.
Surgical gowns/apparel	Anti-bacterial properties, colourfastness to autoclaving, absorbency.
Woollen merchandise	Moth proofing.
Fire-fighters apparel	Flame proofing.
Defence textiles	Rot proofing.
(Tents/Canvas, etc.)	Protective textiles.
Parachute cloth	Air permeability.
Soil-resistant products	Soil-releasing fluorocarbon treatment.
Oil industry applications	Oil-repellent finishes.
Household curtains & drapery	Tensile strength, colourfastness to light, flammability.
Bathmats/table mats	Colourfastness: migration into PVC.
Upholstery	Abrasion resistance.
Industrial uniforms	Strength, oil/soil repellency, flammability.
Sportswear	Abrasion resistance, seam strength & colourfastness to perspiration.
Baby/children's wear	Colourfastness to saliva.
Nightwear	Flammability.
Rainwear	Water repellency, breathability.
Garments for arctic conditions	Ability to withstand extreme cold: flexing/strength at low temperatures.

and wrinkles, i.e., its wrinkle recovery or crease recovery that is important. Therefore, in testing a fabric for this important property, wrinkles or creases, more popularly the latter, are inserted into a fabric specimen under carefully controlled conditions of pressure and fold sharpness, the wrinkle recovery or crease recovery being measured after the load has been removed and the fabric allowed a certain period to recover.

Wrinkle and crease recovery is particularly important for cotton, since untreated cotton is notoriously poor in this respect and considerable research and development work over many decades has been directed towards developing chemical treatments that improve this property without an unacceptable loss in other desirable properties, such as softness, comfort and durability. There are various test methods for measuring fabric wrinkle and crease recovery,[13] it being possible to divide these into two broad categories, namely those which involve the insertion of a single sharp crease and those which insert a family of largely random creases or wrinkles in the fabric. In both cases, the conditions of deformation, i.e., of wrinkle and crease insertion, as well as the conditions of recovery, are critically important and need to be

Table 12.3 Classification of different properties[11]

Woven fabrics	Knitted fabrics	Nonwoven fabrics
1. Structural Properties • Warp and weft linear densities • Warp and weft twist levels • Warp and weft thread densities (number per unit length) • Warp and weft crimp levels • Cover factor • Mass per unit area • Fabric thickness • Fabric skew and bow	• Structure • Yarn linear density • Yarn twist • Courses and wales per unit length • Cover factor • Mass per unit area • Fabric thickness • Spirality	• Fibre orientation in web and bonding method • Fibre fineness • Fibre length • Fibre crimp • Mass per unit area and uniformity • Fabric thickness or bulk density
2. Mechanical properties[a] • Tensile strength • Tear strength • Bursting strength • Abrasion strength • Pilling resistance • Snag resistance • Fatigue (tension, bending and shear)	3. Comfort-related transmission properties[b] • Air permeability • Water vapour permeability • Resistance to penetration of liquid water • Resistance to flow of heat • Electrical conductivity	
4. Low stress mechanical properties[c] • Tensile properties • Compressional properties • Bending properties • Shear properties • Buckling behaviour • Roughness and frictional properties	5. Aesthetic properties • Drape • Crease recovery • Wrinkle recovery	6. Other physical properties and end-use specific tests • Dimensional stability • Flammability • Impact tests • Absorbency • Delamination

a. Related to utility performance and durability.
b. To flow of fluids, heat and electricity.
c. Related to handle and tailorability.

carefully controlled and consistent. Very important, too, are the atmospheric conditions, relative humidity in particular, and the fibre moisture content during both creasing and recovery.

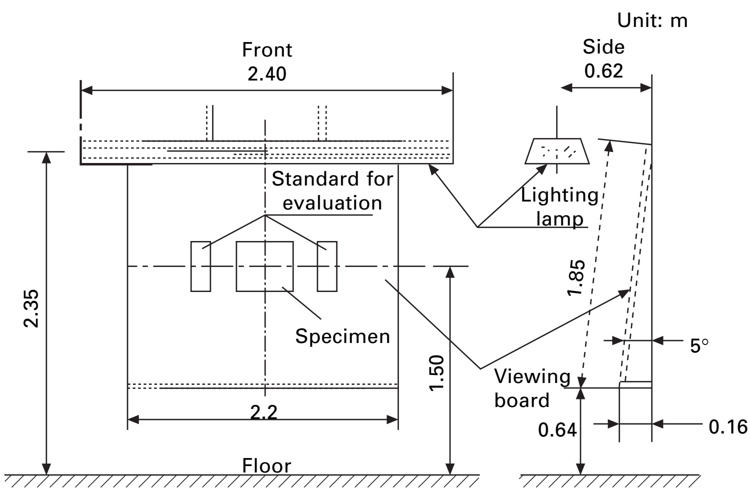
A popular method used by industry to assess the fabric wrinkle recovery is AATCC Test Method 128 ‘Wrinkle Recovery of Fabrics: Appearance Method’ in which wrinkles are induced in the fabric under standard atmospheric

Table 12.4 The utility-value analysis graphics[12]

1st-level objective: long use of the shirt without losing its properties		
2nd level objectives:		
1. Fabric quality	2. Sewing quality 3rd-level objectives:	3. Usage quality
1.1 The fabric should not wrinkle easily	2.1 The seams should not open out	3.1 The colours should not fade after washing
1.2 It should not pill	2.2 The seams should not come off	3.2 The colours should not change in dry cleaning
1.3 It should absorb sweat		3.3 The colours should not change in the light
1.4 It should resist stretching		3.4 The colour purity should be good
1.5 It should not wear out easily		3.5 The size should not change after washing
		3.6 The colours should not pale after ironing
		3.7 The colours should not change by rubbing and should not dye other materials
	Criteria	3.8 The cloth should not include toxic materials
Wrinkling angle (ISO 9867)	2.1.1 Seam slippage (BS 3320)	3.1.1 Colour fastness to washing (ISO 105 C06)
1.2.1 Pilling (ISO BS 5811–1986)	2.2.1 Seam strength (BS 3320)	3.2.1 Colour fastness to dry cleaning (ISO D01)
1.3.1 Water penetration (ISO 811–1992)		3.3.1 Light fastness (ISO 105 B02)
Tearing strength (BS 4304–1986)		3.4.1 Dimensional stability to washing (DIN 53920)
1.5.1 Abrasion resistance		3.5.1 Colour fastness to ironing (ISO 105 B01)
1.5.2 (BS 5690)		3.6.1 Colour fastness to perspiration (ISO 105 EO4)
		3.7.1 Colour fastness to rubbing (ISO 105 $\times$ 12)
		3.8.1 Aromatic amine test (MAK Amin IIIA-1.2)

conditions using a standard wrinkling device under a predetermined load for a prescribed period of time. The specimen is then reconditioned and rated for appearance by comparing it with three-dimensional reference standards (AATCC Wrinkle Recovery Replica). The viewing conditions are illustrated in Fig. 12.7. The same method has been adopted by the International Organisation of Standardisation (ISO 9867) and Japanese Industry. Nevertheless, this suffers from the disadvantage that it is subjective and that fabric colour and pattern have a significant effect on the perception of wrinkles. Considerable research has led to the development of objective assessment techniques. Xiaobo *et al.*[14] for example, reported on a new method based upon computer vision (photometric stereo technology combined with ANFIS adaptive neural fuzzy inference systems) for evaluating the fabric wrinkle grade objectively. Fan *et al.*[15] have discussed various objective methods of measuring and characterising wrinkle recovery, including stylus (contact), laser scanning and image analysis.

In the case of crease recovery testing (using, for example, a Shirley Crease Recovery Tester) the fabric specimen (either wet or dry) is creased and compressed under a specified load and atmospheric conditions for a predetermined period (e.g. 5 min) after which the load is removed and the specimen allowed to recover, once again under specified conditions and time (e.g. 5 min), and the recovery angle (crease recovery angle) measured. Test methods include AATCC 66, BS EN 22313, ISO 2313. This test is frequently used to assess durable-press and easy-care related properties of treated cotton fabrics.



12.7 Lighting equipment for viewing test specimens (source JISL 1905: 2000).

12.3.3 Surface smoothness after repeated laundering

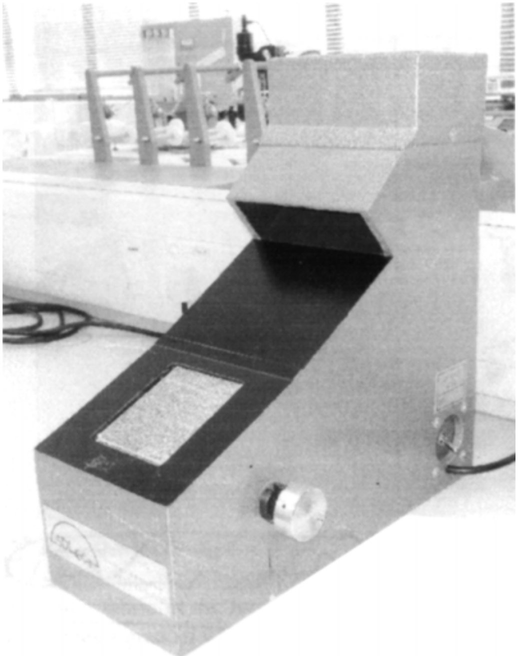
AATCC Test Method 124 (ISO 7768) is designed for evaluating the appearance, in terms of smoothness, of flat fabric specimens after repeated home laundering, this providing a measure of the durable-press and easy-care, or minimum-iron properties of the fabric. The test procedure and evaluation method are almost the same as in the two methods mentioned above, except for the difference in specimen preparation and standard replicas. The Fabric Appearance Evaluator (Fabric Eye) of the Institute of Textiles and Clothing, Hong Kong Polytechnic University can be used to obtain an objective 3-D measure of the surface smoothness of the fabric.

12.3.4 Pilling propensity[15]

The appearance and aesthetic quality of clothing as well as of upholstery are influenced by the fabric propensity to surface fuzzing and pilling. Pills (ASTM D-123), tightly entangled clusters or balls of fibres attached to the fabric by means of one or more fibres, are developed on a fabric surface in four main stages; fuzz formation, entanglement, growth and wear-off.[16] It begins with the migration of fibres to the outside yarn surface causing fuzz to emerge on the fabric surface. Due to friction, this fuzz becomes entangled, thus forming pills which remain attached to the fabric by long fibres.

The pilling resistance of fabrics is normally tested by simulated wear through tumbling, brushing or rubbing on a laboratory testing machine. The specimens are then visually assessed by comparison with visual standards (either actual fabrics or photographs) to determine the degree of pilling on a scale ranging from five (no pilling) to one (very severe pilling). Figure 12.8 shows a viewing device for pilling assessment. The observers are guided to assess the pilling appearance of a tested specimen on the basis of a combined impression of the density and size of pills and degree of colour contrast around the pilled areas.

Several test methods (ASTM, ISO, BS and JIS) have been established for assessment of pilling propensity. They differ in the way the specimens are treated to simulate wear conditions and create a 'pilled' appearance. In BS EN ISO 12945-1 and BS 5811, specimens are mounted on polyurethane tubes and tumbled randomly, under defined conditions, in a cork-lined box, such as the ICI pilling box (see Fig. 12.9) for an agreed period of time (say five hours). In ASTM D 4970 and ISO 12945-2[14] pilling formation during wear is simulated on the Martindale Tester. The face of the test specimen is rubbed, under a light pressure, for a specific number of movements, against the face of the same mounted fabric in the form of a geometric figure. Figure 12.10 shows a Martindale Tester. In ASTM D 3511 (Brush Pilling Tester), and D3512 and D 3514, and DIN 53867 and JIS L 1076 pilling and other



12.8 Viewing device for pilling assessment.

12.9 ICI Pilling Box Tester.

changes in surface appearance which occur in normal wear, are simulated by brushing the specimens to free fibre ends, by random rubbing action produced by tumbling specimens in a cylindrical test chamber lined with mildly abrasive materials (e.g. cork liners), and by controlled rubbing against an elastomeric

12.10 Martindale Tester.

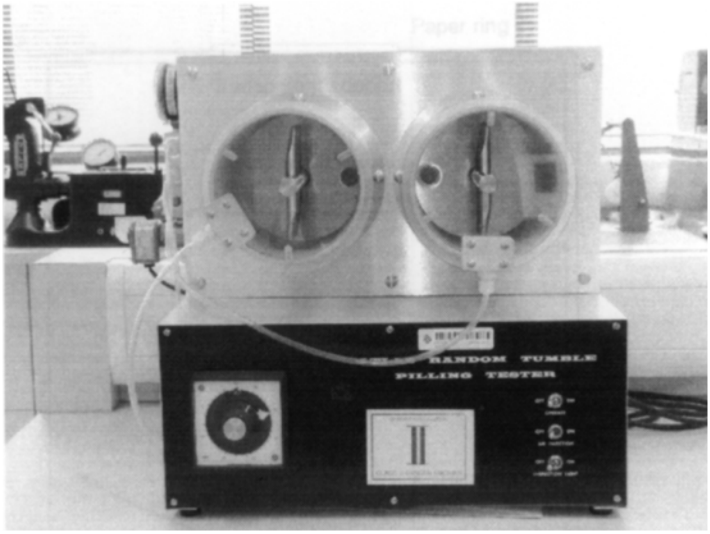
pad having specifically selected mechanical selected properties, respectively. Figure 12.11 shows a Random Tumble Pilling Tester (ASTM D3512). The Japanese standard JIS L 1076 covers six types of testers, similar to those in the ISO, BS and ASTM standards.

The kind of pilling tester used has significant effect on the test results, the most suitable tester depending upon the type of fabric (e.g. knitted or woven) and on the anticipated wear conditions. The chosen tester for the performance evaluation should best simulate the actual wear condition. Cooke and Goksoy[17] compared the results of various pilling testers. Goktepe[18] investigated the pilling performance of fabrics in the wet state. He found that use of the Martindale tester resulted in worse pilling grades than the other two testers, and different pilling testers have different sensitivities for various fibre, yarn and fabric parameters.

The subject of fabric pilling has been reviewed by Ukponmwan,[19,20] while Fan *et al.*[15] have discussed various objective methods of measuring pilling. Chen and Huang[21] reported on an objective method of assessing pilling, based upon optical projection and image analysis, which, it is claimed, eliminates the effects of fabric colour and pattern. Automated three-dimensional grading of pilling (pill density and size distribution), fuzziness and other surface properties are possible using systems, such as the SDL Atlas Pill Grade.

12.3.5 Fabric stiffness

Fabric bending stiffness is very important in terms of drape, making-up performance and comfort, and many testers and test methods are available for measuring fabric stiffness, including the Shirley Fabric Stiffness Tester.



12.11 Random Tumble Pilling Tester.

This stiffness tester is based upon the cantilever principle, with the fabric specimen being slid slowly over the edge of a platform until the front edge reaches a certain angle (45°), after which the length of the projecting specimen is read off from the sliding ruler, and used to calculate the bending length, flexural rigidity and bending modulus of the fabric (ASTM D1388, BS 3356, DIN 53362). The fabric stiffness measurement also forms an important component of composite/integrated tests, such as Kawabata and FAST (CSIRO's Fabric Assurance by Simple Testing) systems.

12.3.6 Drape[15]

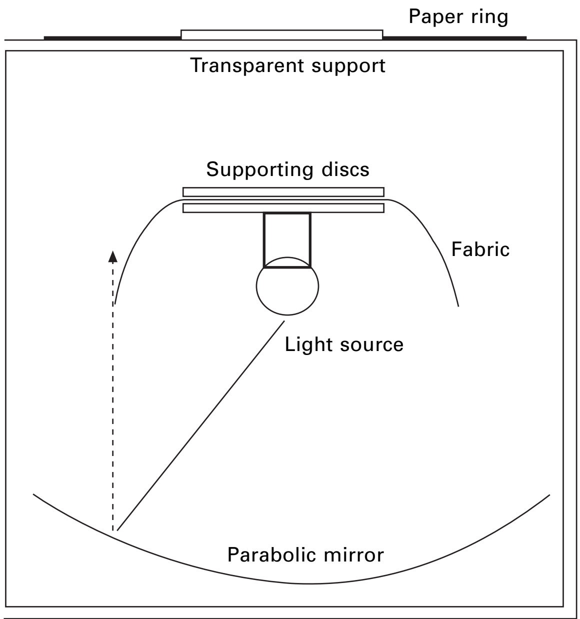
Drape is one of the most important apparel fabric properties, affecting garment appearance, beauty, fit and comfort. It is also important for home textiles, notably drapes and upholstery. The outstanding property of a textile fabric, which distinguishes it from other materials, such as paper or steel, is its ability to undergo large, recoverable draping deformation by buckling gracefully into rounded folds of single and double curvature.[22] According to the *Textile Terms and Definitions* of the Textile Institute,[23] drape is defined as 'The ability of a fabric to hang limply in graceful folds, e.g., the sinusoidal-type folds of a curtain or skirt'. It refers to the fabric shape as it hangs under its own weight. Cusick[24] defined the drape of a fabric as 'a deformation of the fabric produced by gravity when only part of the fabric is directly supported'. Drape appearance depends not only on the way the fabric hangs in folds, etc., but also upon the visual effects of light, shade and fabric lustre at the rounded folds of the fabric as well as on the visual effects of folding on colour, design and surface decoration.[25] A fabric is said to have good draping qualities when it adjusts into folds or pleats under the action of gravity in a manner which is graceful and pleasing to the eye,[26] the actual assessment greatly depending upon such factors as fashion, personal preference, human perception, etc.

Drape is a complex combination of fabric mechanical and optical properties and of subjectively and objectively assessed properties. Furthermore, there is frequently an element of movement, for example, the swirling movement of a skirt or dress, and therefore dynamic, as opposed to static, properties are also involved. In recent years, therefore, a distinction has been made between static and dynamic drape.

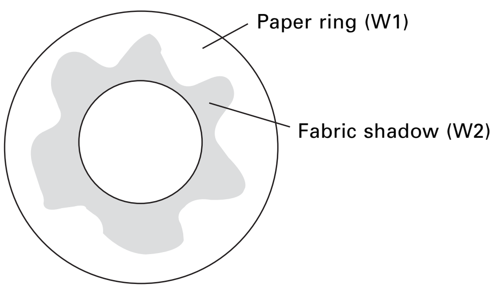
Although drape is usually assessed subjectively, considerable research has been carried out with the view to its objective measurement, and to relate the drape so measured to objectively measure fabric mechanical properties, notably bending and shear stiffness. The most widely adopted method is to allow a circular disc of fabric to drape into folds around the edges of a smaller circular platform or template. Such instruments are commonly referred to as 'drapemeters'.

Cusick[24,27] developed what has become known as Cusick's drapemeter (Fig. 12.12)[28] which has become the standard method of measuring drape coefficient. It uses a parallel light source which causes the shape of the draped fabric to be projected onto a circular paper disc. The drape of a fabric is popularly defined as the area of the flat annular ring covered by the vertical projection of the draped fabric expressed as a percentage of the arc of the flat annular ring of fabric, this being termed the drape coefficient.[24] In practice, the contour of the fabric is often traced onto the paper and cut out for weighing.[29] Cusick[29] defined the drape coefficient ($DC\%$) as the weight of the paper of the drape shadow (W_2) expressed as a percentage of the paper weight (W_1) of the area of the full annular ring (Fig. 12.13).[28] Test methods include BS 5058/EN 9073. A measure of 100% on this instrument, indicates a completely rigid (stiff) fabric while a value of 0% represents a completely limp fabric, the values in practice ranging from about 30% for a loose, open weave rayon fabric to about 90% for a starched cotton gingham, and about 95% for stiff nonwovens.[30] Since different template sizes can be used, which influence the drape coefficient, the diameter of the template must be given together with the drape result. Ideally, the template size should be such that the measured drape coefficient falls between 40 and 70%.

Table 12.5 gives drape coefficients given by Sudnik,[31] using an improved version of Cusick's drapemeter. Sudnik also concluded that the optimum drape coefficient depends upon fashion and end-use. Typical examples of 'drapemeters' include those of CUSICK, F.R.L., I.T.F. and the M.I.T. Drape-O-Meter. Other principles of drape measurement include the force to pull a



12.12 Cusick's Drapemeter (source: Chung 1999).[28]



12.13 Drape image (source: Chung 1999).[28]

Table 12.5 Drape coefficients (%)[31]

End use	Template A (24)	Template B (30)	Template C (36)
Lingerie	<80	<40	<20
Underwear	65–90	30–60	15–30
Dresswear	80–95	40–75	20–50
Suitings	90–95	65–80	35–60
Workwear, rainwear	>95	75–95	50–85
Industrial	>95	>95	>85

Source: Sudnik.[31]

circular fabric sample at a constant speed through a ring, the force being termed the 'drape resistance' of the fabric. Collier[32] developed a digital drapemeter while Matsudaira *et al.*[33] used an image analysis system to measure static and dynamic drape. Vangheluwe and Kiekens[34] also used image analysis (video digital camera and computer-based image processing system) to measure the drape coefficient, while Stylios *et al.*[35] developed a new generation of drape-meters, enabling 3D static and dynamic drape to be measured by means of CCD camera as vision sensor. Image analysis enables many measurements to be made in a relatively short time.

Hunter and Fan[15] have given a detailed review of drape, including its prediction, dependence upon fabric bending and shear properties, as well as internet-based and other modelling and dynamic, as opposed to static drape. Also included is the role of drape in 3D visualisation and CAD internet apparel systems. Various reviews on drape and related properties have been published.[15,30,36-40]

12.3.7 Fabric objective measurement and handle[15]

Discerning and quality-conscious consumers require that their clothing satisfy their requirements and expectations in terms of appearance, fit and comfort, both when new and for an acceptable wear period thereafter. The clothing manufacturer, on the other hand, requires that the fabric is easy to tailor, passes through the making-up (garment manufacturing) process easily and without undue problems and that the finished garment has a good appearance. Traditionally, the quality of fabrics and 'fitness for purpose', including their performance during making-up (tailoring) and in the garment, were assessed subjectively in terms of the fabric handle (referred to as fabric handle or hand), by experts (judges) in the clothing industry. In assessing the fabric (e.g. AATCC Evaluation Procedure 5), these experts used sensory characteristics, such as surface friction, bending stiffness, compression, thickness and small-scale extension and shear, all of which play a role in determining garment making-up (tailorability) and appearance during wear.

Because of the way handle was assessed, i.e. by tactile/touch/feel, and the terminology used, i.e., 'fabric handle or hand', it is sometimes incorrectly assumed that the assessment was purely aimed at arriving at a subjective measure of the fabric tactile-related properties (i.e. handle). In fact, in reality the fabric handle, when so assessed by experts, provided a 'composite' measure of the overall garment-related quality of the fabric, including garment making-up, comfort, aesthetics, appearance and other functional characteristics (see Table 12.1). Nevertheless, although such experts were highly skilled and their judgement sensitive and reliable, the end result was still subjective and qualitative by nature and suffered from the inherent weakness of all subjective assessments, being amongst other things dependent upon the skills, training, background (cultural and other) of the evaluator . In the light of the above, the need to develop an objective (i.e. instrument) measurement system for assessing fabric quality became apparent, fabric objective measurement (FOM) being such an integrated system of measurement. The FOM instruments were designed so as to measure the low deformation forces encountered when the fabric is manipulated by hand and also during the garment making-up (tailoring) process and removes much of the guesswork from garment manufacturing. Two important FOM systems have appeared on the market, namely the Kawabata (KES-F and KES-FB) and CSIRO FAST (Fabric Assurance by Simple Testing) systems.

It is largely the small-scale deformation properties, notably extensibility, shear stiffness, hysteresis, bending stiffness and hysteresis and lateral compression that play a role in fabric making-up and appearance. Although originally developed essentially for wool and wool blend (worsted) fabrics, these systems are finding increasing application in other areas and fibres, for example, cotton shirting fabrics. The reader is referred to Fan *et al.*[15] for a detailed overview of the subject of FOM and to Yick *et al.*[41] for details of its application to cotton and cotton blend fabrics. Yick *et al.*[41] concluding that the scientific basis for the application of fabric objective measurement techniques (FAST and KES-F) can be extended to shirt production, enabling difficulties during the manufacturing process to be predicted.

12.4 Colourfastness[42]

An important quality parameter of dyed and printed fabrics is the fastness of the colours (e.g. BS 1006, BS EN 20105), for example, to light, weathering, water (washing), chlorinated water (pool water), sea water, perspiration, rubbing, gas fumes, ozone and dry cleaning (e.g. AATCC TM 132 and ISO 105-AO1), and various tests are used to measure colour fastness under conditions simulating those which the fabric is expected to encounter during use. Often the staining of or transfer of colour to, an adjacent (multifibre) fabric is measured together with the loss in colour of the test specimen, with standard grey-scales commonly used as a means of assessment or colour change can be measured instrumentally (AATCC 153 and ISO 150-A02). On the standard scale, five grades (5 to 1) are commonly used, 5 indicating no visible change and 1 substantial change. Eight grades (8 to 1) are commonly used for light fastness, 8 representing the highest level of fastness.

12.4.1 Light (daylight)

This test is aimed at determining the potential change in colour when the fabric is exposed to daylight, 'artificial' or 'simulated' daylight, at different temperatures and humidity, generally being used for testing purposes (AATCC 16, 177, 180, 181, ISO 105-BO1 and BO2. Test options include xenon-arc lamp (continuous or alternating light), carbon-arc (continuous light) or daylight.

The test specimen is exposed, together with a standard specimen, and the colourfastness assessed (rated) subjectively by comparing the colour change, using AATCC grey-scales under prescribed lighting and viewing conditions. Light fastness evaluation can also be done against a simultaneously exposed series of AATCC Blue Wool Light Fastness Standards. Instrumental evaluation, using a spectrophotometer, is also possible.

12.4.2 Ozone

This test assesses the colourfastness to ozone in the atmosphere, under two different sets of exposure, namely at room temperature and at a relative humidity not exceeding 67% and at a higher temperature and relative humidity. In both cases, the test and control specimens are exposed to the ozone under the pre-selected atmospheric temperature and relative humidity, until the control specimen exhibits a change in colour corresponding to the standard, this cycle being repeated until a definite change in the colour of the test specimen occurs or for a predetermined number of cycles. Examples of test methods include AATCC 109 and 129 and ISO 105-G03

12.4.3 Rubbing (crocking)

The resistance to rubbing and cross-staining (colour transfer) of a colour can be assessed under either wet or dry conditions using, for example, electronic or other crockmeters or rubbing fastness testers (BS 4655, BS 1006, ISO 105, AATCC 8/165, AATCC 116, DIN EN ISO 105, JIS 0801, 0849, 1084). The fabric specimen is clamped on a base board, in such a way that no wrinkles are formed when rubbed against the rubbing device. There are various other rubbing and crockmeter testers and test methods as well as what is referred to as resistance to colour change due to flat abrasion (frosting), screen wire and emery (e.g. AATCC 119 and 120).

12.4.4 Water

The test specimen, backed by a multi-fibre test fabric, is immersed in water at a specified temperature and for a specified time, occasional stirring ensuring complete wetting of the specimen. The specimen is then passed through squeeze rollers to remove excess liquor and placed between either glass or plastic plates in the perspiration tester under specified conditions of pressure, temperature and time. The specimen is heated in an oven and air-dried, after which the colour change and staining of the multi-fibre test fabric are assessed. Examples of test methods include DIN EN ISO 105-E01 and AATCC 107.

12.4.5 Chlorinated (pool) water

Tests, e.g., AATCC 162 and DIN EN ISO 105-E03, assess the fabric colourfastness to chlorinated water, such as that which would be encountered in a swimming-pool. The fabric specimen is agitated in a dilute chlorine solution under pre-determined temperature, time, pH and water hardness conditions. After drying, the specimen is assessed for colour change.

12.4.6 Seawater

The test measures the colourfastness of dyed or printed fabrics to seawater, using specially prepared (artificial) seawater of a specific composition. The test specimen, backed by a multi-fibre fabric, is soaked in the seawater solution, at room temperature, which is occasionally stirred. Squeeze rollers remove excess water from the specimen to bring its weight to within the required range, after which it is placed between glass or plastic plates in a perspiration tester. The change in the specimen fabric colour as well as the staining of the multi-fibre test fabric provides a measure of the colourfastness to seawater. Examples of test methods include DIN EN ISO 105-E02, AATCC 106.

12.4.7 Domestic and commercial laundering

This test assesses colourfastness when the fabric undergoes domestic or commercial laundering. Examples of test methods include DIN EN 105-C06, AATCC 61.

12.4.8 Perspiration

This test provides a measure of the colourfastness of a fabric to acid perspiration, such as could be encountered in the underarm areas of a shirt. The test, using an AATCC perspiration tester, Perspirometer or other similar device, assesses the colourfastness to acid perspiration. The test specimen is immersed in the perspiration solution which is occasionally stirred, after which the excess solution is removed by squeeze rollers, so as to reduce the wet specimen weight. After this the fabric is placed between plates, subjected to the required pressure and dried at a raised temperature. The change in colour of the test specimen is assessed after conditioning. Test methods include DIN EN ISO 105-E04, AATCC 15.

12.4.9 Acids and alkalis

Specimens are steeped in, or spotted with, the required solutions and then tested for changes in colour with reference to the grey-scales (AATCC 6 and IS 105-E05 and E06).

12.5 Weathering test

Examples of accelerated weathering test instruments include the Weather-Ometer®, Fade-Ometer®, Xenotest® and Apollo Light and Weather Fastness Tester (James Heal) enabling both weather fastness and light fastness to be tested under controlled temperature and humidity conditions, water spray being included for weathering tests. Applicable test methods include:

- AATCC 111 and 186.
- Fade-Ometer:® AATCC 16E, ASTM G 155 – cycle 4, ISO 105 B02/B06.
- Weather-Ometer:® AATCC 16E, ASTM G 155 – Cycle 4, ISO 105 B02/B04/B06.
- Xenotest:® AATCC 16 Option H, ISO 105 B02/B04/B06.
- Light-fastness testers (accelerated) e.g.,
  - MercuryTungsten Lamp (BS 1006 UK/TN).
  - Xenon Arc Testers (BS 1006 UK/TN).

12.6 Dimensional stability

Excessive change, particularly shrinkage, in fabric dimensions can represent a serious problem in virtually all textile applications, more particularly in clothing. Dimensional stability to laundering (washing), including drying, therefore forms an important quality and test requirement. Dimensional change has been defined[43] as a generic term for percentage changes in the length or width of a fabric specimen subjected to specific conditions.

Various test methods are used for testing the dimensional stability of fabrics, the choice of test method often depending upon the particular application (end-use) of the fabric. Standardised washing machines and tests, to assess fabric or garment performance under repeated home laundering cycles, have been developed (e.g. AATCC 888C, 96, 124, 130, 135, 142, 143, 150, 172 and 179). One example of a popular test method, which includes both washing and tumble drying (e.g. five cycles) is AATCC 135.[44] An industry norm for such a test on cotton single jersey is, for example, no more than 8% shrinkage in either length (wale) or width (course) direction. Automatic washing machines, such as the Whirlpool Washcator and the AATCC Launder-Ometer® (AATCC 61, 86, 132, 151 and 190), are specially designed, constructed and programmed to carry out standard tests, such as BS EN 250 77/26 330 and ISO 5077/6330, DIN EN ISO 3759/26 330/

25 077). More recently, accelerated washing and drying tests (in something like 15 minutes, e.g. Quickwash Plus^{TM} system) and the rapid measurement of shrinkage have been introduced, these tests also enabling colour fastness, pilling and finish durability to be measured (e.g. AATCC 187). Systems for automatically measuring fabric dimensional change have also been developed (e.g. Vision and Quickview^{TM}).

The actual changes in fabric dimensions during a test depend upon a number of factors, including the following:

- test medium (liquor), for example, solvent or water, more usually the latter
- liquor to goods ratio
- type and severity of mechanical agitation
- liquor temperature
- number of cycles
- method of drying, for example, line drying, flat drying or tumble drying, the latter generally causing the largest change in dimensions.

12.7 Abrasion resistance

12.7.1 Introduction

The useful life (wear durability) of a textile product is, in many cases, the most important quality factor and property to estimate, by means of laboratory tests. Many studies have been undertaken in an attempt to do so, and these have been discussed.[43–50] During its use, whether it be in apparel, home textiles or industrial textiles, a fabric can be subjected to various mechanical/physical (e.g. rubbing and flexing) actions and chemical actions which lead to changes in the fabric appearance and functionality and ultimately to it no longer being acceptable, either from an appearance or functional point of view. Various laboratory instruments and test methods, particularly fabric abrasion resistance, have been developed over many decades in an attempt to simulate, or at the very least estimate, wear performance and durability. Many of these have for various reasons, been discontinued, it being notoriously difficult to simulate the great variety and complexity of the conditions which a fabric experiences in the diversity of possible end-use applications. Nevertheless, testing of abrasion resistance has remained an important measure of fabric durability since abrasion is one of the main factors involved in fabric wear and failure.

Abrasion during use not only contributes to the failure of the fabric, it also contributes to changes in fabric appearance, such as fuzzing, pilling and frosting (colour change), as well as to changes in fabric performance properties, long before mechanical fracture or rupture occurs. Frequently the consumer will consider a fabric to have reached the end of its useful life on the basis of such properties rather than on the basis of fabric mechanical failure, such as tearing, rupturing, etc. It is, however, generally not possible to draw a meaningful conclusion on the expected wear life (durability) of a fabric based upon abrasion resistance only. During laundering, for example, both chemical and mechanical actions (damage) are involved in the fabric wear or damage.

One or more of three forms of abrasion occur most frequently, namely flat (or surface) abrasion, edge abrasion and flex (bending) abrasion. In practice, flat abrasion occurs as a result of a rubbing action of the fabric surface, either against itself or against another surface, the latter could be one or more of many widely different materials. Edge abrasion, sometimes also referred to as cuff abrasion, frequently takes place at collars and cuffs, and can be a combination of flat and flex abrasion. Flex abrasion mostly occurs as a result of flexing and bending during use, sometimes this also occurring over a sharp edge. It is also referred to as internal abrasion, where fibres rub against fibres or yarn against yarn within the fabric, although sometimes an external object, such as a sharp edge, is also involved, fabric surface properties and lubrication greatly affecting flex abrasion results.

Most abrasion test instruments and methods attempt to provide a measure of one or more of these three different types of abrasion. In practice, however, the fabric may be subjected to all three forms of abrasion. Stoll,[46] for example, stated the wear of army uniforms comprised 30% plane (flat) abrasion, 20% edge and projection abrasion, 20% tear and 10% other mechanical actions. He defined a wear index (WI) as follows: WI = 0.50 (flex abrasion) + 0.20 (flat abrasion) + 0.30 (tear resistance). Elder[45] suggested the following for wear resistance (WR): WR = 0.3 (flat abrasion) + 0.2 (edge abrasion) + 0.3 (flex abrasion) + 0.2 (tear resistance). Not only does the abrasion resistance or durability of a garment or other textile product depend upon the properties of the fabric but it also depends upon the conditions it encounters during wear (even the fit of a garment in the case of apparel).

In the main, three components are involved during abrasion, namely fibre breakage or cutting, fibre removal and fibre attrition (or mechanical breakdown of the individual fibres, e.g. fibrillation), with the first-mentioned two generally the main components of fabric failure. The abrasion resistance of the fabric is in practice quantified by the number of cycles required to produce either a hole or a certain loss in strength or weight, change in colour (appearance), change in air permeability or a change in thickness.

- flat (or relatively flat) abrasion (usually the fabric is rubbed against a fabric or other abradent, such as emery paper, under different pressures)
- flex abrasion
- combination of flat and flex abrasion.

12.7.2 Flat abrasion

Flat abrasion test results are greatly dependent upon variations in fabric surface smoothness (including fabric structure) and friction, fabric thickness and yarn diameter as well as on the ability of the fibres themselves to withstand mechanical forces. Flat abrasion tests therefore tend to provide a better indication of wear performance in applications, such as upholstery and carpets, where the main wear action is a rubbing one, on the surface of the fabric held in a flat position.

Examples of flat abrasion testers include Martindale (ASTM D4966, BS 5690), Stoll (ASTM D3885 and D3880), Taber (ASTM D3884) and Schiefer (ASTM D4158). Probably one of the most popular flat abrasion testers is the Martindale Abrasion Tester (Fig. 12.10), also used for testing pilling propensity, in which a test specimen is rubbed against an abradant (usually an abradant fabric) at pre-determined pressure in a continuously changing direction. Rubbing is continued either for a pre-set number of cycles after which the mass loss and change in appearance are determined or else it is continued until a pre-defined end point is reached, for example, until two fabric threads are ruptured or a hole is formed; as per ASTM 4966 and 4970, BS 3424/5690, BS EN 530, BS EN ISO 12947 – 1, – 2, –3 and –4, ISO 5470 (rubber or plastic coated fabric) and JIS L 1096.

12.7.3 Edge abrasion

Edge abrasion takes place when the wear or abrasion occurs along the fabric edge, generally a folded edge, such as in the edge or fold of the collar of a shirt or the cuff of a sleeve. Tests include the AATCC 'Accelerotor', a rapid tumble test where the sample is folded and stitched prior to testing to accentuate abrasion of edges and laundering and tumble-drying of mock trouser cuffs. Evaluation of the fabric can then be done visually.

12.7.4 Flex abrasion

The Stoll-Flex Abrasion Tester applies uni-directional abrasion to a tensioned strip of fabric drawn over an abrasion bar, the fabric being bent or flexed as it is rubbed against (over) the bar (ASTM D3885).

12.7.5 Tumble abrasion

Tumble abrasion, such as that occurring in the AATCC 'Accelerotor' test, tends to correlate best with that occurring in the use and laundering of sheets. AATCC Accelerotor (AATCC 93) is used for both wet and dry abrasion, samples being tumbled in a circular cylinder, lined with an appropriate abrasion material, a rapidly rotating impeller/propeller shaped rotor creating the tumbling action, beating the sample against the drum wall.

12.8 Fabric strength

Fabric strength is generally regarded as one of the main properties determining wear performance and durability, although it is more important in applications such as upholstery, sheeting and shirting material and industrial textiles than in apparel textiles. Even if strength is not a specific requirement for a certain end-use, for example in knitwear, such as cardigans, it is nonetheless still often used as a measure of fabric quality and deterioration during use. In the main, three types of strength tests are carried out, namely tensile, bursting, and tear, the specific test selected in practice depending upon both the type of fabric (for example knitted or woven) and the intended end-use. Other tests carried out include the peel strength of bonded or laminated fabrics.

12.8.1 Tensile strength

Tensile testing refers to those cases where the force (load) is applied unidirectionally, usually on a strip of fabric, for example in either the warp or weft direction in the case of a woven fabric. The test could either be a ravelled strip test (ASTM D5035) or grab test (ASTM D5034), carried out on what are generally referred to as 'universal testers' e.g., Instron, Micro-CX, Statimat M or ME, which enable the fabric extension (elongation) at break, elastic recovery, etc., to be measured as well. They generally operate on the constant rate of extension principle, with the rate of extension variable according to the test method and the requirements. Test methods include ASTM E-4, D5034, BS 1610/0.5, BS 2576, BS EN 10002-2, DIN 51221/1, DIN ISO BS EN 13934-1.

12.8.2 Bursting strength

Bursting strength represents a composite and simultaneous measure of the strength of the yarns in all directions (biaxial) when the fabric is subjected to bursting type forces, applied by a ball or elastic diaphragm. In certain applications, such as in parachutes, filters and bags, the bursting strength of a fabric (woven, knitted or non-woven) is important. The fabric specimen, usually circular in shape, is usually securely clamped over an elastic (rubber) diaphragm in a ring (annular) clamp and subjected to a hydraulic load, the pressure required to burst the fabric being recorded (ASTM D3786 and D3787, BS 3424-38 and BS 4768, and ISO 2758/2759/3303/3689).

12.8.3 Tear strength

Although tensile strength is frequently taken as a measure of fabric serviceability, tear strength is preferable in this respect, since in many applications product failure occurs as a result of fabric tearing. A combination of tear strength and abrasion resistance is considered to be a fair indicator of the useful life of a fabric. A tear is defined[49] as a rupture, progressively along a line (thread by thread), caused by a moving fabric being caught in a sharp object which is sufficiently fixed in position to exert a tensile force on the fabric as it is moved away. Several methods are used to measure tear strength, e.g., tongue (double tear), rip (single tear, ASTM D2261, BS 4303), trapezoidal (ASTM D5587) and Elmendorf. A popular method of measuring the tearing strength of a fabric is by using a pendulum type tester, such as the Elmendorf Manual or Digital Tearing Testers (ASTM D 1424 and D 5734, ISO 1974 and 9290, BS EN ISO 13937).

12.9 Miscellaneous tests

The reader is referred to various books[11] and manuals (e.g. AATCC, ASTM, BS, ISO, DIN) for detailed information on the following and other fabric tests:

- Air permeability, which measures the resistance of a fabric to the passage of air, often at a specific drop in pressure across the fabric thickness (ASTM D737 and D6476, BS 5636, DIN EN ISO 9237 and JIS L1096A).
- Bagging, more important for knitted, as opposed to woven, fabrics, often occurring in the knee and elbow regions of a garment, particularly in the case of tight-fitting and in elastic garments and loose constructions.
- Barré (AATCC TM178).
- Barrier properties (AATCC 127).
- Bow and skewness (ASTM D3882).
- Breathability (AATCC 127 / ASTM D737).
- Colour and colour difference measurement and shade matching (e.g. AATCC Evaluation Procedure 6, 7 and 9).
- Comfort, generally related to factors such as moisture absorption and permeability and transport, wicking, insulation, softness (and scratchiness), air permeability (breathability), chemical properties and clothing fit.
- Cover factor.
- Electrostatic propensity and electrical properties BS 6524, ASTM D4238, AATCC 76 and 115.
- Fibre composition (ASTM D276, D629, AATCC 20, ISO 3072, ISO 1833).
- Flammability (e.g. vertical or horizontal), particularly important for children's nightwear and certain other applications (ASTM D1230 and

D4372, BS EN 13772, D5132,BS 5438,5722,5866, 5867,6249 and 6341, DIN 75200, DIN 66080 and ISO 6940 and 6941).

- Light fastness testers (accelerated) e.g.:
  - mercury-tungsten lamp (BS 1006 UK/TN).
  - xenon arc testers (BS 1006 UK/TN).
- Mass (weight) per unit area (e.g. BS 2471, BS 2866, ASTM D3776).
- Mildew and rot resistance (AATCC 30, BS 6085).
- Moisture content (ASTM D2654, D4920).
- Oeko-Tex 100, global certification scheme, for textiles which are not harmful to health and environment (www.oeko-tex.com).
- Perspiration test (AATCC), used to measure fabric colour fastness to water and perspiration (AATCC 15, 106 and 107, BS 1006, BS EN 20105 and DIN EN ISO 105-E04).
- Seam failure/strength (ASTM D1683).
- Seam slippage (ASTM D434, D4033 and D4034).
- Seam smoothness (AATCC 88B / 88C, ISO 7770).
- Sett (e.g. BS 2862, DIN 53 853, ASTM D3775).
- Sewing damage (ASTM D1908).
- Shearing (shear being one of the important factors affecting fabric drape) and making-up (tailoring performance).
- Snagging, mostly important for fabrics, particularly knitted fabrics with a raised surface, containing continuous filament yarns (ASTM D5362 and D3939).
- Soiling.
- Spirality, mostly a problem in single jersey fabrics, knitted from twist lively (usually highly twisted) yarns (ISO/CD 16322-1).
- Stiffness, important in determining fabric drape and handle and generally measured by the cantilever method (e.g. Shirley Bending Stiffness Tester) and incorporated in more comprehensive testing systems, such as Kawabata and FAST.
- Stretch and elastic recovery.
- Thermal resistance and transmission (ASTM D1518, BS 4745).
- Thickness test, various testers and test methods are available for testing fabric thickness under different pressures and pressure plate/foot of different sizes (ASTM D1777, BS 3424, ISO 3616/5084/9073).
- UV protection (AATCC 183, ASTM D6603-00, 6544-00, EN 13758, AS/NZS 4399).
- Water absorption (BS 3449).
- Water penetration resistance under pressure, or hydrostatic head tester (AATCC 127, BS EN 20811/3321/3424-24, ISO 811).
- Water repellency rain test, used to measure the fabric resistance to simulated rain, when the fabric is rubbed and rotated, the amount of water absorbed by the fabric specimen, determined by the increase in specimen weight,

providing a measure of water penetration (BS/DIN EN 29865 and ISO 9865). Certain tests (e.g. AATCC Rain Tester) enable the resistance of fabrics to water penetration at different water impacts, simulating rain, to be measured (AATCC 35 and 42, BS EN 20811). The WIRA Shower Tester (BS 5066) is also used to measure the fabric water absorption and penetration of a fabric when subjected to an artificial shower. Water Repellency (Spray) Test (AATCC TM 22 and ISO 4920) measures the resistance of a fabric to wetting by water.

- Water vapour permeability (BS 7209).
- Weathering which attempts to simulate the exposure of a fabric to sunlight (using fluorescent UV lamps), rain and dew, the fabric is exposed to cycles of light and moisture at elevated temperatures, water spray systems also being incorporated (ASTM D4329, JIS D0205, SAE Society of Automotive Engineers J2020).
- Weave (e.g. DIN EN 1049-02).
- Wettability (BS EN 24920, BS 4554).
- Whiteness (AATCC 110).
- Yarn Crimp (ASTM D3883, BS 2863).

12.10 General

The following reviews and books relevant to this chapter have appeared:

- drape[15,30,36-40]
- pilling[19,20,36]
- abrasion and wear[43,44,45,47,49,50]
- consumer studies[10]
- fabric surface wear[48]
- general[2,11,15,52]
- wrinkling[13]
- stiffness and shearing[37,38,39]
- fabric strength[50,53,54]
- fabric quality assessment[9,51]
- UV protection[55]
- yarn irregularity[3,4]
- yarn hairness[6].

12.11 Conclusions

Further technological developments in the area of yarn and fabric testing can be expected to focus on the following:

- on-line monitoring and testing
- integrated testing

- instrument measurement of yarn and fabric appearance-related properties
- knowledge-based systems (e.g. expert and artificial neural network systems) for prediction, diagnostic and trouble-shooting purposes
- internet-based standard test methods and benchmark and reference values and standards, also electronically linked to on-line and off-line testing systems.

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13
Controlling costs in cotton production

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13.1 Introduction

World cotton production and consumption are trending higher, and the industry is being transformed by new technologies, including biotechnology. World cotton production reached 26 million tons in 2004/05, and biotech varieties accounted for about one-third. The average cost of cotton production varies widely across countries, but the cost of production for most producers is between 50 and 60 US cents per pound. While per capita consumption of cotton at the retail level is highest in developed countries, the strongest growth in both retail consumption and mill use of cotton is occurring in developing countries, particularly China (mainland), India and Pakistan.

The elimination of quotas as of January 2005 that limited trade in textiles and apparel for more than 30 years is leading to a shift in textile and apparel production toward China and other low-income producing countries, and the cotton industry is benefiting from increased consumption caused by lower retail prices of textile and apparel products. However, substantial distortions caused by government measures still exist in the market for cotton itself. International cotton prices have declined in real terms over the last six decades because of advances in technology, and this process is continuing. During the 1970s, 1980s and 1990s, the average world price of cotton was 70 cents per pound, but the average international price during the current decade is expected to be between 50 and 60 cents per pound, in line with the costs of production for most producers. See the appendix on pages 256–9 for a table showing cotton supply and use since the 1920s.

13.2 The economic importance of cotton

Cotton is one of the most important and widely produced agricultural and industrial crops in the world. Cotton is grown in more than 100 countries on about 2.5% of the world's arable land, making it one of the most significant in terms of land use after food grains and soybeans. Cotton is also a heavily traded agricultural commodity, with over 150 countries involved in exports or imports of cotton.

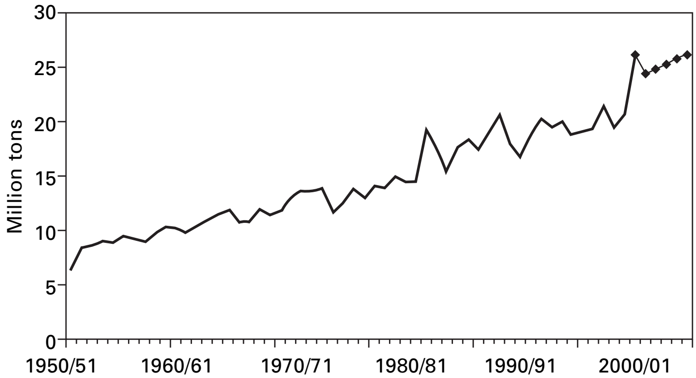
More than 100 million family units are engaged directly in cotton production. When family labor, hired-on farm labor and workers in ancillary services such as transportation, ginning, baling and storage are considered, total involvement in the cotton sector reaches an estimated 350 million people. It also provides employment to additional millions in allied industries such as agricultural inputs, machinery and equipment, cottonseed crushing and textile manufacturing. Cotton cultivation contributes to food security and improved life expectancy in rural areas of developing countries in Africa, Asia and Latin America. Cotton played an important role in industrial development starting in the 17th century and continues to play an important role today in the developing world as a major source of revenue. The value of 26 million tons of world cotton production in 2004/05 at an average world price of 52 cents per pound of lint, or $1.15 per kilogram, was $30 billion.

Cotton, unique among agricultural crops, provides food and fiber. A cellulosic fiber about 96% pure, cotton is one of the world's most important textile fibers, accounting for more than half of all the fibers used in clothing and household furnishings. Cotton is also used in industrial fabrics, and the by-products derived from cottonseed and stalks provide edible oil for human consumption and soap, industrial products, firewood and paper and high protein animal feed supplements. Cotton oil is the fifth largest edible oil consumed in the world.

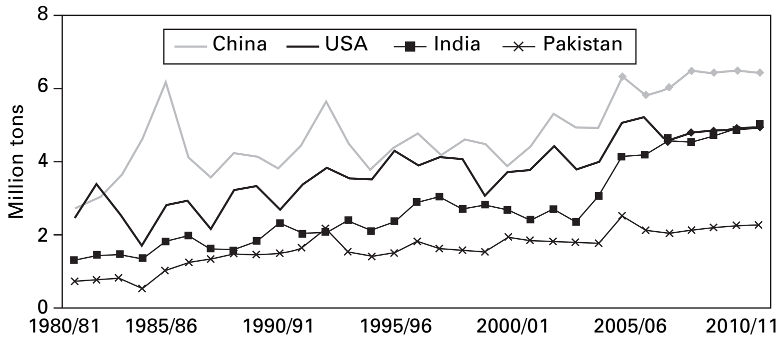
13.3 Production

The world cotton industry has experienced dramatic changes over the last five decades as production nearly quadrupled, rising from 6.6 million tons in 1950/51 to a record of 26.3 million tons in 2004/05 (Fig. 13.1). The average annual rate of growth in world production over the last five decades has been about 2.5% per year. Growth in cotton production was steady during the 1950s and 1960s but slowed during the 1970s because of slower world economic growth and limited gains in cotton yields. World cotton production exploded from 14 million tons in the early 1980s to 19 million tons in 1984/85, as market incentives and the widespread use of better seed varieties and better methods of plant protection led to increased yields. World production climbed to a record of nearly 21 million tons in 1991/92 but leveled off during the 1990s. With the commercial application of biotech cotton varieties beginning in 1996 and the expansion of cotton areas in Francophone Africa, Australia, central Brazil, western China, and Turkey, world production climbed to 26.2 million tons in 2004/05. The main cotton producers since the early 1980s are shown in Fig. 13.2.

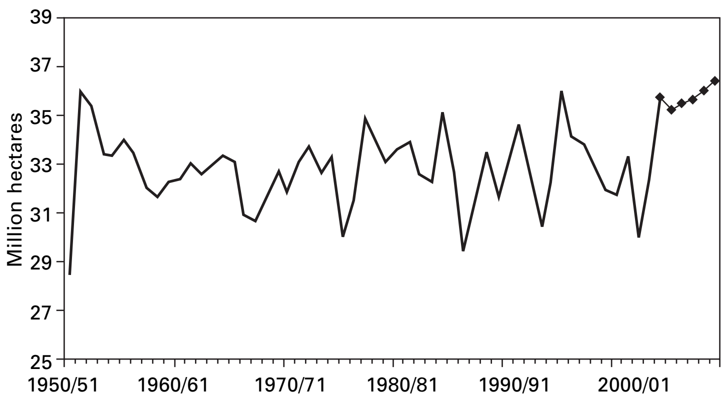
World area dedicated to cotton has fluctuated since 1950/51 between 28 million hectares and 36 million hectares (Figs. 13.3 and 13.4). While there



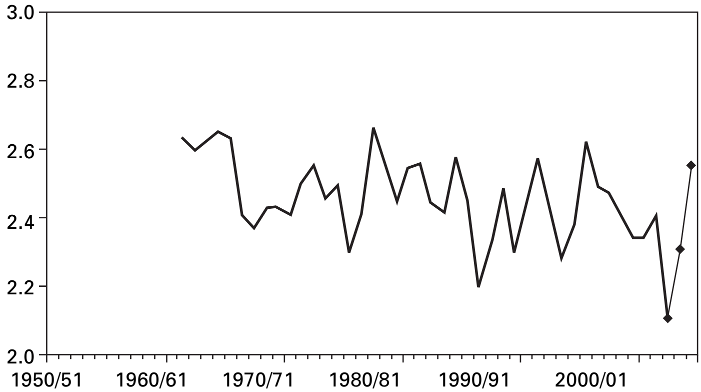
13.1 World cotton production.



13.2 Main cotton producers.



13.3 World cotton area.

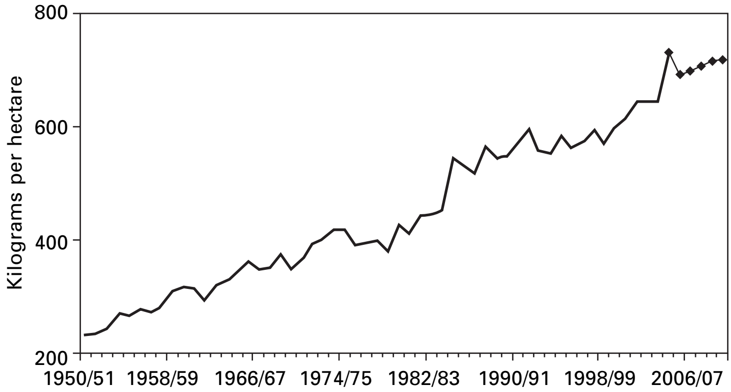


13.4 World cotton area, as a percentage of arable land.

have been dramatic reductions in cotton area in some regions since the 1950s, particularly in the USA, North Brazil and North Africa, there have been equally dramatic increases in Francophone Africa, Australia, China, India, Pakistan and the Middle East. With total area showing no tendency to rise, all the growth in world cotton production since the 1940s came from improved yields. The world cotton yield 50 years ago was 230 kilograms of lint per hectare. Yields rose steadily at an average rate of more than 2% per year during the 1950s and 1960s, and then grew more slowly from the mid-1970s until the mid-1980s. During the 1980s the world cotton yield rose dramatically and reached a record of nearly 600 kilograms per hectare in 1991/92. However, yields stagnated during the 1990s due to problems associated with diseases, resistance to pesticides, and disruption of production due to economic reasons. Yields began rising again in the late 1990s with improvements in seed varieties and the use of biotech varieties, and the world yield in 2004/05 reached more than 720 kilograms per hectare.

New technologies, more extensive use of existing technologies, and new areas dedicated to cotton cultivation have changed the structure of the world cotton market since the mid-1990s (Fig. 13.5). Among the new technologies, the most visible is genetic engineering of cotton. It is estimated that 24% of world cotton area accounting for more than one-third of world production was planted to biotech varieties in 2004/05, up from just 2% in 1996/97. Biotech cotton lowers the use of insecticides and, although it does not guarantee that cotton yields will be higher than with a non-biotech variety, it might lower the cost of production.

Cotton is produced in about one hundred countries, but production has traditionally concentrated in a few (Table 13.1). Over the last three decades, the four leading producing countries have accounted for an increasing share of world production. China (mainland), the United States, India and Pakistan accounted for 48% of world production in 1970/71 and 68% in 2004/05. The



13.5 World cotton yields.

Table 13.1 Top ten producers 2004/05

		Thousand tons	
1	China (M)	6,320	24.2%
2	USA	5,062	19.4%
3	India	4,080	15.6%
4	Pakistan	2,482	9.5%
5	Brazil	1,318	5.0%
6	Uzbekistan	1,150	4.4%
7	Turkey	900	3.4%
8	Australia	624	2.4%
9	Greece	390	1.5%
10	Syria	331	1.3%
	Others	3,472	13.3%
	World	26,129	100.0%

share of industrial countries (the USA, Australia, Spain and Greece) increased from 19% of world production in 1980/81 to 24% in 2004/05. Developing countries accounted for 61% of world production in 1980/81 and 66% in 2004/05. Cotton production in the former USSR declined during the last two decades, accounting for 19% of world production in 1980/81 and 7% in 2004/05.

Production in China (mainland), the largest producer, increased at an average annual rate of 5% during the 1980s and fluctuated within a range of 3.7 to 5.7 million tons during the 1990s. Production in China (mainland) rose to a record of 6.3 million tons in 2004/05. In the United States, cotton production increased from 2.4 million tons in 1980/81 to 3.3 million tons in 1990/91, and fluctuated between 3 and 4.3 million tons during the 1990s before rising to 5.1 million in 2004/05. Cotton production in India rose from 1.3 million tons in 1980/81 to 3.0 million in 1996/97. Thereafter, production fell to 2.3 million tons in 2002/03 before reaching a record of 4.1 million tons in 2004/05. Production in Pakistan expanded rapidly during the 1980s, growing from 700,000 tons in 1980/81 to 2.2 million tons in 1991/92. However, production fell in 1992/93 and remained below the 1991/92 level until 2004/05 when production rose to 2.5 million tons. In Africa, cotton production increased from 1.3 million tons in 1990/91 to 1.8 million tons in 1997/98, but low cotton prices discouraged African production in the years after. African production rose to two million tons in 2004/05. Francophone countries in West and Central Africa produced 1.1 million tons in 2004/05, accounting for 56% of production in the continent.

Cotton production in Brazil declined rapidly between the mid-1980s and the mid-1990s, and recovered in the second half of the decade. Production, which declined from 965,000 tons in 1984/85 to 310,000 tons in 1996/97, climbed back to 940,000 tons in 2000/01 and to 1.3 million tons in 2004/05, surpassing Uzbekistan and Turkey. Cotton production in Turkey increased from 650,000 tons in 1990/91 to 900,000 tons in 2004/05. Cotton production in Australia increased very rapidly during the 1980s and 1990s, from 100,000 tons in 1980/81 to 800,000 tons in 2000/01. Because of drought, production was only 624,000 tons in 2004/05. Cotton production in the European Union (EU) increased from 300,000 tons in 1990/91 to 500,000 tons in 2004/05.

13.3.1 Costs of production

The structure of production varies substantially from country to country and even from region to region in the same country, depending on relative resource endowments (Table 13.2). Countries with abundant capital, sophisticated systems of research and education and developed infrastructure for the supply of credit and inputs to farmers tend to rely on highly mechanized production systems utilizing purchased planting seeds and chemical inputs and employing very little labor per ton of output. Australia and the USA typify this production system, and the structure of production in the EU and Brazil is tending in this direction. Developing countries with relatively abundant land and labor and less intensively developed networks for the distribution of inputs tend to plant, cultivate and harvest cotton by hand and to use fewer purchased inputs per ton of production. In China (Mainland), Central Asia, South Asia, the Middle East, Africa and many areas in South America, cotton is tended mostly by hand. About 55% of world cotton area is irrigated, accounting for about 75% of word output. About 30% of cotton production is machine harvested. As a result, yields and costs of production vary greatly from country to country.

In 2003/04, the cost of production on one hectare ranged from less than $400 in some developing countries to almost $4,000 in Israel. Data from 30 countries indicate that the average cost of production of cotton in 2003/04

Table 13.2 Cost of production 2003/04 (US$)

Country/Region	Cost of Seed : cotton[1]		Variable Cash Expenses[2]		Net Cost [3]	
	Per Ha	Per Kg	Per Ha	Per Kg	Per Ha	Per Kg
Argentina, Santiago del Estero (Irrigated)	410.11	0.21	427.06	0.65	498.01	0.75
Argentina, Rainfed	328.97	0.22	336.60	0.67	392.48	0.78
Australia, Irrigated Upland	886.84		936.49	0.66	1,936.64	1.37
Bangladesh, *G. hirsutum*	406.61	0.25	214.07	0.36	238.14	0.40
Benin, National Average	484.43	0.46	551.39	1.23	597.17	1.33
Bolivia, National Average	457.27	0.28	547.83	1.01	666.45	1.22
Brazil, Central West (Cerrado)	1,122.07	0.31	1,049.13	0.80	1,277.40	0.98
Brazil, Northeast (Semi-arid, Rainfed)	354.06	0.24				
Bulgaria	436.26	0.36	619.59	1.40	674.24	1.52
Cameroon, National Average	324.37	0.27	362.59	0.74	407.51	0.83
China (Mainland), National Average	886.29	0.32	706.15	0.67	1,069.35	1.02
Colombia, Cesar	869.93	0.38	924.12	1.12	984.64	1.19
Colombia, Sinu	874.48	0.35	804.16	0.89	907.43	1.01
Côte d'Ivoire, Manual Cultivation	356.90	0.29				
Côte d'Ivoire, Animal Powered	416.43	0.29				
Ethiopia, Afar	495.05		344.01		861.40	
India, North Zone, Irrigated	357.42	0.21				
India, Central Zone, Irrigated	394.35	0.27				
India, Central Zone, Rainfed	302.85	0.31				
India, South Zone, Rainfed	411.31	0.32				
Iran, National Average	892.05	0.36	782.66	0.98	1,001.29	1.25
Israel, Upland/Pima	2,570.00		2,490.00		3,380.00	
Mali, National Average	388.18	0.34	545.97	1.15	626.94	1.32
Mexico, Central (South of Chihuahua)	1,059.83					
Mexico, Sonora (South)	1,578.60		1,445.85		1,773.80	
Nigeria, National Average	466.92		375.88			
Pakistan, Punjab	742.03	0.37	564.91	0.85	638.63	0.96
Paraguay	341.63	0.28				

Table 13.2 Continued

Country/Region	Cost of Seedcotton[1]		Variable Cash Expenses[2]		Net Cost[3]	
	Per Ha	Per Kg	Per Ha	Per Kg	Per Ha	Per Kg
Peru, Central Coast, Tanguis Cotton	1,133.43	0.92	1,161.39		1,360.59	
Philippines, Luzon	405.53	0.23	418.76	0.66		
Philippines, Mindanao	236.56	0.18	242.85	0.52		
Philippines, Visayas	250.54	0.17	268.55	0.50		
South Africa, Orange River – Irrigated Bt	810.89	0.16				
South Africa, North West (Stella) – Rainfed Bt	255.61	0.21				
Spain, National Average	2,027.53	0.58				
Sudan, Gezira	499.75	0.43	551.24	1.41	652.77	1.67
Tanzania, Eastern Cotton Growing, Area	164.46	0.16				
Togo, North Region	399.66	0.44	450.72	1.18	498.90	1.30
Togo, Central and South Region	516.93	0.57	565.06	1.48	613.24	1.60
Turkey, National, Average	1,208.80	0.32	1,534.37	1.12	1,827.47	1.34
Turkey, GAP, (Southeastern Anatolian Project)	970.00	0.26	1,322.32	0.98	1,566.32	1.16
Turkey, Çukurova	1,198.00	0.28	1,546.62	1.00	1,801.62	1.16
Turkey, Ege (Aegean)	1,305.00	0.34	1,647.18	1.20	1,968.18	1.44
Turkey, Akdeniz (Antalya)	1,555.00	0.39	1,932.54	1.34	2,274.54	1.58
USA, National Average	671.02		670.70	0.92	1,082.02	1.48
USA, Heartland	584.64		602.13	0.63	1,033.02	1.08
USA, Mississippi Portal	793.02		799.54	0.82	1,245.60	1.27
USA, Fruitful Rim	1,142.22		1,007.91	0.71	1,457.09	1.02
USA, Prairie Gateway	467.29		474.96	1.16	885.00	2.15
USA, Southern Seaboard	780.10		819.51	1.00	1,179.83	1.44
Vietnam, Highland	473.33	0.32	443.88	0.81	625.47	1.14

1. Cost of seed : cotton production does not include the cost of land rent.
2. Variable cash expenses include the cost of seed: cotton production plus ginning, but they do not include land rent and seed value.
3. Net cost is total cost (including economic and fixed costs) but does not include land rent and seed value.

was $1,140 per hectare, including the costs of growing, harvesting and ginning. Out of the total cost, the average cost of land rent was $240, and the average value of cottonseed sold after harvest per hectare of production was $166. Economic costs, such as management and administration, interest on capital, repairs and general farm overhead, and fixed costs, such as depreciation on equipment, averaged $115 per hectare. Consequently, the costs of production, net of land values, net of the value of cottonseed sales, and net of economic and fixed costs, averaged $620 per hectare in 2003/04.

Assuming an average total cost of production of $1,140 per hectare, the total cost of production of cotton on 32.1 million hectares in 2003/04 was approximately $37 billion. The value of world cotton production in 2003/04, 20.7 million tons of lint at an average price of 68 cents per pound, was about $31 billion. Consequently, the value of world cotton production in 2003/04 was about $6 billion less than the cost of production. Subsidies paid to growers accounted for about $4 billion in 2003/04, and the remaining $2 billion in economic losses would have been mostly accounted for by depreciation on equipment and lost wages for management and administration.

Based on a world yield of 642 kilograms of lint per hectare in 2003/04, the average total cost of production, including land, the value of cottonseed and economic and fixed costs, was $1.77 per kilogram of lint ($0.80 per pound). Excluding the cost of land rent and subtracting the value of cottonseed sold after harvest, the net cost of production averaged $1.14 per kilogram of lint ($0.52 per pound), and if economic and fixed costs are excluded, the resulting cash costs of production averaged $0.96 per kilogram ($0.44 per pound). These data indicate that the average land owner, producing cotton at average cost and gaining average yields in 2003/04, will tend to maintain or expand production when farm prices exceed 44 US cents per pound.

Costs of production vary substantially by region. Based on data from 2003/04 and using exchange rates that prevailed at that time, cotton production costs per kilogram of lint are the highest in Europe and the USA and the lowest in Asia, South America and Australia. The net cost of production per kilogram of lint (excluding the cost of land and subtracting the value of cotton seed; world average equal to $1.14) averaged $1.48 in the USA and $3.72 in Europe. Farmers in the USA, Greece and Spain are supported by government measures.

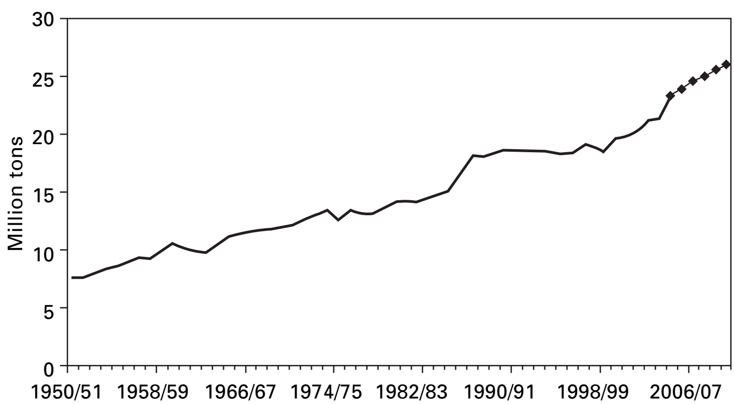
The net cost of production in Africa averaged $1.40 per kilogram, which is above the world average. An earlier study done using data from 2000/01 indicated that costs of production in Africa were less than the world average, but between 2000 and 2003, the CFA (currency of Francophone Africa) strengthened by more than 30% against the US dollar, changing cost of production measures. The net cost of production in South America averaged $1.09 per kilogram of lint in 2003/04, the average in Asia was $1.14 per kilogram and the average in Australia was $1.08 per kilogram.

The greatest source of variation in costs of production per kilogram of lint are caused by differences in the costs of ginning, economic costs and fixed costs. The cost of producing seed cotton is relatively stable across most countries, averaging \$0.33 per kilogram and with a variation of only 3 cents per kilogram between the highest-cost and lowest-cost producing countries. However, when costs of ginning, seed values, economic costs and fixed costs are considered, variations among countries become apparent.

13.4 Consumption

World textile fiber consumption is driven by three major economic variables, income, population growth and fiber prices (Fig. 13.6). World final demand for textile fibers has increased at an impressive pace since the 1950s. From 7.6 million tons in 1950, textile fiber consumption increased to 56 million tons in 2004. While about 50% of the increase was the result of population growth, the remaining 50% was the result of higher income per capita, declines in real textile prices, and competition, which generated new uses for textile fibers. However, the rate of growth of fiber consumption has decelerated gradually. The average annual rate of growth of textile fiber consumption was 3.7% during the 1960s, 3.1% during the 1970s, 2.5% during the 1980s and 2.7% during the 1990s. Growth of the two major economic variables that determine textile consumption, income and population, decelerated during the 1990s compared with the 1960s.

An exogenous factor that has supported textile consumption in the last few years is the gradual integration of textile trade into World Trade Organization (WTO) rules. (The WTO is an international economic organization headquartered in Geneva. The WTO serves as the forum for negotiation of international trade rules among countries.) As of December 2004, just over half of world textile trade had already been gradually integrated, and on



13.6 World cotton mill use.

January 1 2005, all textile trade was integrated into WTO rules. Therefore, quotas agreed under the Multifiber Arrangement (MFA) no longer exist. Research by the Secretariat, using previous joint work with the Food and Agriculture Organization of the United Nations (FAO), suggests that because of textile quota elimination, the world would consume half a million tons more cotton by the end of 2005. A portion of the gains in cotton consumption due to quota elimination are likely to have occurred between 1995 and 2004, particularly since January 1 2002.

Consumer research and demand enhancement activities, especially those of Cotton Incorporated in the USA, have also supported cotton consumption. The budget of Cotton Incorporated is approximately $60 million per year, collected from US cotton producers and importers of textiles and apparel. Cotton Incorporated conducts textile research to enhance the quality of cotton products, and it spends about $38 million per year on direct consumer advertising to enhance cotton consumption at the retail level. Research by the Secretariat suggests that as a result of research and demand enhancement efforts, 300,000 tons more cotton per year has been consumed since 1998.

For cotton, competition with chemical fiber is an insidious challenge. At the start of the 20th century, cotton had a dominant share of the textile market. At the beginning of the 21st century, cotton is one of many fibers available and has been surpassed by polyester. Cotton consumption per capita has been almost constant since 1960, while total textile fiber consumption per capita more than doubled. Cotton's share of world textile fiber use fell from 79% in 1950 to below 40% in 2004.

Most of the increase in world cotton consumption at the end-use level during the 1980s and 1990s took place in industrial countries. However, since 2000, most of the increase in cotton end use is taking place in developing countries as consumers in China (mainland) and India accelerate their retail purchases. The share of developing countries in world mill consumption rose continuously from 61% in 1990/91 to 88% in 2004/05. Mill use in developed countries is headed lower.

The elimination of quotas will intensify competition, leading to lower prices for textiles. (Quotas are quantitative limits on imports of textile and apparel products. Beginning in the late 1950s and continuing until the end of 2004, the United States, Canada, and most countries in Europe limited imports of textiles and apparel by setting quotas on products from exporting countries. The quotas were designed to slow the growth of imports in order to protect domestic manufacturing industries.) Final consumers of textile products will benefit from increased supply and lower prices, which in turn could stimulate consumption growth to the benefit of lower-cost cotton textile and apparel industries. Cotton producers themselves will benefit from stronger demand for cotton fiber.

Long-term projections of world gross domestic product (GDP, a measure of total economic activity) and population growth suggest that world textile fiber consumption can expand at an annual average rate of 4% to reach 75 million tons in 2010. World cotton consumption is projected to expand at an annual average rate of 3.5% to reach 26 million tons in 2010. Cotton's share of the world textile fiber market is projected to decline to 37%. China (mainland), India, Pakistan and Turkey will remain major textile economies, with a dependency on cotton imports. Cotton consumption in China (mainland) is projected to surpass 10 million tons in 2009/10, 40% of world mill use.

13.4.1 Retail consumption

In 2003, developed countries as a group accounted for 44% of world cotton retail level consumption, and developing countries accounted for 52%. At the retail level, the USA is the largest consuming country, accounting for 21% percent of total cotton use in 2004. Per capita cotton consumption in the USA was 16 kilograms in 2004, compared with a world average of only 3.5 kilograms. High consumer incomes, a history of cotton consumption, consumer preferences in favor of cotton bolstered by industry advertising, and fashion trends that favor cotton explain the high level of per capita cotton use in the USA.

Retail consumption of cotton in Latin America accounted for 9% of world cotton use in 2000, and per capita consumption was 3.2 kilograms per year. Consumers in Brazil and Mexico account for two-thirds of Latin American retail level cotton use. Retail consumption in the EU-15 accounts for 16% of world cotton use, and per capita cotton consumption in Europe was about 7 kilograms in 2000. The lower level of per capita consumption of cotton in Europe compared with the USA reflects lower average income levels, less consumer-oriented retail structures, and differences in tastes and preferences between American and European consumers.

Retail consumption in Russia and other countries of the former USSR accounted for 2% of world cotton use in 2000, and per capita cotton use was below the world average at just 2.7 kilograms. Retail consumption in the Middle East, including Turkey, accounted for 6% of world use in 2000, and per capita consumption was equal to the world average at 3.6 kilograms per year. Africa, including South Africa and Egypt, accounts for only 2% of world cotton use at the retail level, and per capita consumption of cotton in Africa is less than 1 kilogram per year.

Retail consumption in Japan equalled 6% of world cotton use in 2000, and per capita consumption in Japan was 9 kilograms, 2 kilograms higher than the EU average, but lower than in the USA. Consumption in the rest of East Asia, including China, and in South Asia accounted for 31% of world cotton use at the retail level in 2000, but per capita consumption averaged just 1.8 kilograms because of low incomes and government policies that favor the use of polyester to conserve land devoted to cotton. One of the great challenges for the cotton industry is to raise per capita consumption in the countries with the largest populations, including China where cotton use per capita was just 1.9 kilograms in 2000, India, with per capita cotton use of 1.7 kilograms and Indonesia, with per capita use of 1.4 kilograms. It is hoped that rising incomes in India, Indonesia and China (mainland) will lead to increases in per capita cotton consumption during the current decade.

13.4.2 Mill consumption

Mirroring end-use consumption, world mill consumption of cotton was stagnant during the first half of the 1990s, growing by only 0.6% between 1990 and 1997, but increased rapidly thereafter (Table 13.3). In the early 1990s, mill consumption of cotton declined dramatically in Eastern Europe and the former USSR, from 2.5 million tons in 1990/91 to 730,000 tons in 1998/99, offsetting gains elsewhere in the world. Mill consumption of cotton in the former Council Mutual Economic Cooperation (COMECON) group of countries recovered to 900,000 tons in 2004/05. Mill consumption of cotton in industrial countries remained at about 4 million tons during the early 1990s, but declined rapidly after 1998/99 to 2.2 million tons in 2004/05. High cost structures and increased import competition from developing countries caused the cotton textile industries in many industrial countries to reduce production beginning in the late 1990s.

Mill consumption of cotton in developing countries increased at an annual rate of 3.9%, from 8.5 million tons in 1980/81 to 12.3 million tons in 1990/91. Growth of mill consumption decelerated during first seven years of the 1990s to an average annual rate of 2.7% reaching 14.3 million tons in 1997/

Table 13.3 Top ten cotton consumers

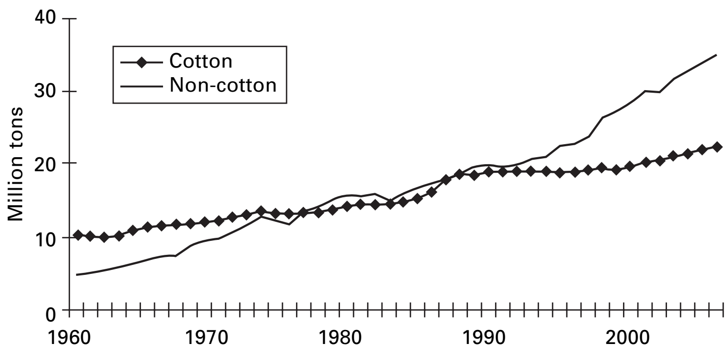
		Thousand tons	
1	China (M)	8,200	35.0%
2	India	3,300	14.1%
3	Pakistan	2,300	9.8%
4	Turkey	1,550	6.6%
5	USA	1,361	5.8%
6	Brazil	935	4.0%
7	Indonesia	490	2.1%
8	Mexico	450	1.9%
9	Thailand	450	1.9%
10	Bangladesh	394	1.7%
	Others	3,970	17.0%
	World	23,400	100.0%

98, but regained strength since 1998/99, growing at an average annual rate of 5% to reach 20 million tons in 2004/05. The bulk of the increase since 1998 occurred in China (mainland), but important expansions were also registered in India, Pakistan and Turkey. As a result, the processing of cotton continued to concentrate in developing countries, and their share of world mill consumption rose from 67% in 1990/91 to 86% in 2004/05, compared to 46% in 1970/71 and 28% in 1950/51.

For the past seven years, China (mainland) has been the driving force of the world textile industry. Between 1998/99 and 2004/05, the increase in mill consumption of cotton in China accounted for 91% of additional consumption worldwide. The Chinese industry processed 8.2 million tons of raw cotton in 2004/05, an increase of 4.3 million tons since 1998/99, and 35% of global mill use, up from 23% in 1998/99. The textile industry in China (mainland) is highly dependent on the export market, and China (mainland) has increased its share of world textile and apparel exports in the last six years. During the 1990s, mill consumption of cotton became more concentrated in the largest processing countries. In 1980/81, the six countries that are the largest processors today, China (mainland), India, Pakistan, the United States, Turkey, and Brazil, accounted for 51% of world mill consumption. These countries accounted for 57% of world mill consumption in 1990/91, and 76% in 2004/05.

13.4.3 Inter-fiber competition

World consumption of all textile fibers, including cotton, chemical fibers and wool, increased at an impressive pace, from 9.6 million tons in 1950, to 58 million tons in 2004 (Fig. 13.7 and Table 13.4). Several variables are associated with changes in cotton consumption, including growth in income and population, changes in cotton prices relative to prices of competing fibers, consumer preferences and changes in fashion. Fibers competing with



13.7 World fiber use.

Table 13.4 World consumption of major textile fibers

	Total	Cotton	Wool	Chemical fibers*			Cotton	Wool	Chemical fibers*		
				All 1,000 Metric tons	Non-Cellu-losics	Cellu-losics			All Percent	Non-Cellu-losics	Cellu-losics
1960	15,153	10,356	1,495	3,302	702	2,600	68.3	9.9	21.8	4.6	17.2
1961	15,102	10,085	1,505	3,512	830	2,682	66.8	10.0	23.3	5.5	17.8
1962	15,339	9,902	1,501	3,936	1,080	2,856	64.6	9.8	25.7	7.0	18.6
1963	16,003	10,147	1,475	4,381	1,331	3,050	63.4	9.2	27.4	8.3	19.1
1964	17,256	10,830	1,460	4,966	1,687	3,279	62.8	8.5	28.8	9.8	19.0
1965	18,182	11,318	1,473	5,391	2,052	3,339	62.2	8.1	29.6	11.3	18.4
1966	18,796	11,539	1,545	5,712	2,371	3,341	61.4	8.2	30.4	12.6	17.8
1967	19,212	11,695	1,473	6,044	2,730	3,314	60.9	7.7	31.5	14.2	17.2
1968	20,434	11,763	1,565	7,106	3,578	3,528	57.6	7.7	34.8	17.5	17.3
1969	21,248	11,911	1,604	7,733	4,178	3,555	56.1	7.5	36.4	19.7	16.7
1970	21,741	12,105	1,500	8,136	4,700	3,436	55.7	6.9	37.4	21.6	15.8
1971	23,037	12,493	1,480	9,064	5,609	3,455	54.2	6.4	39.3	24.3	15.0
1972	24,417	12,903	1,578	9,936	6,377	3,559	52.8	6.5	40.7	26.1	14.6
1973	26,031	13,288	1,443	11,300	7,640	3,660	51.0	5.5	43.4	29.3	14.1
1974	25,267	12,986	1,262	11,019	7,487	3,532	51.4	5.0	43.6	29.6	14.0
1975	24,717	13,047	1,358	10,312	7,353	2,959	52.8	5.5	41.7	29.7	12.0
1976	26,537	13,211	1,515	11,811	8,601	3,210	49.8	5.7	44.5	32.4	12.1
1977	27,025	13,117	1,478	12,430	9,149	3,281	48.5	5.5	46.0	33.9	12.1
1978	28,246	13,415	1,481	13,350	10,032	3,318	47.5	5.2	47.3	35.5	11.7
1979	29,440	13,897	1,558	13,985	10,614	3,371	47.2	5.3	47.5	36.1	11.5
1980	29,580	14,295	1,567	13,718	10,476	3,242	48.3	5.3	46.4	35.4	11.0
1981	29,731	14,124	1,576	14,031	10,827	3,204	47.5	5.3	47.2	36.4	10.8
1982	28,895	14,248	1,556	13,091	10,145	2,946	49.3	5.4	45.3	35.1	10.2
1983	30,166	14,548	1,612	14,006	11,076	2,929	48.2	5.3	46.4	36.7	9.7

Table 13.4 Continued

	Total	Cotton	Wool	Chemical Fibers*			Cotton	Wool	Chemical fibers*		
				All 1,000 Metric tons	Non-Cellu-losics	Cellu-losics			All Percent	Non-Cellu-losics	Cellu-losics
1984	31,251	14,830	1,621	14,800	11,804	2,996	47.5	5.2	47.4	37.8	9.6
1985	32,813	15,768	1,625	15,420	12,489	2,931	48.1	5.0	47.0	38.1	8.9
1986	34,956	17,462	1,708	15,786	12,927	2,859	50.0	4.9	45.2	37.0	8.2
1987	36,546	18,226	1,754	16,566	13,741	2,825	49.9	4.8	45.3	37.6	7.7
1988	37,427	18,210	1,904	17,313	14,417	2,896	48.7	5.1	46.3	38.5	7.7
1989	38,227	18,677	1,861	17,690	14,747	2,943	48.9	4.9	46.3	38.6	7.7
1990	37,882	18,602	1,628	17,652	14,894	2,758	49.1	4.3	46.6	39.3	7.3
1991	38,069	18,562	1,801	17,706	15,273	2,433	48.8	4.7	46.5	40.1	6.4
1992	38,871	18,627	1,757	18,488	16,161	2,327	47.9	4.5	47.6	41.6	6.0
1993	39,109	18,544	1,649	18,916	16,587	2,329	47.4	4.2	48.4	42.4	6.0
1994	40,334	18,369	1,723	20,242	17,939	2,303	45.5	4.3	50.2	44.5	5.7
1995	40,720	18,353	1,554	20,813	18,377	2,436	45.1	3.8	51.1	45.1	6.0
1996	42,245	18,770	1,440	22,035	19,765	2,270	44.4	3.4	52.2	46.8	5.4
1997	45,034	19,007	1,361	24,666	22,396	2,270	42.2	3.0	54.8	49.7	5.0
1998	45,443	18,669	1,293	25,481	23,254	2,227	41.1	2.8	56.1	51.2	4.9
1999	47,073	19,120	1,393	26,560	24,485	2,075	40.6	3.0	56.4	52.0	4.4
2000	49,553	19,739	1,380	28,434	26,219	2,215	39.8	2.8	57.4	52.9	4.5
2001	49,789	20,102	1,361	28,326	26,244	2,082	40.4	2.7	56.9	52.7	4.2
2002	52,298	20,813	1,308	30,177	28,052	2,125	39.8	2.5	57.7	53.6	4.1
2003	54,165	21,256	1,206	31,703	29,432	2,271	39.2	2.2	58.5	54.3	4.2
2004	57,833	22,434	1,219	34,180	31,689	2,491	38.8	2.1	59.1	54.8	4.3

Sources: ICAC, Commonwealth Secretariat, International Wool Secretariat, and Fiber Economics Bureau.

cotton include natural fibers and chemical fibers, primarily polyester. Cotton's share of world textile fiber use fell from more than 70% in the 1950s to less than 50% by the end of the 1970s. Cotton did better in the 1980s. However, cotton's share of world textile fiber fell below 40% in 2002. Over the last five decades, cotton experienced an erosion of both price and non-price competitiveness.

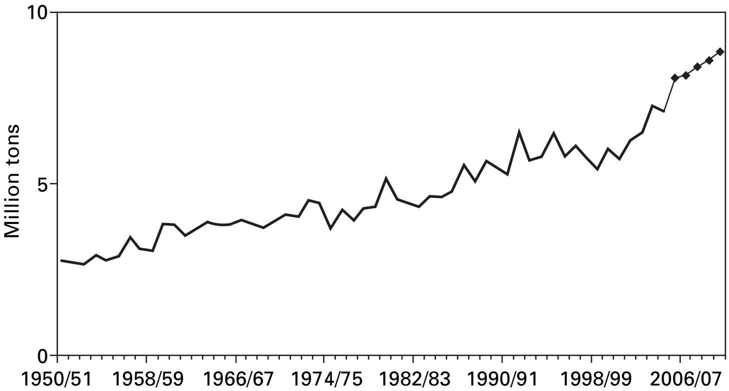
Cotton's major advantages over its primary competitors in the chemical fiber complex include wearing comfort, natural appearance, moisture absorbency, its status as a renewable resource and the important economic role of cotton in many producing countries. However, cotton also suffers from several disadvantages relative to chemical fibers, including contamination introduced during harvest, ginning and handling, annual fluctuations in the quantity and quality of production and consequent variability in prices. Cotton also has difficulty meeting the needs of modern spinning equipment for strength, uniformity and other quality parameters.

Relative fiber prices are extremely important in determining fiber market shares. During most years in the 1980s and 1990s, cotton prices were higher than prices of polyester, explaining much of the decline in fiber market share for cotton during those years. However, since 1998/99, cotton prices have been lower and polyester prices have been higher. As a consequence, cotton consumption rose at an average rate of 4% per year during the period from 1998 to 2004, compared to average growth of 1.5% per year in the two decades prior to 1998.

One common area of misunderstanding is the relationship between oil prices and prices of polyester fiber. Many people assume that because polyester is derived from chemicals refined from oil, that increases in crude oil prices lead to increases in polyester prices. However, the precursor chemicals used to make polyester account for only a small fraction of oil consumption, and each of the chemicals have multiple uses. As a consequence, there are separate markets for the chemicals used to make polyester, and those markets have little correlation with oil prices. Therefore, prices for polyester fiber are not determined by the price of oil, and in fact there is almost no statistical correlation between oil prices and polyester fiber prices.

13.5 Trade

World trade in cotton rose from 2.6 million tons in 1950/51 to 4 million tons in the early 1970s and reached 5.8 million tons in 1986/87. Cotton imports averaged 5.9 million tons during the 1990s and climbed to a record of 7.3 million tons in 2004/05 (Fig. 13.8). Among the top seven cotton producing countries, only Uzbekistan does not rank among the top seven consuming countries. Trade accounted for 28% of world cotton production in 2004/05, and the value of world exports was $8.4 billion.



13.8 World cotton imports.

World trade in cotton is projected at 7 million tons in 2004/05. Production is falling behind mill use in China (mainland), Pakistan, India and Turkey. The four countries accounted for 15% of world imports in 2000/01 and for an estimated 37% in 2004/05, while imports by the rest of the world decline. In 2005/06, world trade in cotton is projected to reach 8 million tons and the share of the four countries is projected to reach 49% of world cotton imports.

The largest and most significant impetus to the growth of world trade in cotton is provided by a sharp increase of cotton use in China (mainland) (Table 13.5). A record surge of cotton imports by China (mainland) to 1.9 million tons, or 26% of world imports in 2003/04, led world trade to a record. With the reduction of stocks in China (mainland) to minimum levels, the government began to provide full support to imports by issuing sufficient import quotas as a measure to balance supply and use, reduce domestic prices and make the textile industry more competitive. Imports by China (mainland) are estimated at 1.5 million tons in 2004/05 and are projected to reach 2.8 million tons in 2005/06.

For the third season in a row Turkey is the second largest importer of cotton accounting for 650,000 tons or 8% of world imports in 2004/05. The textile industry in Turkey continues to expand, driven by rising exports of textiles and apparel to Europe, USA and other markets. Between 2000/01 and 2004/05, mill use in Turkey rose by 300,000 tons and reached 1.45 million tons. Because cotton production in Turkey remains behind increasing use, imports remain a significant source of supply. Turkey was the largest importer of cotton in 2001/02 with imports estimated at 624,000 tons. In 2002/03 and 2003/04 imports were at 516,000 tons. The USA provides General Sales Manager-102 credit guaranties to Turkey and is the largest supplier of cotton to Turkey. In 2003/04, Turkey imported 317,000 tons from the USA accounting for 61% of total imports, the same as in 2002/03. About $120 million of USA cotton sales to Turkey or 31% of all imports were registered

Table 13.5 Top six cotton importers 2004/05

		Thousand tons	
1	China (M)	1,394	19.4%
2	Turkey	750	10.5%
3	Indonesia	511	7.1%
4	Thailand	480	6.7%
5	Bangladesh	394	5.5%
6	Mexico	365	5.1%
	Others	3,277	45.7%
	World	7,171	100.0%

under the GSM 102 program in 2002/03 and $170 million or 36% of all imports in 2003/04. Greece was the second largest supplier of cotton to Turkey, accounting for 82,000 tons or 16% of imports in 2003/04. Syria and Central Asia are other major suppliers of cotton to Turkey, accounting for approximately 6% each. An increase in cotton production in Turkey in 2004/05, estimated at 50,000 tons, could result in a similar reduction in imports.

India became one of the leading importers of cotton starting in 1999/2000 because of reduced production due to reduced planted area and drought. During the same period, Indian mill consumption was stable at around 2.9 million tons, supported by strong exports of cotton yarn and textile exports to Asian markets, USA, Canada and Mexico. In 2001/02, India imported 520,000 tons of cotton accounting for 8% of world imports. Indian area and yields rose during 2004/05, resulting in a crop of 3.9 million tons and as a result of increased domestic supply, imports by India declined to 150,000 tons. In 2005/06 Indian imports are projected to increase to 175,000 tons.

Because of reduced domestic production, low prices and increased demand for fine count yarns, India became one of the largest importers of extra-fine cotton, with imports of this category reaching 40,000 tons in 2003/04. Most extra-fine cotton was imported from Egypt and the USA. It is expected that India will remain the major importer of extra-fine cotton in 2004/05. Cotton consumption in Pakistan continues to expand rapidly in response to export-driven demand. During 2004/05, cotton mill use in Pakistan rose by 10% and reached 2.3 million. Imports by Pakistan doubled during 2003/04 to 400,000 tons, but is projected decline in 2004/05 to 200,000 tons because of increased production. Projected decline in domestic supply of cotton in 2005/06 in Pakistan could lead to an increase of imports to 290,000 tons.

The largest share of increased world import demand was met during the past three seasons by exports from the USA (Table 13.6). Large supplies of cotton in the USA, declining mill use and the effects of the marketing competitiveness provisions of the government program, known as the marketing

Table 13.6 Top six cotton exporters 2004/05

		Thousand tons	
1	USA	3,048	39.9%
2	Uzbekistan	850	11.1%
3	Australia	420	5.5%
4	Brazil	360	4.7%
5	Mali	268	3.5%
6	Greece	263	3.4%
	Others	2,434	31.8%
	World	7,643	100.0%

loan and Step 2, led to record US exports of 3 million tons in 2003/04. In 2004/05, US exports are expected to decline to 2.75 million tons because of a projected decline in imports by producing countries, but the USA will still account for 40% of world exports. In 2005/06, US exports are projected to exceed 3 million tons because of expected record imports by China (mainland).

The other largest exporters are Uzbekistan, Australia, West Africa and Brazil. Together these countries will account for 33% of world shipments in 2004/05. Because of a projected decline in import demand during 2004/05, exports by most of the major exporters are expected to decline, except for Uzbekistan where because of projected rebound in production exports are projected to increase by 14% to 730,000 tons, and Brazil, where an expected sharp increase in production could cause exports to double.

Exports from Uzbekistan were mostly declining from 1.3 million tons in 1992/93 to 650,000 tons in 2003/04. The reason for the steady decline in exports was a decline in production and increased mill use. In 2004/05, production in Uzbekistan is projected to rebound and exports are projected to increase to 760,000 tons, accounting for 11% of world exports. Cotton area in Uzbekistan is projected to remain stable during the next several seasons. At the same time, Uzbekistan is expected to continue expansion of spinning capacity, increasing utilization of cotton domestically and reducing the availability of supplies for exports.

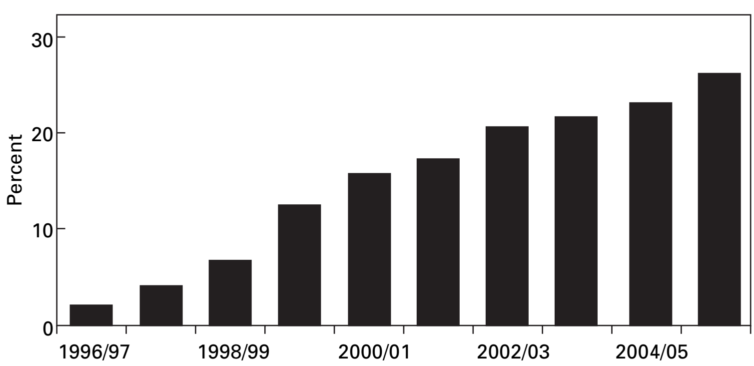
Between 1991/92 and 2002/03, Brazil was a net importer of cotton. During the past several seasons cotton production began to rise rapidly because of new high yielding commercial production in Central Brazil, including, Mato Grosso. In 2003/04, cotton production in Brazil exceeded consumption by almost half a million tons. Exports by Brazil estimated at 210,000 tons in 2003/04 are projected to double in 2004/05 to 400,000 tons. A large crop is projected for Brazil in 2005/06, and Brazil will likely remain a net exporter of 450,000 tons of cotton.

Exports from the Currency of Francophone Africa (CFA) zone reached a record of 1.1 million tons in 2003/04, an increase of more than 200,000 tons from 2002/03. Cotton production in the CFA zone reached a record of 1.03 million tons in 2001/02, an increase of 300,000 tons. Political difficulties in Cote d'Ivoire impeded shipments from the region, leading to a build up of large stocks estimated at over 500,000 tons in 2002/03. Exports from the CFA zone are estimated at 790,000 tons in 2004/05, because of reduced import demand, and at 1.1 million tons in 2005/06 accounting for 15% of world exports 2004/05.

Australian production suffered from severe drought during the past several seasons leading to a sharp decline in exports. In 2004/05, Australian exports fell to 420,000 tons compared with 850,000 tons in 2000/01. Australian cotton production in 2004/05 is projected to increase to 610,000 tons from 350,000 tons in 2003/04. Exports from Australia are projected to increase to 550,000 tons during 2005/06 as a result of increased production. Australia will account for only 7% of world exports in 2004/05, compared with 14% during 2000/01.

13.5.1 Biotech cotton

Biotech cotton is entering the world textile trade pipeline in increasing volumes as a result of growing world production and exports from the USA and Australia and textile exports from China (mainland) (Fig. 13.9). Based on the production shares of biotech cotton in exporting countries, it is estimated that biotech cotton accounted for 34% of world exports in 2002/03 and 36% in 2003/04. In 2004/05 the share of biotech cotton in world exports is declining to 31% because of an expected decline in export volumes from the USA and Australia. A larger share of world production will be consumed domestically in China (mainland). In 2003/04, an estimated 64% of all exports of biotech



13.9 GE cotton area.

cotton went to Asia and Oceania (not counting the Middle East) compared with 58% in 2002/03.

Based on domestically produced and imported biotech cotton, especially in China (mainland), it is estimated that 60% of mill use in Asia and Oceania were accounted for by biotech cotton in 2003/04 compared with 31% in 2002/03. Taking into account that Asia and Oceania account for more than 65% of world exports of cotton textiles, it is evident that the share of biotech cotton in textiles traded in major markets in Europe and America is rising. Despite an increasing share of biotech cotton traded in the world, there are no price differentials for biotech and non-biotech cotton fiber, or textiles containing biotech cotton. There is no evidence of rejection of biotech cotton by any segment of the market or region. In practice, markets do not identify biotech cotton content, but rather evaluate cotton properties based on quality characteristics.

13.5.2 China (mainland)

Substantial impacts on world textile trade have been caused by the entry of China (mainland) into the World Trade Organization in late 2001. The textile industry in China (mainland) is highly dependent on the export market, and can be sensitive to world affairs. Nonetheless, low labor costs and Chinese government policies have improved the country's competitiveness compared with other textile exporting developing countries, and China (mainland) has increased its share of world textile and apparel exports in the last four years. China (mainland) became the leading supplier of textile manufactures to the USA market, the largest retail market for textiles and apparel in the world.

China (mainland's) success in the world textile market stems from an early recognition that the development of its textile complex had to focus on where it was most competitive, in the apparel sector. China (mainland) has a substantial labor cost and supply advantage compared with other major textile and apparel producers. Development of the competitive apparel production sector served as a catalyst for expanded investments in modernization of the capital-intensive textile sector. China (mainland) has invested heavily in the modernization of the textile and apparel sectors during the past ten years, and investments in the textile sector rose by 80.4% in 2003 alone reaching $10.7 billion according to the National Bureau of Statistics. China (mainland) imported $11.8 billion worth of textile machinery between 2000 and June 2003 according to International Textile Manufacturers Federation (ITMF) data. As a result, China (mainland) became the world's largest textile economy, the largest exporter of textiles and clothing, the largest cotton and chemical fiber producer, with the textile sector generating 10% of GDP. Per capita fiber consumption in China (mainland) rose from 8.3 kg in 2000 to

10.8 kg in 2002, and the population is rising by 11–12 million annually to reach 1.32 billion in 2005. The rate of growth of retail apparel sales in China (mainland) reached 20% in January–February 2005 compared to a year earlier and the rate of growth in rural areas is outpacing urban sales. China (mainland) is positioned to increase its market share with the elimination of quotas. However, other developing countries could find new opportunities with open competition.

13.5.3 Turkey

A similar strategy of modernization and investments was implemented by Turkey, where combined exports of textiles and clothing rose from $474 million in 1980 to $15.180 billion in 2003. During that period exports of textiles rose by 1,428% while exports of apparel rose by 7,487% reaching $9.4 billion. In 2004 apparel output in Turkey rose by 5.5% in volume compared to 2.8% growth recorded in 2003, while textile output rose by 4.2% in 2004 after declining by 0.9% in 2003. Turkey's top export market is the EU, while exports of cotton apparel suffered a 4.3% decline in the USA in 2004, losing to rising volumes from China (mainland), India and Pakistan.

13.5.4 India

India has been developing its textile and apparel sectors at impressive growth rates. Between 1980 and 2003, exports by both sectors in India rose by 647%. In India, the second largest cotton processing country, mill consumption of cotton between 1990/91 and 1997/98 increased at an average annual rate of 4.3%, or seven times more rapidly than world consumption growth. Demand for Indian textile products has been supported mainly by very strong exports, in particular exports of cotton yarn. Taking advantage of relatively low costs of cotton processing, Indian exports to other Asian markets increased faster than to other destinations between 1990/91 and 1997/98. In addition, promotion of exports to the USA, Canada and Mexico, as well as to Latin American countries has been developed since 1996. Nonetheless, Indian mill consumption of cotton remained at 2.9 million tons between 1998/99 and 2003/04, due to increased competition from China (mainland) and other textile exporters. However, Indian mill consumption of cotton is projected to rise by 12% in 2004/05 to reach 3.4 million tons because of improved competitive advantage of cotton yarn and apparel production in India and the expansion of exports of textiles and apparel.

In 2005/06 Indian cotton consumption is projected to reach 3.4 million tons or 14% of world mill use. One of the important effects of lower cotton prices is an increase in the market share of cotton in India, and as a result a decline in the output of man-made fibers. During most of 2004, cotton prices in India were lower than cotton prices in China (mainland). In December 2004 monthly output of man-made fibers was the lowest since February 2004, while cotton yarn and fabric output reached a record rising by 7.4% during 2004. India has been one of the three top winners of the post-quota era along with China (mainland) and Pakistan, exercising a competitive advantage in yarn and fabric production. India's apparel production began rising strongly during the second half of 2004 and by December 2004, rose 38.2% in volume compared with December 2003.

13.5.5 Pakistan

In Pakistan, during the past 20 years, more emphasis was given to the development of the textile sector compared with clothing industries, and the combined export growth between 1980 and 2003 was 770%. However, recently Pakistan began to expand apparel and fabric production, while reducing exports of cotton yarn due to increased competition from Indian yarns and increased domestic demand for yarns from weavers and knitters. Knitwear exports from Pakistan soared 35.8% during 2004.

13.5.6 Winners and losers

The elimination of quotas provided an opportunity for large competitive textile producers like China (mainland), India and Pakistan to increase their market share. However, the elimination of quotas will also intensify competition in the open marketplace and will necessitate and stimulate a number of developing countries to restructure their textile economies investing in the modernization of the sectors where their competitive advantage lies in an attempt to capture a larger share of the market. The end of quotas lowers the barriers to entry by new exporters with a wider range of products and could lead to lower prices for textiles. Countries enjoying a guaranteed quota earlier, or quota-free access to the most lucrative markets, could lose market share if their products are of low quality and not competitive. Quality, product innovation, reliability, demand responsiveness, market proximity, quick turnover and preferential tariffs are become increasingly important competition factors.

In 2005, Mexico lost its advantage of quota-free access to the US market provided by the North American Free Trade Agreement (NAFTA) trade regime, but will continue to have an advantage of market proximity and tariff-free access. As a result Mexico could lose market share to China (mainland). Similarly, countries of Central and Eastern Europe and the Mediterranean will lose the advantage of quota-free access to the EU, but will continue to benefit from market proximity and duty-free access.

Market shares in textile trade of countries with quota-free and duty-free access to large markets in the USA or EU, but with relatively weak industries or/and remote locations, such as Bangladesh (EU and USA agreements), Mauritius (EU agreement), Sub-Saharan Africa (African Growth and Opportunity Act, or AGOA, an agreement providing preferential access to the USA market for textile and apparel products from Africa), Hong Kong (large quotas) and countries in similar positions could decline.

13.6 Government measures

An important factor explaining the location of cotton production in relatively high-cost countries is government measures that distort production and trade (Table 13.7). Direct income and price supports for cotton worldwide ranged between \$3.8 billion in 1997/98 and \$5.8 billion in 2001/02. For 2004/05, direct income and price support programs for cotton are estimated at \$4.7 billion. Fourteen countries representing three-fourths of world cotton production offered direct income and price support programs to cotton growers in 2001/02, a season of record low prices, resulting in higher production and forcing the burden of adjustment to low cotton prices onto growers in countries that did not provide similar measures of protection. Developed countries and China (mainland) accounted for 86% of assistance provided worldwide.

In 2004/05, the greatest government assistance per pound of cotton production was provided by the European Union to producers in Greece and Spain, with support averaging 95 cents per pound of lint production, or approximately \$1.1 billion in total. Support in the EU is paid to cotton ginners, and ginners are required to provide the support to farmers based on seed cotton deliveries adjusted for quality. The amount of support paid to each farmer is based on the difference between market prices at the time of harvest and a target price set by the EU. The EU does not try to restrict cotton imports in order to keep domestic prices above the world level. The EU announced in 2004 that 65% of the value of support for cotton will be paid to farmers directly and decoupled from current cotton production beginning in January 2006. This means that beginning in 2006, cotton farmers in Greece and Spain will receive 65% of the support they used to receive whether they continue to produce cotton or not, and only 35% of government support will be based on current production. This change, known as decoupling, will lead to lower production. The EU produced 500,000 tons in 2004/05, and cotton production is forecast to decline by one-fourth by 2006/07.

In 2004/05, direct support to cotton farmers in the USA averaged 20 cents per pound of production, about equal to the average since the early 1980s. The total value of direct support was \$2.2 billion. Support in the USA included payments to farmers based on the difference between average farm prices and a target price. US growers also received a fixed payment based on

Table 13.7 Level of direct assistance provided by governments to the cotton sector

(a) Through production programs*

Country	2003/04			2004/05**		
	Production 1,000 tons	Average assistance per pound produced US cents	Assistance to production US$ Millions	Production 1,000 tons	Average assistance per pound Produced US cents	Assistance to production US$ Millions
China (mainland)	4,871	12	1,303	6,320	8	1,145
USA	3,975	12	1,021	5,025	20	2,244
Greece	320	108	761	400	95	836
Spain	98	108	233	110	95	230
Turkey	910	1	22	900	6	115
Egypt	198	2	9	285	14	89
Mexico	68	4	6	138	16	49
Benin				125	12	34
Colombia				61	8	11
All Countries	10,440	15	3,354	13,364	16	4,753

* Income and price support programs only. Credit and other assistance not included.
** Preliminary.

Table 13.7 Continued

(b) Through export program

Country	2003/04			2004/05**		
	Exports 1,000 tons	Average assistance per pound exported US cents	Assistance to exports US$ Millions	Exports 1,000 tons	Average Assistance per pound exported US cents	Assistance to exports US$ Millions
USA	2,996	4	235	2,745	6	375
Upland cotton	2,878	3	190	2,574	3	165
Pima	118	17	45	171	56	210
Egypt	89	1	2	130	3	8
India				150	2	7
Total	3,085	3	237	2,875	6	383

* Preliminary.

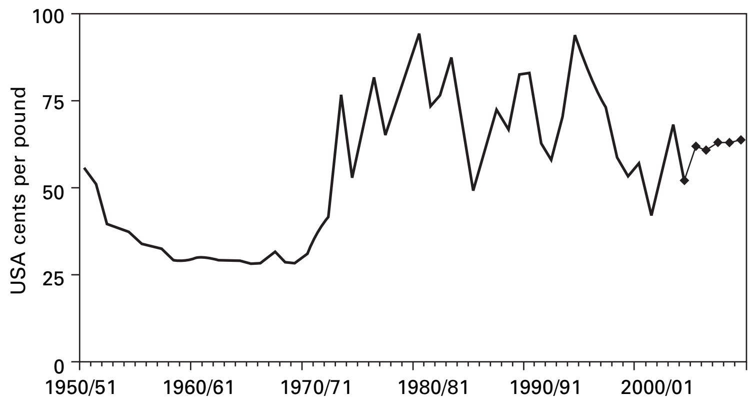
historical production. As in Europe, the USA does not attempt to restrict cotton imports in an effort to bolster domestic prices. Elements of the US cotton program came under specific criticism from the international community during the Doha Round of trade negotiations under the auspices of the WTO because of the unique roll played by cotton in the economies of many developing countries. During the Doha Round talks, the USA agreed to lower or eliminate subsidies to cotton, but only within the context of an overall agreement on agriculture.

The value of government support for the cotton sector of China (mainland) is estimated at 8 cents per pound in 2004/05, or about $1.1 billion. In contrast to Europe and the USA, China does not provide direct payments to cotton growers but instead uses a complex system of import quotas and licenses to restrict trade and maintain domestic prices above the world level. The Government of China claims in the WTO that it does not subsidize cotton, but the differential between international prices and equivalent domestic prices in China, adjusted for quality and common location, are persistent and substantial and well documented.

Government measures that boost cotton production have a negative impact on average international cotton prices in the short run. However, if subsidies were eliminated, production would expand in other countries within two to three seasons in response to higher prices, and many researchers feel that the long run impact of government measures on cotton prices is probably small. Nevertheless, the distortions to cotton production caused by government measures are significant. In the absence of government support for cotton and other commodities, cotton production in the USA would decline by an estimated one-third over several seasons, and production in China (mainland) would probably fall by about one-tenth. As a consequence, between two and three million tons of cotton production would shift from Europe, the USA and China toward lower cost producing countries if government measures were eliminated.

13.7 Prices

International cotton prices have declined over time due to more efficient production practices. During the 1950s and 1960s, as production rose while consumption was affected by growth in the use of chemical fibers, cotton prices generally trended lower (Fig. 13.10). The Cotlook A Index, an indicator of world cotton prices (method of calculation), dropped from more than 50 cents per pound in 1950 to less than 30 cents by the end of the 1960s. During the 1970s cotton prices were influenced by the same factors of inflation, rising demand, concerns about trade embargoes and increases in production costs that affected all commodity markets, and the Cotlook A Index rose to more than 70 cents per pound. During the ten years to 1985/86 international cotton prices averaged 75 cents per pound. Between 1985/86 and 1994/95,



13.10 Cotlook A Index.

prices averaged 70 cents per pound, and in the nine years to 2004/05, prices averaged 60 cents per pound.

Several factors influenced the long-term decline in average prices, among which are new technologies, more extensive use of existing technologies, and new area dedicated to cotton. Nevertheless, despite distortions caused by government measures, cotton supply and demand are price-responsive. Average international prices rebounded from a 19-year low of 42 cents per pound in 2001/02 to 68 cents in 2003/04 before falling to an average of 52 cents in 2004/05.

When adjusted for inflation, cotton prices have declined since the 1950s. In 2005 US dollars, the Cotlook A Index fell from nearly $4 per pound in the early 1950s to approximately $1.2 in the early 1970s. With the rise in commodity prices in the mid-1970s, the Cotlook A Index climbed to more than $2 per pound but has tended lower in real terms since and collapsed to $0.43 per pound in 2001/02, the lowest since the invention of the cotton gin in 1793. Despite the increase in average yields, real average revenue per hectare of cotton also declined over the last five decades. In 2005 US dollars per hectare at an average world yield, the average revenue from cotton fell from about $2,000 in the early 1950s to $1,000 in the late 1960s. In the mid-1970s, the average revenue rose to about $2,400 per hectare but relapsed to $1,000 during the 1990s. Average revenue per hectare is estimated at $830 in 2004/05.

13.8 Future trends

World production and consumption in 2009/10 are estimated at approximately 27 million tons, and world trade is estimated at 9 million tons, including imports by China (mainland) of 4 million tons. New technologies, the development of new areas dedicated to cotton and government measures are expected to continue to support cotton production in the next five seasons.

Area dedicated to biotech cotton varieties is expected to climb to 40% of world area accounting for 50% of cotton production. The average world yield is expected to surpass 800 kilograms per hectare. Over the next five years, cotton consumption is expected to expand at an annual rate of 3%. Consumption in China (mainland) is projected to climb to 11 million tons in 2009/10, approximately 40% of world mill use. Cotton's share of the world textile fiber market is projected to remain near 40%.

Because of the increasing importance of China (mainland) to the world cotton market, net trade between China and the rest of the world will continue to play an important role in determining cotton prices. World ending stocks are projected to average 45% of global consumption over the next five years, down from 50% on average from 1997/98 to 2004/05. In contrast, the stocks-to-use ratio (the ratio of stock on 31 July each year (the end of the season) divided by consumption during the season – a measure of how tight stocks are relative to demand (used as a key indicator of the direction of prices)) outside China (mainland) is expected to average 70% over the next five seasons, sharply up from an average of 40% during the 1990s.

Year-to-year changes in cotton production are determined by marginal costs, not by average production costs. Therefore, cotton prices tend toward the marginal cost of the most efficient producers, not the world average production cost. Costs of production worldwide are coming down. At current exchange rates, marginal production costs – and in the case of more efficient producers, total costs – are below 55 cents per pound in several countries. Competing chemical fibers will put additional pressure on cotton prices. The consequence will be lower average prices over the next decade compared to the 70 cent average of the last 30 years, and the Cotlook A Index is expected to average between 45 and 55 cents per pound between 2005 and 2015.

13.9 Sources of further information

Statistical information about the world cotton industry is available from three main sources. The International Cotton Advisory Committee provides comprehensive statistics on world cotton supply, use and prices by country from the 1920s. The ICAC provides extensive information on fiber use and market share by country, government measures, trade by country of origin and destination, and statistics on production and trade in cotton yarn and woven cotton fabric. In addition, the ICAC provides technical information on cotton production practices, costs of production, and new technologies affecting cotton production. Information is available at www.icac.org.

The US Department of Agriculture has several important web sites for cotton information. Data on area, yield and production by state, as well as reports on input use in cotton are available from the National Agricultural Statistics Service at www.USDA.Gov/Nass/. Data on consumption, market share, production and trade are available from the Economic Research Service at www.ERS.USDA.gov/Briefing/cotton. Data on trade in cotton and reports from USA agricultural attaches in embassies around the world are available from the Foreign Agriculture Service at www.FAS.USDA.gov/Cotton.

A private company in Liverpool, UK publishes an industry magazine and information service known as *Cotton Outlook* at www.cotlook.com. This is the best source for data on cotton prices. The International Textile Manufacturers Association, ITMF, provides valuable statistics on industry capacity and textile machinery shipments at www.ITMF.org. The International Cotton Association in Liverpool provides data on arbitration of disputes that arise from trade in cotton. Their address is www.LCA.org.uk.

Several interesting books for general readership have been published in the past year dealing with different aspects of cotton and providing insight into the culture and workings of the international cotton industry. The best for objective information about the economics of the cotton industry is, *The Travels of a T-Shirt in the Global Economy*, by Pietra Rivoli. Another book, *Big Cotton*, by Stephen Yafa provides insights into the role of cotton in the industrial revolution and how cotton has influenced the politics of the United States. A third book, *The King of California*, looks at the history of one family in California that became the largest cotton producer in the USA.

A number of magazines and industry journals provide in-depth reports on various subjects of national and international interest to the cotton industry. In addition to *Cotton Outlook* mentioned earlier, there is *Cotton International (CI) World Report* from Meister Publishing. A free weekly newsletter is available at www.ciworldreport.com/newswire.

A magazine, *Cotton Bangladesh*, contains stories about the structure of the cotton textile industries in South Asia. Contact them at CottonBangladesh@aol.com.

An excellent source of information about developments in the textile industries of Asia, especially China (Mainland) is the magazine, *Textile Asia*, published in Hong Kong. Contact them at www.textilasia-businesspress.com.

13.10 References

All statistics and information in this chapter were sourced from publications of the Secretariat of the International Cotton Advisory Committee.

Appendix: World cotton supply and use

(Thousand metric tons)

	Area (000 Ha)	Yield (kgs/ha)	Production	Beginning stocks	Imports	Consumption	Exports	End stocks	S/U* Ratio
26/27	0	0	6,365	0	3,294	0	3,553		
27/28	0	0	5,288	0	3,201	0	2,826		
28/29	0	0	5,973	0	3,158	0	3,132		
29/30	0	0	6,073	0	3,135	0	2,806		
30/31	**0**	**0**	**5,895**	**0**	**2,947**	**0**	**2,762**		
31/32	0	0	6,081	0	2,875	0	2,897		
32/33	0	0	5,507	0	2,829	0	2,879		
33/34	0	0	6,004	0	3,125	0	2,995		
34/35	0	0	5,300	0	2,820	0	2,502		
35/36	0	0	6,023	0	2,859	6,343	2,971		
36/37	33,096**	201**	7,018	0	3,227	7,007	3,093		
37/38	0	0	8,346	0	2,818	6,384	2,749		
38/39			6,422	0	2,569	6,609	2,557		
39/40	0	0	6,353	0	2,723	6,557	2,811		
40/41	**0**	**0**	**6,934**	**0**	**1,643**	**6,130**	**1,467**		
41/42	0	0	6,223	0	1,587	5,597	1,262		
42/43	0	0	5,813	0	1,244	5,312	834		
43/44	0	0	5,399	0	938	4,987	880		
44/45	0	0	5,329	0	895	4,997	1,097		
45/46	22,305	209	4,651	6,509	1,882	5,350	2,005	5,696	1.06
46/47	22,547	211	4,757	5,696	2,118	6,134	2,084	4,259	0.69
47/48	23,914	230	5,501	4,259	2,077	6,486	1,935	3,270	0.50
48/49	25,425	254	6,450	3,270	2,524	6,341	2,419	3,351	0.53
49/50	28,732	249	7,154	3,351	2,628	6,749	2,767	3,708	0.55
50/51	**28,537**	**233**	**6,645**	**3,708**	**2,724**	**7,638**	**2,636**	**2,678**	**0.35**
51/52	36,040	234	8,427	2,678	2,661	7,657	2,671	3,417	0.45
52/53	35,448	246	8,736	3,417	2,612	8,044	2,594	4,070	0.51

Appendix: (continued)

	Area (000 Ha)	Yield (kgs/ha)	Production	Beginning stocks	Imports (Thousand metric tons)	Consumption	Exports	End stocks	S/U* Ratio
53/54	33,422	271	9,068	4,070	2,877	8,443	2,916	4,626	0.55
54/55	33,445	267	8,930	4,626	2,756	8,678	2,686	4,862	0.56
55/56	34,078	279	9,508	4,862	2,882	8,972	2,830	5,349	0.60
56/57	33,417	275	9,183	5,349	3,409	9,352	3,438	5,124	0.55
57/58	32,032	283	9,053	5,124	3,092	9,343	3,061	4,810	0.51
58/59	31,657	308	9,760	4,810	3,043	9,942	2,937	4,609	0.46
59/60	32,326	318	10,286	4,609	3,788	10,531	3,772	4,407	0.42
60/61	**32,445**	**314**	**10,201**	**4,407**	**3,804**	**10,231**	**3,667**	**4,551**	**0.44**
61/62	33,057	297	9,832	4,551	3,463	9,982	3,367	4,532	0.45
62/63	32,633	320	10,444	4,532	3,638	9,845	3,450	5,260	0.53
63/64	32,968	330	10,877	5,260	3,879	10,362	3,910	5,845	0.56
64/65	33,366	345	11,504	5,845	3,811	11,165	3,721	6,312	0.57
65/66	33,133	359	11,898	6,312	3,809	11,429	3,712	6,879	0.60
66/67	30,915	350	10,836	6,879	3,934	11,618	3,974	6,032	0.52
67/68	30,670	351	10,780	6,032	3,828	11,752	3,805	5,068	0.43
68/69	31,692	374	11,856	5,068	3,718	11,772	3,640	5,240	0.45
69/70	32,658	348	11,379	5,240	3,932	12,010	3,880	4,724	0.39
70/71	**31,778**	**369**	**11,740**	**4,656**	**4,086**	**12,173**	**3,875**	**4,605**	**0.38**
71/72	33,024	392	12,938	4,681	4,031	12,721	4,111	4,799	0.38
72/73	33,818	402	13,595	4,851	4,528	13,034	4,640	5,358	0.41
73/74	32,558	418	13,615	5,434	4,408	13,469	4,294	5,727	0.43
74/75	33,285	418	13,926	5,727	3,734	12,641	3,814	7,373	0.58
75/76	30,001	390	11,706	7,352	4,188	13,336	4,183	5,770	0.43
76/77	31,513	393	12,385	5,770	3,951	13,122	3,806	5,232	0.40
77/78	34,966	396	13,860	5,232	4,250	13,133	4,239	5,963	0.45
78/79	34,000	380	12,933	5,963	4,320	13,703	4,346	5,257	0.38
79/80	33,100	425	14,084	5,255	5,093	14,127	5,073	5,257	0.37

Appendix: (Continued)

(Thousand metric tons)

	Area (000 Ha)	Yield (kgs/ha)	Production	Beginning stocks	Imports	Consumption	Exports	End stocks	S/U* Ratio
80/81	**33,667**	**411**	**13,831**	**5,152**	**4,555**	**14,215**	**4,414**	**4,994**	**0.35**
81/82	33,948	442	14,991	4,994	4,405	14,147	4,373	5,852	0.41
82/83	32,569	445	14,479	5,852	4,350	14,452	4,261	5,926	0.41
83/84	32,137	451	14,499	5,926	4,617	14,655	4,309	6,121	0.42
84/85	35,217	546	19,247	6,121	4,602	15,108	4,520	10,247	0.68
85/86	32,792	532	17,461	10,247	4,763	16,589	4,479	11,366	0.69
86/87	29,503	518	15,269	11,366	5,516	18,198	5,755	8,251	0.45
87/88	31,238	564	17,609	8,251	5,094	18,117	5,121	7,668	0.42
88/89	33,522	546	18,301	7,668	5,654	18,470	5,726	7,312	0.40
89/90	31,640	549	17,365	7,312	5,431	18,675	5,293	6,146	0.33
90/91	**33,050**	**574**	**18,978**	**6,146**	**5,220**	**18,574**	**5,073**	**6,709**	**0.36**
91/92	34,710	596	20,677	6,709	6,497	18,636	6,091	9,312	0.50
92/93	32,238	557	17,943	9,313	5,690	18,634	5,525	8,694	0.47
93/94	30,430	554	16,861	8,694	5,766	18,496	5,911	7,028	0.38
94/95	32,114	584	18,762	7,028	6,458	18,278	6,312	7,561	0.41
95/96	36,056	564	20,330	7,561	5,805	18,405	5,999	9,129	0.50
96/97	34,111	575	19,599	9,129	6,134	19,049	6,049	9,844	0.52
97/98	33,746	595	20,094	9,844	5,737	18,990	5,973	10,672	0.56
98/99	32,846	569	18,705	10,674	5,390	18,451	5,508	10,937	0.59
99/00	31,929	598	19,095	10,937	6,034	19,603	6,111	10,359	0.53
00/01	**31,766**	**612**	**19,457**	**10,359**	**5,734**	**19,845**	**5,881**	**9,953**	**0.50**
01/02	33,381	644	21,490	9,953	6,229	20,305	6,448	10,771	0.53
02/03	29,924	645	19,294	10,771	6,538	21,235	6,676	8,661	0.41
03/04	32,190	644	20,720	8,661	7,292	21,325	7,255	8,111	0.38

Appendix: (Continued)

(Thousand metric tons)

	Area (000 Ha)	Yield (kgs/ha)	Production	Beginning stocks	Imports	Consumption	Exports	End stocks	S/U* Ratio
04/05 est.	35,757	733	26,219	8,111	7,171	23,400	7,643	10,450	0.45
05/06 proj.	35,238	689	24,272	10,450	8,078	23,925	8,078	10,795	0.45
06/07 proj.	35,490	699	24,814	10,795	8,191	24,609	8,191	11,001	0.45
07/08 proj.	35,657	709	25,286	11,001	8,313	25,090	8,313	11,197	0.45
08/09 proj.	36,011	716	25,787	11,197	8,482	25,575	8,482	11,409	0.45
09/10 proj.	36,421	718	26,165	11,409	8,788	26,084	8,788	11,491	0.44

* Stocks-to-use ratio equals ending stocks divided by consumption.
** Annual average during 1934–1938.

14
Health and safety issues in cotton production and processing

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14.1 Introduction

Health and safety are key components of responsible production and processing of cotton and of a responsible management system for cotton operations. Workers handle and process cotton in many work operations from planting the cottonseed, to the finished cotton textile (i.e., from 'field-to-fabric' or from 'dirt-to-shirt') – production, harvesting, ginning, yarn and fabric manufacturing, and preparation, dyeing and finishing. Each cotton industry sector has its own particular health and safety considerations. This chapter addresses the more pertinent health and safety issues for each sector of the cotton industry.

In the USA, health and safety guidelines and regulations are issued or promulgated and enforced by the US Occupational Safety and Health Administration (OSHA), which is part of the US Department of Labor (DOL). The purpose of OSHA is to ensure that the employers maintain a safe and healthful workplace. In the UK, health and safety regulations and guidelines are developed and enforced by the Health & Safety Executive (HSE). The mission of the HSE is to protect people's health and safety by ensuring risks in the changing workplace are properly controlled. Australia incorporates government occupational health and safety legislation into a best management practice (BMP) approach (Chaudhry, 2004; Slack-Smith, 2000; Australian Cotton Industry, 2006) for cotton production. Adoption of the BMP system is used by growers as a positive feature in marketing Australian cotton, because it demonstrates safe pesticide use and ecologically safer practices for workers and the surrounding communities.

In addition to regulations and guidelines by the individual countries, there are voluntary standards for occupational health and safety developed by international organizations, such as the International Organization for Standardization (ISO) and the European Union (EU), European Committee for Standardization (CEN). ISO standards are routinely adopted or incorporated by reference by over 100 countries and include standards for agriculture, (ISO ICS 65 Agriculture Standards (2006)), and textiles (ISO ICS 59 Textile and Leather Technology (2006)), as well as standards for quality management (ISO, 9000) and environmental management (ISO 14000) (ISO 9000 and ISO 14000,2006), which are among ISO's most widely known standards ever. ISO 9000 and ISO 14000 standards are implemented by some 760,900 organizations in 154 countries. ISO 9000 has become an international reference for quality management requirements in business-to-business dealings, and ISO 14000 enables organizations to meet their environmental challenges. The American Conference of Governmental Industrial Hygienists (ACGIH), an independent standard setting organization is the USA, has threshold limit values ('TLVs'; worker/workplace exposure limits) for hazardous substances and exposures (ACGIH, 2006) that some countries (e.g., Canada) in the world routinely adopt or incorporate by reference into their regulations.

Most of the about 80 countries in the world where cotton is grown and/or processed have workplace health and safety regulations, procedures, and guidelines and routinely adopt international standards to help provide safe and healthful workplaces. The USA occupational health and safety standards and guidelines are comprehensive and represent a good model for cotton industry segments in other countries to consider. In this chapter, USA safety and health regulations and guidelines are used, for the most part, as illustrations of prudent occupational health and safety procedures for providing safe and healthful workplaces in the various cotton industry segments.

US OSHA agriculture standards (29 Code of Federal Regulation [CFR] 1928) apply to cotton production and ginning. US OSHA general industry standards (29 CFR 1910) apply to post-harvest cotton operations (i.e., warehouses and textile manufacturing and processing). In addition, the US Occupational Safety and Health Act (Sec. 5(a)(1) of the 'OSH Act') requires the employer to maintain a safe and healthful workplace.

Both hazard – anything that can cause harm (e.g., chemicals) – and risk – the chance, high or low, that someone will be harmed by the hazard – are discussed. Hazard is the innate nature of the product, whereas risk is determined by exposure. Thus a monomer or dye component may be a hazardous substance but the insoluble polymer or dyed fabric (i.e., the final product) are not a risk because there is no exposure to the hazard.

When cotton is grown and processed (including yarn manufacturing and wet processing) in a responsible manner, the production and processing of cotton should not have any adverse effects on the worker (because of acute or chronic effects), the consumer (because of acute or chronic effects), or the environment (through crop protection product/chemical use, external emissions, wastewater effluents, and solid wastes) (Wakelyn, 1994).

14.2 Cotton production

The agricultural transitions to mechanized power, and from mechanical to chemical to genetically engineered tools, have increased farm productivity, but have not decreased the health and safety stresses upon farmers (Batie and Healy, 1980, 1983 (or the original publication in 1980); Martin and Olmstaed, 1985). Since the early 1960s, agriculture has become one of the most hazardous occupations (Batie and Healy, 1983; Mutal and Donham, 1983), mainly because of modern farm equipment. Cotton production potentially has most of the same health and safety considerations as other row crops.

The production of cotton in the developed countries is heavily mechanized and is dependent on chemical based production systems. The proper use and handling of crop protection products is the most important health and safety activity in cotton production in developed as well as developing countries. Health hazards of pesticide/crop protection products application, disposal of pesticide containers and many other aspects of pesticide storage, handling and disposal have caused damage to human life and the environment in the past and still do in some of the about 80 countries (59 countries grow at least 5000 ha) where cotton is grown. The development of new crop protection products, less persistent and less toxic to humans, has been helpful in reducing risks to human life and the environment. Many countries like the USA have strict regulations for approval of crop protection products (US EPA, 2006) as well as strict worker protection standards for pesticide handlers and agricultural workers for application of crop protection products (US EPA, 2006a) and regulations for safe storage and disposal of used containers (US EPA, 2006b). These regulations, if followed, greatly reduce health risks to workers and the environment.

There are occupational safety and health requirements for all mechanical equipment (29 CFR 1928.51-53) and guides to protect workers from heat stress (US OSHA, 2002, 2006; US OSHA/EPA, 1993). Because of the high temperatures, the state of California in 2006 finalized regulations for heat stress (CAL OSHA, 2006). There are also heat stress requirements in the worker protection standard (WPS) (US EPA 2006a).

14.2.1 Safety with agricultural equipment and machinery

Many farm accidents and fatalities involve mechanized farm equipment and machinery. Many times these accidents and fatalities occur with children. There is a US OSHA standard for the protection of employees from the hazards associated with moving machinery parts of farm field equipment, farmstead equipment, and cotton gins used in any agricultural operation (29 CFR 1928.57). Proper machine guarding and equipment maintenance according to manufacturers recommendations can help prevent accidents. Specific requirements for cotton gins are discussed in section 14.3.

Tractor-related accidents are the leading cause of agricultural death in the US. US OSHA has regulations for roll-over protective structures (ROPS) for tractors used in agricultural operations (29 CFR 1928.51) and for protective frames and enclosures for wheel type agricultural tractors (29 CFR 1928.52-53). Using protective equipment, such as seat belts on tractors, and personal protective equipment (such as safety gloves, coveralls, boots, hats, aprons, goggles, face shields) also can significantly reduce farming injuries.

14.2.2 Worker protection standard for agricultural pesticides

There are anecdotal stories of adverse effects of prolonged exposure of pesticide use on cotton, such as a community reputed to have high levels of the chlorinated hydrocarbon, toxaphene, in fish. Dichlordiphenyltrichloroethane (DDT) is still found in soil samples and birds and small animals can be scarce in fields treated with agricultural chemicals. A much greater awareness of potential harm to workers and the community and government regulations has led the cotton industry in all developed countries and in most developing countries now to be very vigilant in regulating and monitoring pesticide use.

Overview of the WPS

The Australian BMP program (Chaudhry, 2004; Slack-Smith, 2000; Australian Cotton Industry, 2006) and the US Worker Protection Standard ('WPS', 40 CFR 170) (US EPA, 2006a; NCC, 2004, 2005) are aimed at reducing the risk of pesticide poisonings and injuries among agricultural workers and pesticide handlers. The US WPS contains requirements for

- pesticide safety training
- notification of pesticide applications
- use of personal protective equipment
- restricted entry intervals (REI) following pesticide application (e.g., for carbofuran, a broad spectrum insecticide, the REI is 48 hrs following application)
- decontamination supplies
- emergency medical assistance.

The WPS covers two types of employees on farms from occupational exposure to agricultural pesticides:

- Pesticide handlers – those who mix, load, or apply agricultural pesticides; clean or repair pesticide application equipment or assist with the application of pesticides in any way.

- Agricultural workers – those who perform tasks related to the cultivation and harvesting of plants on farms or in greenhouses, nurseries, or forests. Workers include anyone employed for any type of compensation (including self-employed) doing tasks related to the production of agricultural plants on an agricultural establishment.

There are some WPS requirements that apply to all persons and some that apply to anyone who handles pesticide application equipment or cleans or launders pesticide-contaminated personal protective equipment

Summary of WPS requirements

- Pesticide safety training and safety posters – training is required for all workers and handlers, and a pesticide safety poster must be displayed.
- Access to labeling and site-specific information – Handlers and workers must be informed of pesticide label requirements. Central posting of recent pesticide applications is required.
- Notification to workers – workers must be notified about treated areas so they may avoid inadvertent exposures.
- Personal protective equipment – personal protective equipment must be provided and maintained for handlers and early-entry workers.
- Protection during applications – applicators are prohibited from applying a pesticide in a way that will expose workers or other persons. Workers are excluded from areas while pesticides are being applied.
- Restricted-entry intervals – restricted-entry intervals must be specified on all agricultural plant pesticide product labels. Workers are excluded from entering a pesticide-treated area during the restricted-entry interval, with only narrow exceptions.
- Decontamination supplies – Handlers and workers must have an ample supply of water, soap, and towels for routine washing and emergency decontamination.
- Emergency assistance – transportation must be made available to a medical care facility if a worker or handler may have been poisoned or injured. Information must be provided about the pesticide to which the person may have been exposed.

WPS glove requirements for workers, handlers, and pilots

All agricultural pesticide handlers and early-entry workers covered by the WPS are permitted to wear separate glove liners beneath chemical-resistant gloves and agricultural pilots do not have to wear chemical-resistant gloves when entering or exiting aircraft. Handlers and early-entry workers may choose whether to wear the liners. The liners may not be longer than the chemical-resistant glove, and they may not extend outside the glove. The liners must be disposed of after ten hours of use, or whenever the liners become contaminated. Lined or flocked gloves, where the lining is attached to the inside of the chemical-resistant outer glove, remain unacceptable. Regulatory action was taken to reduce the discomfort of unlined chemical resistant gloves, especially during hot or cold periods. Additionally, chemically resistant gloves do not add any appreciable protection against minimal pesticide residues found around the cockpit of an aircraft.

Avoiding heat illness

The WPS requires employers to take any necessary steps to prevent heat illness (too much heat stress) while personal protective equipment is being worn. The special clothing and equipment worn for protection from exposure to pesticides can restrict the evaporation of sweat. In addition, pesticides are absorbed through hot, sweaty skin more quickly than through cool skin. The many precautions against heat illness that employers should take are summarized in section 14.2.3.

14.2.3 Heat stress

High air temperatures and humidities put agricultural workers at special risk of heat illness (CAL OSHA, 2006; US OSHA, 2006). In the US, worker compensation claims for heat illness among agricultural workers are among the highest of any occupation. Pesticide handlers and early entry workers are at even greater risk. As stress from heat becomes more severe, there can be a rapid rise in body temperature and heart rate. Mental performance can be affected with an increase in body temperature of 2 °F (1.1 °C) above normal. An increase of 5 °F (2.8 °C) can result in serious illness or death. EPA/OSHA's *A Guide to Heat Stress in Agriculture* (US OSHA/EPA, 1993) offers practical, step-by-step guidance for non-technical managers on how to set up and operate a heat stress control program. The worker needs to be trained, the workload needs to be reduced, shade needs to be available as well as plenty of water (US OSHA, 2002 and 2006; California 2006).

As discussed above, the WPS also has requirements to prevent heat illness. Some of the requirements to prevent heat illness are:

- Training. Train workers and supervisors how to control heat stress and how to recognize symptoms of heat illness.
- Monitoring and adjusting workloads. Take into account the weather, workload, and condition of the workers, and adjust work practices accordingly. Higher temperatures, high humidity, direct sun, heavy

workloads, older workers, and workers unaccustomed to heat are more likely to become ill from heat. Things to do:
  - monitor temperature, humidity, and workers' responses at least hourly in hot environments;
  - schedule heavy work and PPE-related tasks for the cooler hours of the day;
  - acclimatize workers gradually to hot temperatures;
  - shorten the length of work periods and increase the length of rest periods;
  - give workers shade or cooling during breaks; and
  - halt work altogether under extreme conditions.
- Drinking. Make sure employees drink at least the minimum required amounts of water to replace body fluid lost through sweating. Thirst does not give a good indication of how much water a person needs to drink.

14.3 Harvesting and ginning

14.3.1 Harvesting

About 75% of world cotton production is hand picked and 25% is harvested by machines. Hand harvesting can be a source of ergonomic problems. There should be work practices in place that helps prevent such wrist and back injuries. If the cotton is mechanically harvested, the US OSHA standard for the protection of employees from the hazards associated with moving machinery parts of farm field equipment and farmstead equipment (29 CFR 1928.57) or similar practices should be followed. Proper machine guarding and equipment maintenance according to manufacturers recommendations can help prevent accidents.

14.3.2 Ginning

Since cotton ginning is essentially a continuation of harvesting, it is considered to be an agricultural operation (Wakelyn *et al.*, 2005). The only standards that US OSHA can apply to agricultural operations are the agriculture standards in 29 CFR Part 1928 (US OSHA, 2002a) and the few general industry standards referenced in 29 CFR 1928.21. The general industry standards that apply to cotton gins include, the Hazard Communication Standard (29 CFR 1910.1200) and temporary labor camps (29 CFR 1910.142). Machine guarding of cotton gins is covered by 29 CFR 1928.57. OSHA's cotton dust standard at 29 CFR1910.1043(a)(2), specifically excludes cotton ginning from coverage. The dust in the cotton ginning workplace should be considered a 'nuisance' dust or 'particulate not otherwise regulated' (29 CFR 1910.1000) not as cotton dust. In some countries cotton dust regulations may apply to ginning and it is prudent health and safety practice to keep dust levels below 1 mg/m^3 respirable dust.

If hazards are found at cotton ginning operations that are not covered by specific regulations, there should be practices in place to address all hazards to workers. For example, standards for the control of hazardous energy ('lockout/tag out'; 29 CFR 1910.147), confined space (29 CFR 1910.146), and noise (29 CFR 1910.95) do not specifically apply to cotton gins in the US. However, the gin workplace should be monitored and, if there is risk of these hazards, consideration should be given to voluntarily complying with these regulations in efforts to keep a safe and healthful workplace.

Machine guarding for cotton gins

Machine guarding (29 CFR 1928.57) is the only US agriculture standard specifically for cotton gins. At the time of initial assignment and at least annually thereafter, the employer should instruct every employee in the safe operation and servicing of all covered equipment at the gin with which he is or will be involved, including at least the following safe operating practices:

1. Keep all guards in place when the machine is in operation.
2. Stop the engine, disconnect the power source, and wait for all machine movement to stop before servicing, adjusting, cleaning, or unclogging the equipment, except where the machine must be running to be properly serviced or maintained, in which case the employer shall instruct employees as to all steps and procedures which are necessary to safely service or maintain the equipment.
3. Make sure everyone is clear of machinery before starting the engine, engaging power, or operating the machine.
4. Lock out electrical power before performing maintenance or service on farmstead equipment.
5. Where guards are used to provide the protection required, they shall be designed and located to protect against inadvertent contact with the hazard being guarded.

14.4 Yarn and fabric manufacturing

The health and safety concerns for the processing of cotton into yarn and fabric are similar to those for the textile processing of most staple fibers (Wakelyn, 1997). Accidents can occur on all types of cotton textile machinery, though the frequency rate is low. Effective guarding and training of operators is important as is described below (section 14.4.1). Noise can also be a problem, particularly in older textile mills (section 14.4.2). Since spinning sometimes requires high temperatures and high humidification of air, heat stress can also be a problem for textile workers. Well designed and maintained air-conditioned plants are replacing the primitive methods of trying to control temperature and humidity, In addition, the worker needs to be trained, the workload needs to be reduced, shade needs to be available as well as plenty of water, as was discussed in section 14.2.3. Cotton dust can be a major health and safety concern in yarn manufacturing of cotton (see section 14.4.3).

14.4.1 Machinery guarding

Effective guarding of the moving parts presents problems and need constant attention. Training of operators in safe practices is essential and efforts need to prevent repairs to machinery while it is in motion. The facility should identify energy sources, provide necessary equipment and train personnel to ensure that all hazardous energy sources are turned off while working on equipment. Inspections should be performed on a regular basis to ensure that all lockout/tagout procedures are followed and that workers do not remove machine guards while equipment is operating. The US OSHA standard for textile safety, 29 CFR 1910.262, applies to the design, installation, processes, operation, and maintenance of textile machinery, equipment, and other plant facilities in all plants engaged in the manufacture and processing of textiles, except those processes used exclusively in the manufacture of synthetic fibers. Other standards covering issues of occupational safety and health, which are of general application, are incorporated by reference in this rule. General safety requirements are in 29 CFR 1910.262 (c), including means of stopping machines, machine guarding, housekeeping, identification of physical hazards. 1910.262 (d) addresses openers; 1910.262 (e) cotton cards; 1910.262 (h) slashers (where size is applied); and 1910.262 (j) drawing frames, roving, combers, spinning, and twisters.

14.4.2 Noise

Noise can be a problem in some yarn and fabric manufacturing operations, particularly in older yarn manufacturing operations and in weaving operations that do not use shuttleless looms. In most modern textile operations the noise levels are below 90 dBA, the US standard (29 CFR 1910.95), and most likely below 85 dBA, which is when hearing conservation programs are required in the US and the noise standard in many countries. The US hearing conservation program (29 CFR 1910.95b), required when noise levels exceed 85 dBA, includes noise-level monitoring, audiometric testing and making hearing protection available to all employees when noise levels cannot be engineered below 90 dBA. The abatement efforts of machinery manufacturers and industrial noise engineers are continuing to decrease noise levels as machinery speeds increase. The main solution for high noise levels is the use of more modern, quieter equipment.

14.4.3 Inhalation/respiratory disease (cotton dust)

Inhalation of cotton-related dust generated during the textile manufacturing operations, where cotton fiber is converted into yarn and fabric, has been shown to cause an occupational lung disease, byssinosis, in a small number of textile workers (The Task Force for Byssinosis Prevention, 1995; US OSHA, 1985; Schilling and Rylander, 1994). It usually takes 15 to 20 years of exposure to higher levels of dust (above 0.5 to 1.0 mg/m^3) for workers to become reactors.

Cotton dust is an airborne particulate matter released into the atmosphere as cotton is handled or processed in textile processing. It is a heterogeneous, complex mixture of botanical trash, soil, and microbiological material (i.e., bacteria and fungi), which varies in composition and biological activity (Wakelyn *et al.*, 1976). The etiological agent and pathogenesis of byssinosis are not known (The Task Force for Byssinosis Prevention, 1995; Nichols, 1991; Pickering, 1991; Rohrbach, 1991). Cotton plant trash associated with the fiber and the endotoxin from gram-negative bacteria on the fiber, plant trash, and soil are thought to be the causative or to contain the causative associated with worker reaction to dust. The cotton fiber itself, which is mainly cellulose, is not the causative, since cellulose is an inert dust that does not cause respiratory disease (Jacobs and Wakelyn, 1998). In fact, cellulose powder has been used as an inert control dust in human exposure studies.

The US OSHA regulations for cotton dust apply to textile processing and weaving but do not apply to handling or processing of woven or knitted materials, harvesting, ginning, warehousing, classing/merchandizing, or knitting operations. OSHA permissible exposure limits (PEL) for cotton dust measured as an eight-hour time-weighted average with the vertical elutriator cotton dust sampler are (US OSHA, 1985, 2006a):

1. yarn manufacturing, 200 μg/m^3
2. textile mill waste house, 500 μg/m^3
3. slashing and weaving, 750 μg/m^3
4. waste processing (waste recycling and garneting), 1000 μg/m^3.

The US OSHA cotton dust standard requires that these PELs be complied with using engineering controls and work practices. There are also requirements for monitoring, medical surveillance, and information and training for workers. Washed cotton may also be used to comply with the cotton dust standard. A mild water washing of cotton, by batch kier washing systems (The Task Force for Byssinosis Prevention, 1995; Perkins and Olenchock, 1995) and continuous batt systems (Wakelyn *et al.*, 1986; US OSHA, 1985), reduces the residual level of endotoxin in both lint and airborne dust to below levels associated with a zero percentage change in acute reduction in pulmonary function as measured by forced expiratory volume in one second (FEV_1) (The Task Force for Byssinosis Prevention, 1995).

Levels of endotoxin from Gram-negative bacteria generated during the processing of cotton are associated with the occupational respiratory disease that affects some textile workers (Glindmeyer *et al.*, 1991, 1994; Castellan, *et al.*, 1987; The Task Force for Byssinosis Prevention, 1995). Washed cotton is determined by levels of potassium and water-soluble reducing substances (WSRS) in the washed lint (Perkins and Olenchock, 1995). OSHA has accepted several mild washing systems as qualifying as 'washed cotton' exemptions under the cotton dust standard (US OSHA, 1985, 2000):

1. Mild washing by the *continuous batt system or a rayon rinse system* is with water containing a wetting agent, at not less than 60 °C, with water-to-fiber ratio of no less than 40:1, with bacterial levels in the wash water controlled to limit bacterial contamination of the cotton.
2. The *batch kier washing system* is with water containing a wetting agent, with a minimum of one wash cycle followed by two rinse cycles for each batch, using fresh water in each cycle, and with bacterial levels in the wash water controlled to limit bacterial contamination of the cotton.
   a. For *low* temperature, at not less than 60 °C, with water-to-fiber ratio of no less than 40:1, or
   b. For *high* temperature, at not less than 93 °C, with a water-to-fiber ratio of no less than 15:1.

Control studies in experimental cardrooms and a longitudinal study of a large multi-mill population of workers processing cotton and synthetic fibers suggest that, in today's world, appropriate engineering controls in cotton textile processing areas, along with work practices, medical surveillance, and personal protective equipment for the most part can eliminate incidence of workers' reaction to cotton dust (Glindmeyer, 1991, 1994; The Task Force for Byssinosis Prevention, 1995). In US textile mills today, workers are not getting respiratory disease due to exposure to cotton-related dust. This should be true in all textile mills where dust exposures are controlled and workers are medically monitored.

14.5 Wet processing (preparation, dyeing, and finishing)

Prior to dyeing, printing and finishing, cotton fibers, yarns, and fabrics require pretreatments (referred to as 'preparation') to remove natural and other impurities (Cotton Incorporated, 1996). The common preparation processes for cotton include singeing, desizing, scouring, bleaching, and mercerization. Cotton is dyeable in fiber form (raw stock), yarn, or fabric form with an extensive number of dye classes, including, azoic, direct, indigo, pigment, reactive, sulfur, and vat dyes. The selection of the appropriate dyes and dyeing processes for cotton is based on numerous factors depending on the application for which the dyed cotton fibers are to be used. Cotton finishing operations include durable press/easy care, flame retardancy, soil release, water repellency and stain-resistance.

Many chemicals and processes are used in the preparation, dyeing and finishing of cotton. Workers can be exposed to formaldehyde and other finishing chemicals such as flame retardants and strain-resistant/water repellent finishes that can be of concern.

The safety standards for textile machinery also apply to preparation, dyeing and finishing operations: 29 CFR 1910.262 (p) covers bleaching equipment for cotton; (s) mercerizing ranges; (u)-(v) dyeing; (dd) printing; (oo) handling caustic soda and potash; and (rr) workroom ventilation for all workrooms in which potentially toxic chemicals are used.

14.5.1 Potential dye hazards

Dyes exist as powders, liquids, pastes, granules, pellets tablets, and other forms. They all are a potential source of exposure to the worker that handles them. Some dyes pose a significant risk to health while others do not. All dyes can be used safely as long as exposures are adequately controlled. Work practices are one of the biggest factors determining exposure to dyes in the workplace.

Powdered dyes can be an inhalation and sensitization problem and some dyes have been removed from use because of their potential to cause chronic health effects (US National Institute of Occupational Safety and Health (NIOSH), 1997; UK Health and Safety Executive (HSE), 2005; Imada, 2005). To prevent some of the problems with powdered dyes, most dyes today are sold as a paste (already partially solublized) and work practices.

Control of dust from dye handling operations

The manual transfer of powder dyes from bulk containers to smaller process containers generates significant amounts of dust. Worker exposure to dye dust through breathing or skin contact can result in adverse health effects such as occupational asthma, eczema, and severe allergic reactions. In addition, benzidine, benzidine congener (o-tolidine and o-dianisidine) and some other azo dyes, which by reductive cleavage of one or more azo groups may release one or more aromatic amines, are recognized as potential occupational carcinogens because of their carcinogenic amine breakdown products (see

Table 14.1 and discussion below). Therefore, dye exposures should be limited to the lowest feasible concentrations to prevent these health problems.

Workers in powder dye handling operations should be protected from dust exposure with the following combination of controls: hazard information, adequate ventilation, redesigned bulk containers, and appropriate work practices (US National Institute of Occupational Safety and Health (NIOSH), 1997; UK HSE, 2005; The Ecological and Toxicological Association of Dyes and Organic Pigments Manufacturers (ETAD), 1997).

- Know the hazard: find out what happens if you get the dye on your skin or in your eyes; if you breath in dye dust, vapors, or mist; if you swallow the dye; and the acute and chronic health effects from exposure to the dye. Read the material safety data sheet.
- Ventilation: semi-downdraft ventilation booths are recommended for use during the manual transfer of dyes.
- Work practices: workers should use slow, smooth movements when handling dye to keep dust concentrations low. Dye transport distances between the bulk and process containers should be kept to a minimum. The height at which the dye is dropped into a container should also be kept to a minimum. Workers should avoid skin contact with the dyes by using protective clothing such as gloves, long-sleeved shirts, and aprons.

Reactive dyes

Reactive dyes have a high degree of water solubility and chemically bond to cotton. Fiber reactive dyes are brighter, longer-lasting, and easier-to-use than other cotton dyes and are extensively used in women's and other apparel. If they are ingested or inhaled they can react within the body (UK HSE, 2005a). Sometimes this can affect the body's immune system causing the person to be sensitized to that dye. Sensitization may mean that that the next time a person is exposed to the same dye, their body could react dramatically, even if the amount is very small. Reactive dyes can be respiratory and/or skin sensitizers, however skin sensitization is rare.

Sensitization is unpredictable. Some may become sensitized, others may suffer no adverse effects. There is no validated test procedure for assessing the propensity of an individual reactive dye to cause respiratory sensitization. Thus, it is prudent to handle all reactive dyes as if they are respiratory sensitizers. All practicable steps should be taken to reduce exposure of employee to reactive dyes, thereby reducing the risk of someone becoming sensitized. If someone does become sensitized, take steps to prevent their symptoms from becoming worse by avoiding any contact with that dye. The health hazard from reactive dyes is only a concern before the application to the fabric – there is no known risk to anyone handling or wearing the dyed materials.

Table 14.1 List of carcinogenic amines produced by decomposition of azo dyes

MAK III	Chemical name	CAS no.	German & EU regulations	OEKOTEX	Japan EcoMark
Category 1	4-Aminobiphenyl	92-67-1	*	*	*
	Benzidine	92-87-5	*	*	*
	4-Chloro-o-toluidine	95-69-2	*	*	*
	2-naphthylamine	92-59-8	*	*	*
Category 2	o-Amnoazotoluene	97-56-3	*	*	*
	2-Amino4-nitrotoluene	99-55-8	*	*	*
	p-Chloroaniline	106-47-8	*	*	*
	2,4-Diaminoanisole	615-05-4	*	*	*
	4,4′-Diaminobiphenylmethane	101-77-9	*	*	*
	3,3′ Dichlorobenzidine	91-94-1	*	*	*
	3,3′-Dimethoxybenzidine	119-90-4	*	*	*
	3,3′-Dimethylbenzidine	119-93-7	*	*	*
	3,3′-Dimethyl-4,4′′ diaminobiphenylmenthane	838-88-0	*	*	*
	p-Cresidine	120-71-8	*	*	*
	4,4′-Methylene-bis-(2-chloroaniline)	101-14-4	*	*	*
	4,4′-Oxydianiline	101-80-4	*	*	*
	4,4′-Thiodianiline	139-65-1	*	*	*
	o-Toluidine	95-53-4	*	*	*
	2,4-Toluyendiamine	95-80-7	*	*	*
	2,4,5-Trimethylaniline	137-17-7	*	*	*
	o-Anisidine	90-04-0	*	*	*
	p-Aminoazobenzene	60-90-3	*	*	*
	2,4-Xylidine	95-68-1	-	*	*
	2,6-Xylidine	87-62-7	-	*	*

* indicates that the amine is subject to the indicated regulations.

Benzidine and benzidine congener azo dyes

Many of the direct dyes that used to be used on cotton are benzidine-based dyes. US OSHA, US NIOSH and other groups in the world have extensively reviewed the literature on benzidine-based dyes (US NIOSH, 1978, 1980, and 1980a). Available studies indicate that some benzidine-based dyes cause cancer in experimental animals because they are converted in animals and humans to benzidine. Benzidine-based dyes may contain residual amounts of benzidine as well as other substances such as 4-aminobiphenyl that are considered to be human and animal carcinogens. There is evidence from animal studies that o-tolidine, o-dianisidine, and dyes based on o-tolidine are carcinogenic and that dyes based on o-tolidine and o-dianisidine, except for metalized dyes based on o-dianisidine, may be metabolically converted to the parent compounds. Dyes manufactured from o-dianisidine and o-tolidine may also contain residual amounts of the respective parent compounds.

From the accumulated evidence, US OSHA and US NIOSH conclude that benzidine-based dyes are potential human carcinogens. In a Special Hazard Review, US NIOSH recommended that the commercial use of benzidine-based and benzidine congener dyes be discontinued and appropriate substitutes be utilized. US OSHA also concluded that exposure of workers to the dyes should be reduced to the lowest feasible levels. The use of dyes derived from benzidine, o-tolidine, and o-dianisidine has been discontinued in the USA and the EU but could still be used in some developing countries.

Other azo dyes

Azo dyes make up 60–70% of all dyes used and are the most important chemical class of dyes. Many of the dyes used on cotton are azo dyes (e.g., fiber reactive, direct, azoic). Some azo dyes, if absorbed by the human body, can undergo reduction decomposition to form carcinogenic amines due to enzymes in the body that have reduction properties. Currently this includes the 24 amines classified as substances known to be human carcinogens (Group III A 1 of the German MAK III list) and substances that are animal carcinogens, i.e., potential human carcinogens (Group III A 2) that are shown in Table 14.1. (The number of amines varies according to the different regulations because the regulations were drawn up at different times. When regulations are revised in the future, they will presumably cover all 24 amines.)

Azo dyes that produce carcinogenic amines due to reduction decomposition are subject to regulations in the European Union, the German government, through the German Goods Ordinance (ETAD, 1998), and the Oeko-Tex Standard 100 (Austrian and German eco-label association; see Oeko-Tex Association, 2006 and Oeko-Tex Initiative, 2006) and Japan Eco-label (Imada, 2005). Not all azo dyes that are made using the amines listed in Table 14.1

as a raw material are regulated/banned, only the azo dyes that can break down producing these amines. Only about 5% of azo dye structures are affected by these regulations and they are largely already phased out for textiles in the EU and US. A dyeing facility should get verification from the supplier or dyes manufacturer that the dyes they use are not subject to the EU and German restrictions (EC, 2002). Testing to verify that a dye is not subject to regulation involves conducting reduction degradation tests with extracts of the dye and analyzing the amines that are produced. It is important to note that different dyes with the same color index number can produce different results due to differences in the purity of the raw materials and in their impurities.

14.5.2 Skin irritation/dermatitis

Handling or processing conventional US cotton does not cause skin irritation/dermatitis. Cellulose is essentially an inert substance and nothing on the fiber surface is known that could cause dermatitis problems. However, it is remotely possible that some very atypical cottons that have been treated with substances that are not approved for use or that are off-grade and perhaps are highly microbiologically damaged might cause skin irritation. These rare atypical cottons should be evaluated on a case-by-case basis, if they are to be used in a conventional way. The processes for preparation of cotton for dyeing and finishing should remove anything that could cause skin irritation.

Some dyes used to color textiles are allergic contact dermatitis (ACD) allergens (Hatch *et al*., 2003). Hatch *et al*. (2003) showed by positive patch-test results that patients can have colored clothing ACD. They recommend that the term ‘textile-dye ACD’ be used to name cases of ACD in which the patient’s skin eruption is due to direct contact with dye molecules and the term ‘colored-textile ACD’ for cases in which the patient’s skin eruption was due to transfer of dye from a textile to the skin.

14.5.3 Formaldehyde

Formaldehyde is a component of some finishes used on cotton (e.g., formaldehyde and formaldehyde containing resins are used to impart easy care/durable press properties to cotton fabrics; the precondensate-ammonia flame retardants). Dyeing and finishing operations potentially can expose workers to formaldehyde in concentrations that exceed workplace exposure limits, if proper control procedures are not followed, since it can be released to the workplace during finishing operations and from some dyed and finished cotton fabrics.

It was classified in 1987 by the US EPA as a 'probable human carcinogen' (an animal carcinogen and limited evidence that it is a carcinogen in humans) under conditions of unusually high or prolonged exposure (US EPA, 1987). Since that time studies of industrial workers have suggested that formaldehyde is associated with nasopharyngeal cancer and possibly leukemia. In June 2004, the International Agency for Research on Cancer (IARC) reclassified formaldehyde as a known human carcinogen for nasopharyngeal cancer (IARC, 2004, 2004a; Anonymous, 2004). Non-cancer effects of exposure to low airborne concentrations of formaldehyde are sensory irritation of the mucous membranes of the eyes and the respiratory tract, and cellular changes in the nasal cavity (US EPA, 1987, 1991; IARC, 2004, 2004a).

The US OSHA workplace permissible exposure limit (PEL) for formaldehyde (29 CFR 1910.1048) is 0.75 ppm of air as an eight-hour time-weighted average concentration and 2 ppm of air as a 15-minute short-term exposure limit (STEL) (US OSHA, 2006b). These limits have to be met with engineering controls and work practices; there are also requirements for monitoring, medical surveillance, and information and training for workers. The ACGIH threshold limit value (TLV) for formaldehyde is 0.3 ppm short term exposure limit (STEL/ceiling) (ACGIH, 2006).

Exposure to formaldehyde from cotton textiles is controlled (i.e., reduced to an insignificant level) by the chemical technology low emitting formaldehyde resin technology and formaldehyde-free wrinkle resistance finishes (Welch, 1990, 2000; Welch and Andrews, 1989) and by increased ventilation. It should be noted that in the 1980s, the US Consumer Product Safety Commission (US CPSC) studied the effects of various dyeing and finishing treatments, including durable-press finishing of cotton (US CPSC, 1984), and found no acute or chronic health problems of concern to consumers due to exposures to formaldehyde or other finishing chemicals from textiles (Robbins, *et al.*, 1984; Robbins and Norred, 1984).

14.5.4 Brominated flame retardants

The flame retardants of most concern are polybrominated diphenyl ethers (PBDE). Penta-BDE and octa-BDE are banned in Europe and some states in the US. Deca-BDE, which is used along with antimony oxide to backcoat fabrics to meet the British flammability standard for upholstered furniture (BS 5852), has been thoroughly reviewed and is not considered toxic, although Denmark and some other EU countries want it banned also. Hexabromocyclododecane (HBCD), used to backcoat upholstery fabric, is also under review in the EU. Antimony oxide, which is usually used with brominated flame retardants to convey flame resistance is being reviewed in the EU.

14.5.5 Perfluorinated chemicals

The degradation/breakdown of short-chain fluorinated alcohols (mixed short-chained perfluorinated telomers), used as finishes to make textiles resistant to water, stains, and grease, are thought to be sources in the environment of perfluorooctanoic acid (PFOA). PFOA is persistent in the environment, it has been detected in low levels in wildlife and humans, and animal studies conducted have indicated effects of concern. PFOA is under consideration in the US to be classified as a 'likely' human carcinogen (Schultz and Dodd, 2005; Ritter, 2004). Eight US companies that make or use PFOA and related chemicals were asked by the US EPA (Jan. 25, 2006) to voluntarily (voluntary initiative is the '2010/2015 PFOA Stewardship Program'; http://www.epa.gov/opptintr/pfoa/pfoastewardship.htm) reduce releases of those chemicals and to limit the amount of PFOA in products by 95% by 2010 and to work toward eliminating exposure to PFOA from other chemicals by no later than 2015.

Perfluorooctyl sulfonate (PFOS), which was used in the 3M Scotchgard stain-resistant finish, and related compounds were voluntarily phased out of use in the US May 2000 (effective the end of 2002) following negotiations between US EPA and 3M, because data showed it to be persistent, bioaccumulative, and toxic (Ritter, 2004). In 2002 the Organization for Economic Cooperation and Development (OECD) found exposure to PFOS causes liver damage and death in laboratory animals (OECD, 2002). 3M has found substitutes for the specific PFOS chemicals of concern that were used in a wide range of their products. These are smaller telomers that are not sulfonates. PFOS also is being considered for restricted use in the UK (UK Defra, 2005). Most companies no longer use these fluorinated chemicals for fear of liability. Most, if they use fluorinated chemicals, use ones that are not potential sources of PFOA or PFOS.

14.5.6 Solvents

Millions of workers are exposed to solvents on a daily basis. Health hazards associated with solvent exposure include toxicity to the nervous system, reproductive damage, liver and kidney damage, respiratory impairment, cancer, and dermatitis. Solvents share many chemical, physical, and biological properties that warrant attention be directed to them as a group. In addition, many solvent groups or individual substances have special properties requiring more specialized control measures. US OSHA standards for permissible exposure limits (PELs) (see below) and the hazard communication standard (HCS) (see section 14.5.5) would apply. Work practices and engineering controls to limit exposures below the PEL (29 CFR 1910.1000) and material safety data sheets (MSDSs) are required.

14.5.7 Air contaminants

The air contaminants standards (29 CFR 1910.1000) are intended to reduce the risk of occupational illness for workers by reducing permissible exposure limits (PEL) for chemicals. PELs are eight-hour time-weighted average (TWA) exposures. To achieve compliance with the PEL, administrative or engineering controls must first be determined and implemented, whenever feasible. When such controls are not feasible to achieve full compliance, personal protective equipment, work practices, or any other protective measures are to be used to keep employee exposure below the PEL. ACGIH has TLVs for hazardous substances (ACGIH, 2006) as does HSE in the UK and ISO, the EU, and most countries in the world. In the case of a mixture of contaminants, an employer has to compute the equivalent exposure when the components in the mixture pose a toxic effect on the same target organ to a worker's health.

14.5.8 Hazard communication

The Hazard Communication Standard HCS (29 CFR 1910.1200) requires all employers to provide information to their employees on the hazardous chemicals to which they are exposed through written hazard communication programs, labels and other forms of warning, material safety data sheets (MSDS), training programs, and recordkeeping. A substance is a 'hazardous chemical' if it is a 'physical hazard' or a 'health hazard' (29 CFR 1910.1200 (c)). A flammable or explosive liquid is a 'physical hazard'. A flammable liquid means 'any liquid having a flashpoint below 110 °F (37.8 °C), except any mixture having components with flashpoints of 100 °F (37.8 °C) or higher, the total of which make up 99% or more of the total volume of the mixture'. 'Health hazard' means 'a chemical for which there is statistically significant evidence based on at least one valid study that acute or chronic health effects may occur in exposed employees'.

Chemical manufacturers and importers are required to review the available scientific evidence concerning the hazards of chemicals they produce or import, and to report the information to manufacturing employers who use their products (29 CFR 1910.1200(b)). If a chemical mixture has not been tested as a whole to determine whether the mixture is a hazardous chemical, the mixture is assumed to present the same hazards as do the components that comprise 1% or greater of the mixture or a carcinogenic hazard if it contains a component in concentration of 0.1% or greater that is a carcinogen (29 CFR 1910.1200(a)(5)).

The globally harmonized system (GHS) of classification and labeling of hazardous chemicals was adopted by the United Nations in 2003. The goal of the GHS is to promote common, consistent criteria for classifying chemicals according to their health, physical and environmental hazards, and to develop compatible labeling, material safety data sheets for workers, and other information based on the resulting classifications.

Countries are now considering adoption of the GHS into their national regulatory systems. The goal is to have as many countries as possible implement the GHS by 2008. This involves changing the criteria for classifying health and physical hazards, adopting standardized labeling requirements, and requiring a standardized order of information for MSDS. A harmonized system would lead to greater consistency among countries and thereby promote safer transportation, handling and use of chemicals. Harmonized criteria, symbols and warnings will promote improved understanding of hazards and thus help to protect workers and other potentially exposed populations. A more uniform, 'harmonized' system should also reduce costs for companies involved in international trade.

14.6 Consumers

By the time cotton textiles reach the ultimate consumer, there should be nothing known of or extractable from the original cotton fiber that would cause any health concerns to consumers (Wakelyn, 1994). However, various dyeing and finishing treatments that cotton fabrics go through can leave residues on the fabric or release substances that could cause irritation to consumers, if the treatments are not properly applied.

14.7 Future trends

In cotton production there most likely will continue to be more emphasis on environmental stewardship and less use of crop protection products. The products used will be less persistent and less toxic to non-target species. In dyeing and finishing there will be stricter requirements for chemicals used. Also preparation, dyeing, and finishing processes will use less energy and water. The image of cotton production and processing should be greatly improved and workers in cotton industry segments will be safer. We are already seeing this with agricultural workers in areas where biotech cottons are being grown.

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15
Recycling of cotton

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15.1 Introduction

Cotton recycling fits into the broader scope of materials recovery from solid waste generated by producers and consumers of a range of products. This chapter looks at the issues surrounding recycling and the research into specific recycling efforts involving cotton textile products. The stage is set by describing current methods for dealing with textiles in the solid waste stream. The pattern of recycling is then begun with a discussion of the sources of cotton fibers, followed by detailed descriptions of mechanical and chemical recycling processes. The latter involve dissolution of cotton fibers and other cellulosic materials in environmentally safer solvents than those traditionally used to produce regenerated cellulosic fibers. Future trends are discussed and further sources of information given.

15.2 Textile life cycle and waste treatment choices

Environmental imperatives have induced researchers, producers, and consumers to examine and pay attention to the life cycle of products from raw material to waste and disposal. This approach provides a framework for analyzing environmental issues and determining the role and economics of recycling as a method for reducing waste and environmentally disadvantageous disposal (Domina and Koch, 1997). It is understood in applying this approach that much of the environmental impact of a textile product is determined at the design stage by the materials and processes selected (Heely and Press, 1997).

Cotton, and indeed all textiles, require significant energy input for production and processing, and also for laundering and dry cleaning in the consumer's hands. Once an article is no longer serviceable, its ultimate fate is then considered. All these stages from raw material to final disposition are analyzed when a life cycle analysis is performed. The American Fiber Manufacturers Association conducted such an assessment for a polyester knit blouse that included energy requirements and emissions for each step from manufacture through consumer use, but did not consider environmental impacts of disposal (Smith and Barker, 1995). Cotton textiles would probably require more energy in processing and use, and there are additional environmental costs in growing cotton such as pesticides and fuel for large farm machinery. These costs can be balanced against the biodegradability of cotton in discarded items and possibilities for using cotton as a cellulose source for other products. As with all solid waste, there are three primary options for handling textile products no longer considered serviceable by the owner: reuse, disposal, and recycling.

15.2.1 Reuse

Governmental and private programs encourage the reuse of a number of consumer products, textiles among them. Textiles are in fact good candidates for reuse because there are so many options and outlets for clothing and household items. In addition, the US Environmental Protection Agency (EPA) considers that reusing products is even better than recycling because they do not require reprocessing into new or different items (US Environmental Protection Agency, 2005b).

Between 1990 and 2003, the US exported nearly 7 billion pounds of used clothing and worn textile products around the world (World Trade Atlas, 2005). Most of the recycling firms in developed countries are small, family-owned businesses (Rivoli, 2005). In the US the industry as a whole employs approximately 10,000 semi-skilled and marginally employable workers at the primary processing level, and creates an additional 7,000 jobs at the final processing stage. Primary and secondary processors account for annual gross sales of $400 million and $300 million respectively. Industry members are able to recycle 93% percent of the waste they process without producing any new hazardous waste or harmful by-products. Textile recyclers export 61% of their products, thus reducing the US trade deficit. Documented export sales of recycled clothing from the US exceeded $217 million in 1999 (US Census Bureau, 2005).

Worldwide, particularly in developed countries, there are many opportunities for donating or selling used textile products (Chang *et al.*, 1999). Second-hand stores offer sellers and buyers of used clothing and other textile items an exchange forum that keeps the items in the use channel and out of the waste stream. Thrift stores and consignment stores are also outlets for used textiles. Non-profit charitable organizations and churches in various countries accept donations of such items as well, either for domestic distribution or for needs around the world. These organizations and stores often however cannot use all of the donated items and give or sell them to rag makers, or look to materials recovery facilities (MRFs) for reprocessing and recycling (Platt, 1997). The used textile items thus become the starting materials in the recycling process.

Textile items that are reclaimed before disposal can be turned into useful, though low-value, products. All that is usually required is cleaning and cutting. Examples are rags cut from used cotton denim jeans (Denim, Reclaimed, 2005) and diapers retired from diaper services and sold as rags (100% Cotton Rags, 2005).

15.2.2 Disposal

Textile waste is generated by both producers and consumers. Scraps from fiber production, spinning and weaving, and apparel manufacturing, the post production waste, can be collected and recycled into a variety of products. The fiber content in these waste streams is known, making it simpler to target appropriate recycled products (Chang *et al.*, 1999). In addition, it is usually clean and requires less processing during recycling. Post-consumer waste, on the other hand, contains a mixture of fibers, and often dyes, finishes and other additives as well.

Textile waste is part of the solid waste stream that is dealt with in a variety of ways by local government entities throughout the world. In developed countries textiles account for about 4% of the municipal solid waste that must be dealt with in some fashion (Chang *et al.*, 1999; US Environmental Protection Agency, 2005b). The most common methods of solid waste disposal are landfilling and incineration. Recycling is a distant third, primarily because the economics of current recycling processes are not favorable. As the first two disposal methods become less environmentally attractive however, recycling and reuse, the non-disposal alternative described above, become attractive (Grasso, 1995).

Landfilling

Landfilling or burying, a traditional method of dealing with solid waste, while subject to environmental toxicity concerns, was generally considered sufficient for the volume of waste until the last century. Much of the waste placed in landfills was composed of natural materials, such as cotton, and was therefore considered biodegradable. With the advent of synthetic materials and the increase in consumption of both durable and non-durable goods, landfills are filling up, motivating a closer look at alternatives such as recycling. As reported by EPA, the number of US landfills decreased from 7,924 sites in 1988 to 1,767 in 2002, indicating the problem with this disposal method (US Environmental Protection Agency, 2005b).

The biodegradability of cotton makes landfilling an appropriate disposal method for cotton textiles. Problems arise when the fiber is blended with synthetics that are not so easily decomposed. In a study of cotton/polypropylene nonwovens, Warnock found that the cotton core of the composite webs disintegrated when buried in soil, but the polypropylene fibers were not affected after 16 weeks (Warnock and Ferguson, 1997). Landfilling is therefore not as attractive for general textile waste, which is often a mixture of fibers.

Incineration

An alternative to burying solid waste in landfills is incinerating it in large combustion facilities. This controlled burning process reduces the volume of waste and can capture the water generated to convert to steam for heating systems or to generate electricity (US Environmental Protection Agency, 2005b). The energy produced can in fact provide the fuel for the combustion process, decreasing the need for fossil fuels, and can also provide excess energy for other uses such as steam generation. An obvious disadvantage is the generation of carbon dioxide and any volatile pollutants produced by the burning.

15.3 Cotton sources

Primary cotton sources for recycling into current products are cotton rags and linters. Indeed, cotton rags and linters have been the main source of fibers for papermaking dating from the first century and remain today the best material for long lasting quality papers. These sources are high in alpha cellulose, which is the cellulose in the fiber that is not dissolved in 17.5% sodium hydroxide. The higher the alpha cellulose content in the fiber, the better quality and longer lasting the paper that can be manufactured. In addition these sources do not contain any lignin and only require a mild cooking process to clean them for the ultimate paper or other products.

15.3.1 Linters and gin waste

Cotton linters are very short fibers that adhere to the cottonseed even after ginning (Mauney, 1984). Unlike cotton fibers, linters only grow to 5 mm or less and have a thicker secondary wall at the seed surface, accounting for their resistance to removal during ginning. They can however be removed in a subsequent mechanical delinting processes. Typical yield for cottonseed is about 9% linters (Cherry and Leffler, 1984).

Before being converted into various products, linters are physically cleaned to remove seed hulls and other plant matter (Temming *et al*, 1973), and are then bleached. The physical and chemical cleaning produces linters with the appropriate physical and chemical properties for the targeted end use. A low viscosity, following from a reduced degree of polymerization, and the high purity of the cellulose from the cleaning are desirable properties for higher value products such as regenerated cellulose fibers and films. Clean fibers are also required for fine writing paper and filter paper. Uses for lower grade linters are padding and stuffing for mattresses, upholstery, and pillows (Collier and Tortora, 2000).

Short fibers are also collected as waste from cotton gins and yarn spinners. About 4% by weight of gin waste, which includes these short fibers as well as motes and trash, is generated for every bale of cotton fiber processed. With a worldwide production in 2004-2005 of 120 million bales (Collins, 2005), there is a significant amount of short fibers that are recovered and sold to plants making padding, batting, and other coarse nonwovens (Baker and Griffin, 1984). Such products are also made from short fibers combed from cotton slivers during the spinning process. These fibers, called noils, are collected by the spinner and resold.

15.3.2 Rags

Textile waste products that are all cotton have found use primarily in wiping cloths and rags. The absorbent nature of cotton is an advantage in such products. They can also be made into rag rugs, although most of these now use new rather than recycled fabric.

Most of the rags recycled into paper products are new cotton clippings which come from various textile mills and garment factories. They are collected by rag dealers and recycling organizations. The rags and cotton wastes are sorted and graded into over 140 different categories for reuse and recycling (Reading Textile Recycling Project, n.d.). The following grades are graded in the top category for rag papers: unbleached muslins, white shirt cuttings, bleached underwear cuttings, bleached flannel cuttings, bleached shoe cuttings, blue denims, and fancy shirt cuttings. White or unbleached new rags are better than colored ones because they require milder cooking and bleaching, resulting in minor thermochemical degradation and ultimately higher durability and permanence in the manufactured papers.

The quality and durability of paper made from rags are necessary properties for such specialty papers as:

1. banknotes and security papers
2. life insurance policies and legal documents where permanence is of primary importance
3. technical papers, such as tracing paper, vellums, intermediate, blue print and other reproduction papers
4. high-grade bond letterheads for concerns where appearance is of great importance
5. light-weight specialties, such as cigarette, carbon and bible papers
6. high-grade stationery paper, where beauty, softness, and fine texture are demanding.

The main steps from the cotton rags or wastes to the high-quality paper are: mechanical treatment to open the rags for easy dirt removal; removing of foreign matter; cutting for preventing roping in the boiler; dusting; removing of metallic items on magnetic rolls; chemical cooking and bleaching; beating; sizing; and finally paper formation. The cooking step is done using weak lime or caustic soda solutions to minimize chemical degradation of the alpha cellulose. Bleaching is also done at low chlorine concentrations (~ 0.05%) in the form of calcium or sodium hypochlorite. Sizing too should be done with a minimum amount of chemicals for the high-quality papers described above that are expected to last a long time. Chemicals and other additives should be kept at a minimum to prevent degradation of cellulose in time due to side reactions and consequently reducing paper permanence.

15.4 Mechanical reprocessing

Pre- and postconsumer waste is subjected to solely mechanical action to render the textiles into a near fibrous form that can then be processed into other, usually lower value, products.

15.4.1 Preparation

Sorting

Textile products that are recovered from the solid waste stream are usually sorted before being directed to reuse or recycling. Most recycling businesses prefer to sort the waste themselves to assure that the textiles are separated and graded by experienced workers capable of recognizing fiber contents and categories of materials for subsequent destinations (Textile Recycling Association, n.d.). A high percentage of textile products from this sorting step will be directed to reuse or to high-quality papers as described above. Other items will enter the recycling stream, based on fiber content and presence of dyes or finishes.

Shredding

A simple and often used mechanical process for recycling textile waste is shredding or tearing the item into very small pieces that can then be reformed into nonwovens or can be used as padding or stuffing (Fig. 15.1). The advantage of these end uses is that mixed fiber waste is acceptable because the primary function is a factor of bulk volume, not of specific fiber properties. In addition, the appearance of the products is not of primary importance because they are usually covered by other materials. Examples are car insulation, roofing felts, loudspeaker cones, panel lining, and furniture padding (Textile Recycling Association, n.d.).

15.1 Shredded textile waste.

Another area where shredding of cotton products has shown promise is reprocessing of denim fabric and garments. These are usually recognizable and can be separated fairly easily during sorting. A wide variety of recycled products are possible. Denim waste has even been made into pencils by combining with binders and reforming.

15.5 Chemical recycling

Chemical recycling involves use of separated generic fiber types as starting materials for entirely new products. The most commercially successful such process is the melting of polyester soda bottles to spin new polyester fibers. Although there is not an analogous example using cotton fibers, the area of chemical recycling of cotton has received much research attention in the last several years. There is significant potential for further work to balance the economics and develop viable recycling of cotton textiles into new regenerated cellulosic fibers or other products.

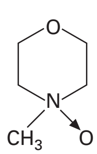
15.5.1 Lyocell

The traditional method for producing regenerated cellulose fibers is the viscose process in which the cellulose is reacted with carbon disulfide to form cellulose xanthate and then dissolved in caustic soda to form a viscous solution. This solution is spun into a coagulation bath containing sulfuric acid and mineral salt to regenerate the cellulose into viscose rayon. The process significantly reduces the degree of polymerization of the cellulose in order to dissolve it and, due to environmental considerations, is severely restricted in the US and other countries.

A more environmentally friendly process, developed in the 1980s, resulted in a new commercial fiber, lyocell. Lyocell fibers are made by dissolving cellulose directly in N-methylmorpholine N-oxide (NMMO) (Fig. 15.2). The lyocell solvent dissolves cellulose by intermolecular interaction only by the formation of hydrogen bond complexes (Johnson, 1969). The near monohydrate form (NMMO•H_2O) is used to produce Tencel® and Lyocell® fibers from blends of dissolving pulps of cellulose. In the commercial process the cellulose solution is spun into a water bath to regenerate cellulosic fibers. The lyocell solvent has essentially no vapor pressure, and therefore over 99% of the solvent can be recovered by filtering, dewatering, and evaporation. Favorable process economics are dependent upon the high solvent recovery rate.

The lyocell process was recognized by the United Nations for its environmentally benign impact since the solvent is biodegradable and lyocell production does not involve derivatization of the cellulose; any waste products are minimal and non-hazardous (Cole, 1992). Lyocell fibers are among the group of textiles that are publicized by the industry as environmentally improved textile products (EITP) (Moore *et al.*, 1999), and as such, production of these fibers from recycled cotton is a doubly advantageous approach.

Experimental work has been conducted to determine the applicability of the lyocell process for forming cellulosic fibers from cotton and cotton/polyester blend fabrics (Negulescu *et al.*, 1998). If all cotton fabrics are used, they are shredded and then dissolved in the lyocell solvent. For cotton/polyester blends the polyester was separated by alkaline hydrolysis to terephthalic acid by precipitation in an acidic environment after removing the cotton. The cotton was then dissolved in the lyocell solvent. Whether from cotton or cotton/polyester blends, the lyocell solution can be converted to either fibers or films by extrusion into water. The degree of polymerization (DP) of cotton may vary between 3,000 and 15,000 (Rydholm, 1965), whereas the typical dissolving pulp used for Tencel® and Lyocell®

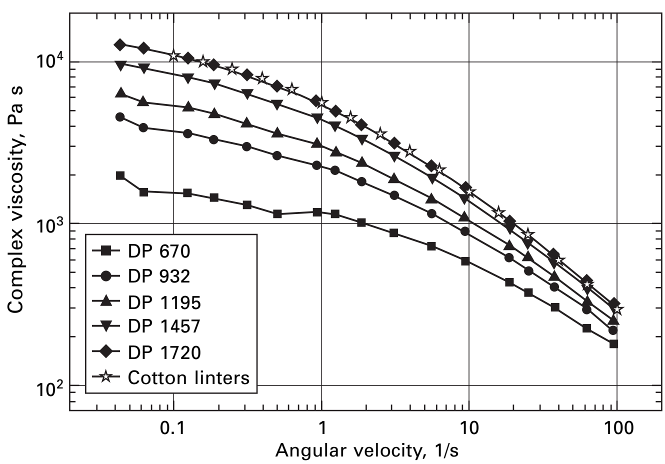


15.2 N-Methyl Morpholine N-Oxide.

fibers is less than 1,000. Therefore, recycled cotton cellulose could be blended with cellulose from other sources to prepare lyocell solutions with appropriate properties.

Cellulose from other sources such as cotton linters, as well as office wastes and agricultural residues could be blended with recovered cotton to form lyocell fibers. The behavior of lyocell solutions from these various sources has been studied and compared to solutions formed with commercial dissolving pulps (Dever *et al.*, 2003; Collier *et al.*, 2000). Cotton linters can be used to prepare lyocell solutions similar to those made with wood cellulose dissolving pulps. Due to the higher DP of cellulose from cotton linters, the viscosity is higher than that of dissolving pulp solutions (Fig. 15.3). Typically commercial lyocell solutions are prepared from dissolving pulps of different DPs. Recycled cotton therefore offers an additional source for blending with other materials to achieve the desired viscosity for spinning.

In addition to spinning fibers, solvent systems for cellulose from various sources were investigated for textiles and other products. Lyocell nonwoven webs have been made using the meltblowing process (Luo *et al.*, 2001) and work continues in this area. Wood pulp, rather than the purer dissolving pulp, was used, demonstrating the applicability of alternative cellulose sources for these processes. Solution viscosity is critical for nonwovens processing. Lyocell nonwoven webs have fibers equal to or smaller than those of cotton, making them superior to air laid or water laid nonwovens for some applications. Since these nonwovens are 100% cellulose they exhibit much higher absorbency than traditional melt processed nonwovens composed of synthetic polymers.



15.3 Complex viscosity of lyocell solutions prepared from cotton linters and wood dissolving pulps with different degrees of polymerization.

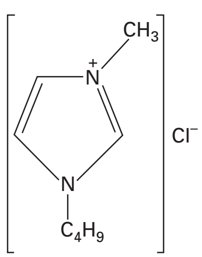
15.5.2 Ionic liquids

A relatively new class of solvents, ionic liquids, has become available and like the lyocell solvent, they have essentially no vapor pressure. The bulk of the work on ionic liquids has been reported in the last four years (Rogers, 2005). They are considered to be green solvents with regard to a lack of vapor formation, but their toxicity in aqueous environments is not yet determined (Seddon, 1997; Huddleston *et al.*, 2001). Some of the ionic liquids are water soluble and others are not.

The ionic liquid 1,3,-dibutylimidazolium chloride ([C_4mim]Cl) (Fig. 15.4) has been shown to be a good solvent for cellulose (Swatloski *et al.*, 2002). Other ionic liquids that also dissolve cellulose are similar [C_4mim] compounds with the chloride ion replaced by other strong hydrogen bond acceptors including Br, SCN, BF_4, or PF_6 (Swatloski *et al.*, 2002). Apparently the anion disrupts the intramolecular hydrogen-bonding of the cellulose hydroxyl groups thereby enabling the cellulose to be dissolved. The strong chloride activity enables dissolution of up to at least 25 wt% of cellulose and at a faster rate than traditional cellulose solvents.

Contacting the cellulose solution in [C_4mim]Cl with water, ethanol or acetone significantly reduces the cellulose concentration reportedly due to competition for hydrogen bonding with cellulose, causing separation of the cellulose and solvent (Swatloski *et al.*, 2002). The [C_4mim]Cl solvent is regenerated as in the lyocell process by filtration, dewatering and evaporation. Recovery and cost of solvent will dictate the economics of the process. If other water soluble ionic liquids are used, they can be recovered in the same fashion. If they are not water soluble, phase separation and recovery can be used. It should be possible to alter all ionic liquids and their properties by ion exchange.

In an initial examination of this ionic liquid solvent system, regenerated cellulosic fibers from [C_4mim]Cl were produced using bleached cotton fibers (DP 2000), rayon yarn (600 denier/98 filaments from North American Rayon DP 700), and bleached wood pulp (International Paper DP 1056). The properties of these fibers were dependent upon processing conditions and cellulose



15.4 Chemical structure of 1-butyl-3-methylimidazolium chloride ([C_4mim]Cl).

source (Table 15.1). The solutions made with cotton fiber produced finer fibers because they were able to be drawn down without breaking. These regenerated fibers from cotton also had lower elongation than those from other sources, but tenacities similar to the rayon source fibers.

Other applications of the regenerated cellulose from ionic liquids are macroscopic particles (powders and nanoparticles); macromolecular inclusions (enzymes and other bioactive molecules and metal-oxide particles, and molecular binding agents for metal); complexing, reactive dyes; and pH responsive sensors (Rogers, 2005). Magnetite was dispersed in an ionic liquid-cellulose solution, coagulated with water, and reconstituted as flocs, washed, dried and milled. The resulting cellulose-encapsulated magnetite exhibited magnetic properties (Rogers, 2005).

The biomolecule laccase from *Rhus vernificera* was used to demonstrate enzymatic activity of entrapped biomolecules in cellulose films prepared from ionic liquids solutions. This naturally occurring enzyme degrades lignin for subsequent separation from cellulose and is used as a catalyst for polyphenolic degradation of waste materials. Activity of the enzyme was maintained even though encapsulated (Turner *et al*., 2004). A mercury (II) sensitive membrane was prepared by encapsulating 1-(2-pyridylazo)-2-naphthol within a cellulose membrane cast from an ionic liquid solution (Rogers, 2005). Homogeneous acetylation of cellulose has been accomplished in an ionic liquid solution (Wu *et al*., 2004). Ionic liquids have also been used to solution blend cellulose with polyacrylonitrile and with polyethylene glycol (Rogers, 2005; Anderson *et al*., 2002).

15.5.3 Conversion to chemicals

Cotton is the purest major cellulosic resource and can be considered as a starting material for the manufacture of a practically unlimited number of chemical products, by derivatization, depolymerization, carbonization, or purification. Cellulose derivatization is the most important route to various chemical products which are then used as such or may be further converted to regenerated cellulose products. Conversion of recycled cotton to cotton derivatives is based on the reaction of cellulose primary and secondary hydroxyl

Table 15.1 Properties of fibers spun from ionic liquid

Cellulose source	Denier	Tenacity (g/den)	Breaking elongation (%)
Cotton	11.3	3.38	3.8
Rayon	38.6	3.43	18.7
Dissolving pulp	27.3	4.41	7.6

Compiled from data in Rogers, 2005.

groups by reacting with an array of reagents and may include further derivatization of obtained products.

Esterification is one of the most important substitution reactions on cellulose and is generally carried out in strongly acid medium to give cellulose esters such as cellulose nitrate, sulfate, phosphate, formate, acetate, propionate, butyrate, aceto-propionate, and aceto-butyrate. From a commercial standpoint, the most important derivatization reactions are nitration and acetylation, producing nitrocellulose and acetylcellulose which have been made into fibers and films. Nitrocellulose has been used for some time in manufacturing explosives, plastics and lacquers. Acetylcellulose is also broadly used to make products of various end-uses. The nitration reaction is performed in a nitration medium consisting of nitric acid, sulfuric acid and water, while acetylation is done in a mixture of acetic acid, acetic anhydride and an acid catalyst.

Etherification is the second cellulose derivatization route and is carried out in alkaline medium with alkyl halides as etherifying agents, resulting in many cellulose ethers such as methyl, ethyl, propyl, isopropyl, butyl, isobutyl, amyl, methyl-ethyl, methyl-hydroxyethyl, methyl-hydroxypropyl, carboxymethyl, benzyl, to name but a few. The end-use properties of cellulose derivatives mainly depend on the esterification or etherification agent, cellulose degree of polymerization, and the degree of substitution. The degree of substitution (DS) is defined as the average degree of substitution per glucose unit from the derivative polymeric chain and may vary from zero to a maximum of three, if all three hydroxyl groups from a structural unit are substituted.

In a demonstration of derivatization of recycled cotton, nonwovens of low apparent density were prepared by carding together recycled cotton fibers and cotton fibers previously carboxymethylated with chloroacetic acid (DS of 0.3) (Negulescu *et al.*, 2005).

$$\begin{aligned} &\mathrm{CELL(OH)_3 + nClCH_2CO_2H} \\ &\mathrm{+\ nNaOH \rightarrow CELL(OH)_{3\text{-}n}(OCH_2CO_2Na)_n + nNaCl} \qquad 15.1 \end{aligned}$$

where n reflects the degree of substitution, DS, which is the average number of carboxymethyl [-CH_2COO^-] groups per anhydroglucose unit of cellulose.

The resulting nonwoven webs were treated subsequently with aqueous solutions of urea (U), saturated aqueous melamine (M) solution, or the adduct of phosphoric acid with urea (A), and dried at 110 °C. The nitrogen content determined from the add-on amounts of nonwovens was around 0.04–0.2g N/g fabric, depending upon the reagent and the type of nonwoven. The carboxymethylated bagasse/cotton nonwoven treated with the adduct solution retained A corresponding to a nitrogen content of 0.053g/g nonwoven and to a phosphorus content of 0.059g/g nonwoven. Finally the treated nonwovens were stabilized with a concentrated lyocell solution also obtained from recycled cotton fibers. The nonwoven products were aimed as fertilizing components in nonwoven geotextiles or as filtering media for sequestering heavy metals.

Cellulose depolymerization is another route to a broad class of cellulosic products. Cellulose in industrial products has a much lower DP than native cotton and can be obtained from cotton and other natural sources using mechanical and thermochemical methods to reduce the length of the polymeric chains. Cotton and cotton waste are used to manufacture different grades of cellulosic products, depending on the DP required. Dissolving pulps and cellulose grades to be used for chemical derivatization are prepared by a multistep chemical treatment process comprising prehydrolysis, pulping and bleaching to reduce the DP to a range between 350 and 800, depending on the final product. The alpha-cellulose content should be 95% or higher.

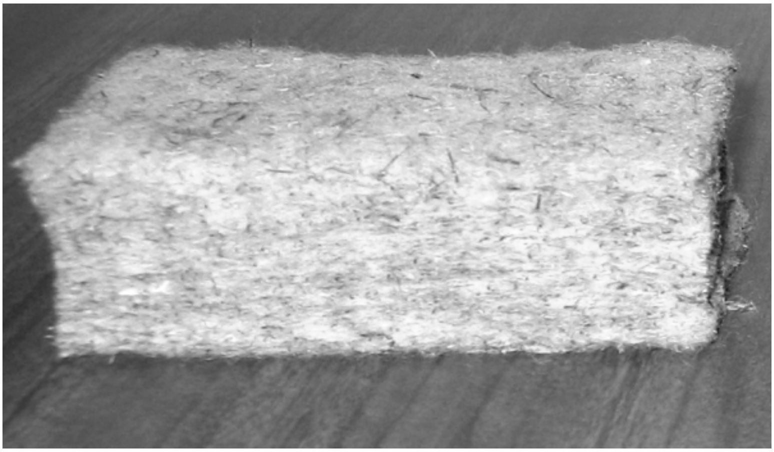
Microcrystalline cellulose, or micronized cellulose, is the grade of cellulose with the lowest DP, generally lower than 300. The best raw material for this type of product is cotton or cotton waste, mainly when it comes to uses in the field of medicine or as food additives.

Cellulose depolymerization can proceed to simple sugar or glucose by hydrolysis (chemical or enzymatic) and the product can be used as a chemical or for making fuel by fermentation. Carbonization of cellulose from cotton waste at about 700 °C results in activated carbon or carbon fibers with a wide range of applications (Iwamoto and Nakamura, 1998; Nakamura and Iwamoto, 1998).

Pure cellulose can be also manufactured from cotton waste. By a proper combination of prehydrolysis, alkaline pulping, and bleaching sequences, cellulose with a purity as high as 99.9% alpha-cellulose can be obtained (Abou-State, 1977; Abou-State and Abd El Megeid, 1977).

15.6 Future trends

As the economics of collecting and sorting textile waste become more favorable, and the pressure for environmentally friendly products spreads, recycling of cotton and other textile waste will see increased interest. The technologies and products categories have been developed and await successful marketing efforts and consumer interest. Lower value end uses, as described in sections 15.3 and 15.4 above should see growth, much of which will be in the area of nonwoven products. These are simple and easy to manufacture, not requiring significant capital or labor investment nor demanding a high price. One of the primary operations is the formation of composite webs by blending together recycled cotton fibers with other cellulosic or synthetic fibers using a carding machine (Fig. 15.5). The webs can be then stabilized in final nonwoven products by melting the synthetic component (Negulescu *et al.*,

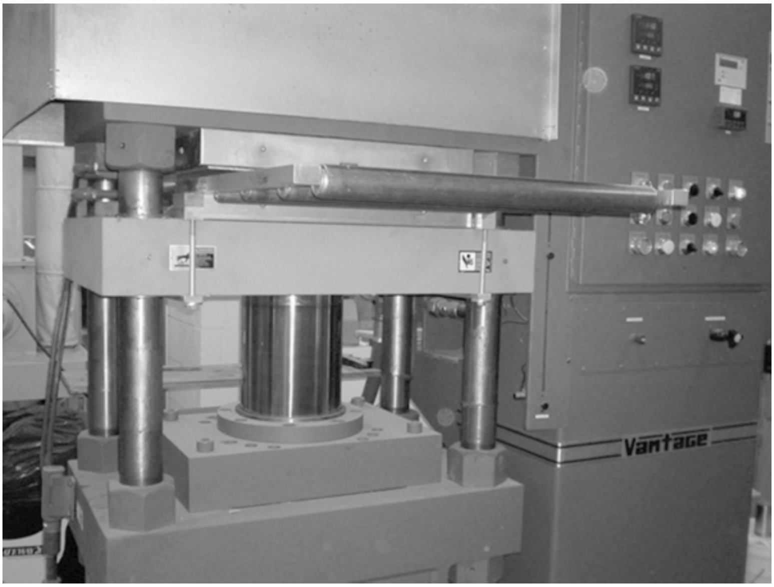


15.5 Webs of recycled cotton fibers carded with coarser bagasse fibers.

2004) or using lyocell solutions (Negulescu *et al.*, 2003). Panels and boards of pre-established densities, according to their end-use, can be easily manufactured by pressing (Fig. 15.6).

Chemical recycling should see increased research, development, and subsequent commercialization. Use of lyocell and ionic liquids to dissolve and reform cellulosic materials with and without inclusion of particles to alter properties will enable the use of cotton based materials in new areas and enhancements of other applications. Traditional uses of cotton are as fibrous products whether woven or nonwoven. With these new solvents however films, membranes, flacks, particles and extruded and processed forms can be achieved. Traditional polymer processing and forming operations will not need to be significantly altered to handle the solutions. Film and membrane casting of polymers are well established and capable of handling these viscous solutions. Lyocell solutions derived from recyclable cotton fibers have been used also for stabilization of composite nonwoven webs made of recycled cotton fibers carded together with coarser fibers derived from annual plants (Negulescu *et al.*, 2003). Extrusion and resin transfer molding can be adapted to processing these solutions by controlled contact with water, acetone or an alcohol, and adjustments made to remove the solvent and contact liquid. Shrinkage or void formation as the solvent is removed should be controlled by process changes.

Other polymers are also soluble in the lyocell and/or ionic liquids solvents making it possible to form intimate blends of cellulose and the other polymer. Furthermore, with controlled solubilities it could be possible to form multiple thin layer membranes or films from solution. Dispersing or dissolving other components in the solution enables encapsulation of these components in the



15.6 Press used for forming nonwovens from composite webs.

fibers or films. The other components can be biocides, pigments, etc., and due to incorporation into the fibers their effects should be more permanent.

15.7 Sources of further information

The research literature, as cited below, covers much of the work in chemical recycling. Current activities and players in the recycling area are easily found on the internet. The Council for Textile Recycling in the US (www.textilerecycle.org) and the Textile Recycling Association in Britain (www.textilerecyclingass.sageweb.co.uk) have general web pages that provide links to other sources. These sources include buyers and sellers of textile waste and used products, manufacturers of recycling equipment, and local governments with collection and recycling programs. EPA's Jobs Through Recycling (JTR) program offers grants designed to expand recycling and reuse markets for commodities like textiles (US Environmental Protection Agency, 2005a).

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16
Nonwoven technology for cotton

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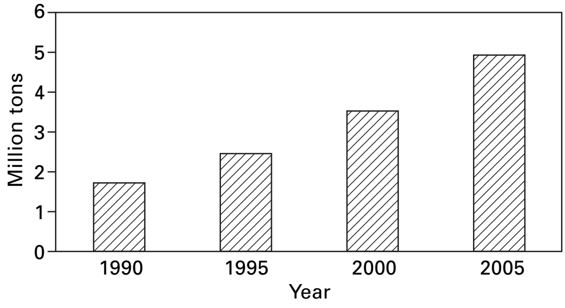
Traditionally fabrics have been produced by weaving or knitting, which involve conversion of fibers into yarns and subsequently arranging the continuous yarns into two-dimensional structures. In the past few decades, non-traditional fabrics, called nonwovens, have become more and more popular. Nonwovens are the fastest growing sectors of textile materials, and they continue to grow all over the world. A significantly large share of these are used as single use, or short life products, leading to disposability related problems. Many of these disposable products are used in health and hygiene applications. In such situations, cotton becomes the fiber of choice. Additional advantages of cotton include superior wet strength as well as a quick drying surface. Bleached cotton fibers have high levels of absorbency, are soft to the touch, breathable and biodegradable. However, there are other issues such as quality, processability and cost, which have limited the share of cotton to relatively low values among other fibers. With recent advances in science and technology, it is possible to obtain cleaner cotton at a cheaper price. Also, with increasing cost of petroleum products, and change in polymer and fiber supply market, synthetic fibers are becoming expensive, and the future looks brighter for cotton in nonwovens with increasing opportunities for growth. The methods of producing nonwovens, especially those applicable to cotton fibers, their application potential, the nonwoven market, and recent research in different areas for cotton nonwovens are discussed in the following sections.

16.1 Nonwovens

Nonwoven fabrics are flat, porous sheets or web structures that are made directly from separate fibers or from molten plastics or from plastic films by entangling fibers or filaments mechanically, thermally or chemically. According to the International Nonwovens and Disposables Association (INDA),[1] 'Nonwovens are a sheet, web, or batt of natural and/or man-made fibers or filaments, excluding paper, that have not been converted into yarns, and that are bonded to each other by any of several means.' Nonwovens can be produced from both natural and synthetic fibers or directly from polymers by a variety of techniques that involve web formation and bonding.

Over the past two decades, consumption of nonwoven products has grown at the rate of almost 10% per year (Fig. 16.1). This tremendous growth has been due to their ease of manufacture, higher processing speeds, lower cost of production, and ability to produce fabrics with a range of properties. Unlike traditional textiles, nonwoven fabrics are not manufactured by the conventional processes of weaving or knitting, and converting of fibers to yarns is not required. Both natural and synthetic fibers, organic and inorganic, can be used to produce nonwoven fabrics. The fibers in these structures may be staple or continuous, or may be formed *in situ*, and may be directionally or randomly oriented, depending on the nature of the manufacturing method used.

Nonwoven fabrics demonstrate specific characteristics such as strength, stretch, resilience, absorbency, liquid repellency, softness, flame-retardancy, cushioning, washability, filtering, bacterial barrier and sterility. Nonwoven fabrics can be used in a wide variety of applications, which may be limited life, single-use fabrics as disposable materials or as durable fabrics.[2,3] Demand for nonwoven materials in the USA is expected to increase by 3.9% per year to be nearly $5 billion in 2007. The growth rate in rest of the world is expected to be much higher, in the range of 6–7% per year. This increasing market share will be driven by the strong growth in many key disposable markets such as adult incontinence products, filters, and protective apparel, and key non-disposable markets such as geotextiles and battery separators. The market for disposable products represents the majority of nonwoven demand, accounting for a 64% share in 2002.[4] Disposable consumer products, which primarily include baby diapers, adult incontinence and feminine hygiene products, and wipes, were the largest market for nonwovens in 2002.[5]



16.1 Worldwide nonwoven production data (from ref. 4, with permission from INDA).

Nonwovens are used almost everywhere, in agriculture, construction, military, clothing, home furnishing, travel and leisure, healthcare, personal care, and household applications. Whereas in some areas the nonwovens are replacing traditional fabrics, because of their unique properties, they are finding many new applications as well.

Cotton nonwovens are used as swabs, puffs, wipes, filters, waddings, personal care products such as diapers and feminine hygiene products, semi-durable segments like bedding, household furnishing, pillow fillers, etc. Some of the major uses are listed in Table 16.1. Additional advantages of cotton and other natural fibers include superior wet strength as well as a quick drying surface, notably in wipes. Bleached cotton fibers have high levels of absorbency and are soft to the touch, breathable and biodegradable. One quickly growing area, especially throughout Europe and Japan, is spunlaced cotton used for cosmetic wipes and other disposable products; these trends are likely to spread to other markets as well.

16.2 Production of nonwovens

In most cases, the formation of nonwovens consists of two basic steps, web formation and bonding. The web formation in nonwoven production is a critical contributor of the end-use product performance. Three basic methods are used to form a web: dry laid; wet laid; and polymer laid, the latter of which consists of spun laid and melt blown web formations. Electrospinning,

Table 16.1 Products from cotton nonwovens

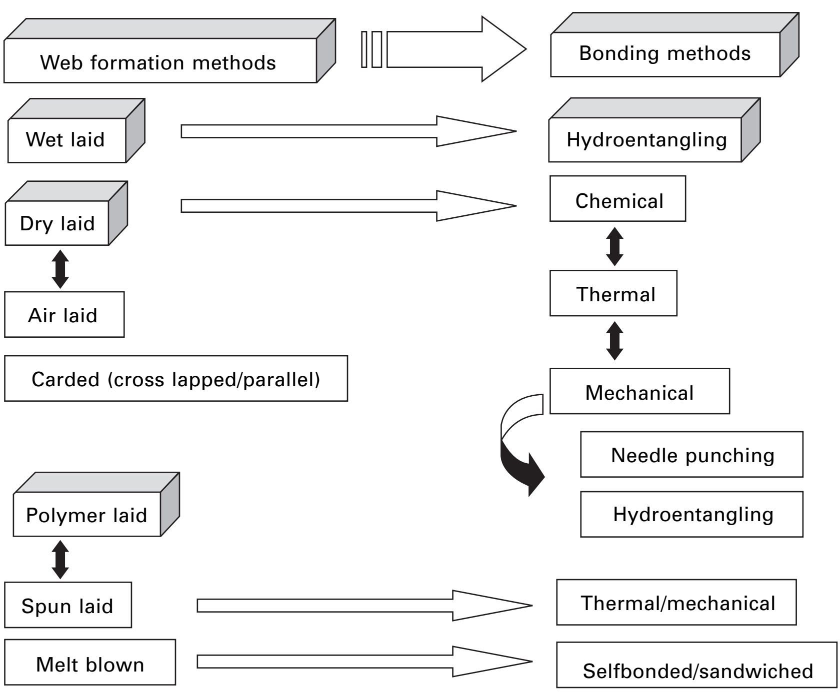
Personal care products
Swabs
Cosmetic pads
Tissues
Medical/dental – wipes, sponges, plugs
Diaper components – coverstock, acquisition layer, cores, back sheet
Feminine hygiene – pads, tampons
Adult continence
Baby and consumer wipes
Durable/semi/durable products
Apparel – clothing, performance wear, outerwear, medical gown and drape, interlinings
Home furnishings – bedding, mattress pads, wall coverings, decorative felts
Industrial products
Filter media
Geotextiles
Protective apparel
Absorbent media – oil and chemical
Insulation – thermal and acoustical
Packaging

an area of continuing research and some commercialization, is also a variation of the polymer laid process. Webs have little strength when they are formed and must therefore be consolidated or bonded in some way. There are three basic types of bonding: chemical, thermal, and mechanical. Whereas cotton webs can be successfully bonded by mechanical process, additional binder polymer or fiber is required to use the chemical or thermal bonding. The nonwoven formation methods used in the industry are summarized in Fig. 16.2.

16.2.1 Web formation

Dry laid

In the dry-laid process, conventional staple fibers are used, which are usually 12 to 100 mm or longer. The fibrous web is prepared using the classical textile carding machine or air laying machine to separate and orient the fiber mechanically. Carding is the most common process to produce nonwoven fabrics from staple fibers. The objective of carding is to separate the fiber stock into individual fibers with minimum fiber breakage. Thus, the carding process consists of opening and blending of different species of fibers

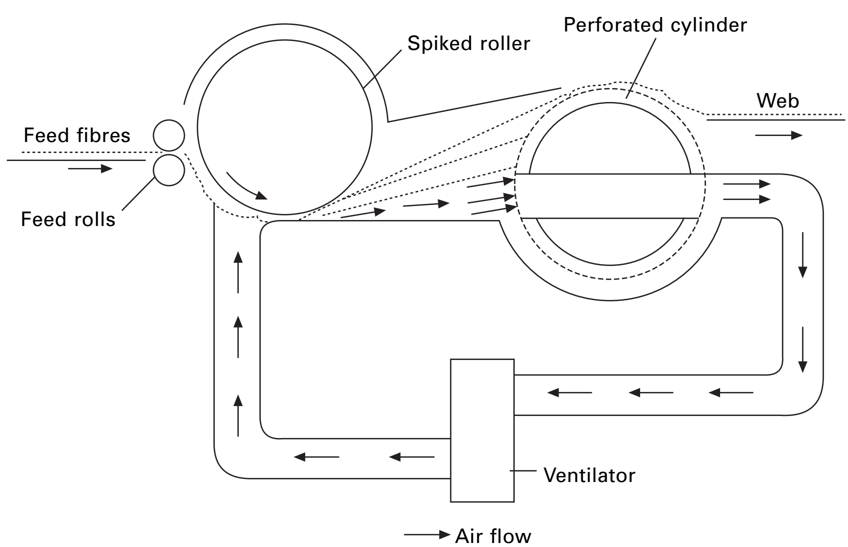


16.2 Nonwoven formation methods.

thoroughly. Carding is performed by the mechanical action in which the fibers are held by one surface while the other surface combs the fibers, causing the separation of individual fibers, as described in earlier chapters. In a normal carding process, the fibers are more oriented along the machine direction than the cross direction. More random web structures can be obtained by cross lapping or a centrifugal dynamic random card system.

The orientation created by carding is improved by capturing fibers on a screen from an air-stream (Fig. 16.3). Starting with a lap or plied card webs fed by a feed roller, the fibers are separated by a licker-in or spiked roller and introduced into an air stream. The total randomization excludes any preferred orientation when the fibers are collected on the condenser screen. The web is delivered to a conveyor for transporting to the bonding area. The length of fibers used in air laying varies from 20 to 60 mm. Shorter fibre lengths allow higher production speeds as they are transported easily in the air stream with larger amount of fibers per unit volume of air and deposited on the collector. Longer fibers require higher air volume, i.e., a lower fiber density to avoid tangling. Problems associated with air laying are speed, web uniformity and weight limitations. Due to uniformity problems across the width due to variation in air and fiber volume, it is not practical to make isotropic webs lighter than 30 g/m^2 by the air laid process.

Some advantages of air laying are the isotropic web structure, that voluminous webs can be produced and that a wide variety of fibers such as natural, synthetic, glass, steel, carbon, etc., can be processed. This will allow the production of webs from blends of cotton with other staple fibers. Some



16.3 Schematic of the air laid process.

of the disadvantages are the low level of opening fiber material by the licker-in, the variation in web structure across the width of layer due to irregular air flow close to walls of the duct and possible entanglement of fibers in the air stream.

The centrifugal dynamic random card forms a web by throwing off fibers from the cylinder onto a doffer with fiber inertia, which is subject to centrifugal force, in proportion to the square of the rotary speed. This is different from the conventional card used in spinning systems, where the fibers are preferentially oriented along the machine direction. The random card can produce a 12 to 50 g/m^2 web with fine fibers of 1.5 den and webs up to 100 g/m^2. Orientation in the web is three-dimensional and is random or isotropic with no preferred orientation of the fibers in any particular direction. Production of the random card is generally about 30 to 50% higher than conventional cards. The machine direction versus the cross-direction strength is better than those produced in the conventional card, but is not as good as that of the air-laid webs.

Nonwovens can be made into the desired structure by the layering of the webs from either the card or garnett. Garnetts are similar to roller top cards, with a group of rolls placed in an order and wire configuration to transport, comb and interlock fibers to form a web. Layering of webs can be accomplished in several ways (i.e., longitudinal, perpendicular or cross) to achieve the desired weight and structure. Carded or air-laid webs usually have basis weights ranging from 30 to 2500 g/m^2. Typical end uses for dry-laid nonwoven fabrics are the fabrics for carpet backing, interlinings for garments, apparel and upholstery backings, filter media, diaper coverstock, wipes, insulation, auto linings, medical fabrics, geotextiles and personal hygiene products.

Wet laid

Wet-laid nonwovens are webs made by a modified papermaking process. First, the fibers are mixed with chemicals and suspended in water to make the slurry. Then, specialized paper machines are used to drain the water off the fibers to form a uniform sheet of material, which is then bonded and dried. Thus, three steps are needed for the wet-laid process, the dispersion of the fiber in water, transporting the suspension onto a continuous traveling screen to form the continuous web, and drying and bonding of the web. Short fibers, which are usually less than 10 mm, are needed for wet-laid processing and the resulting fabric has a basis weight ranging from 10 to 540 g/m^{-2}. The wet-laid process has advantages of high productivity, control of orientation of properties, and high uniformity at low basis weight when compared with the air-laid process. Typical applications for wet-laid nonwovens include tea bags, wipes, surgical gowns and drapes, towels, etc.[6]

Spun laid

Spun laid or spunbonding is a one-step process, which involves polymer melting, filament extrusion, drawing, laydown and bonding of the web to impart strength, cohesiveness and integrity to it.[7] The spinning process is similar to the production of continuous filament yarns and similar extrusion conditions are used for a given polymer. Fibers are formed as the molten polymer exits the spinnerets and are quenched by cool air. Unlike in the typical fiber spinning process, there is no positive take-up, and fibers are directly deposited on a moving collector to form a web. Before deposition on a moving belt or screen, the individual filaments must be attenuated to orient molecular chains within the fibers to increase fiber strength and decrease extensibility by rapidly stretching the plastic fibers immediately after exiting the spinneret either mechanically or pneumatically. Then the web is formed by the pneumatic deposition of the filament bundles onto the moving belt. The fibers have to be distributed on the belt using some type of randomization so that a fairly uniform random web is formed.

The formed webs are bonded either by mechanical, chemical, or thermal methods depending on the ultimate fabric applications. Of the different options, thermal point bonding is the commercially popular method, wherein the bond area is about 15%. At these bond points fiber surfaces are partially melted to form fusion between neighboring fibers, thereby imparting strength to the webs. Today spunbonded fabrics are widely used throughout automobiles as backing for tufted automobile floor carpets, trim parts, trunkliners, interior door panel, and seat covers, etc. For civil engineering applications, spunbond fabrics have been applied for erosion control, revetment protection, railroad bed stabilization, canal and reservoir lining protection, highway and airfield black top cracking prevention, roofing, etc.[18] Spunbonded fabrics have also been widely used in sanitary, medical and packaging industries. Spunbonding is one of the fastest growing processes. Although spunlaying uses thermoplastic polymers and is not suitable for cotton, recently there has been work done to produce cotton containing composites in a spunlay process as will be discussed later.

Melt blown

Melt blowing is one of the most popular processes of making super fine fibers on the micron or sub-micron scale. In a melt-blowing process a thermoplastic polymer is extruded through an extruder die which is rapidly attenuated by the hot air stream to form the extremely fine diameter fibers. The attenuated fibers are then blown by high-velocity air to a collector screen to form a fine-fibered, self-bonded web. The combination of fiber entanglement and fiber-to-fiber bonding generally provides enough web cohesion so that the web can be used without further bonding. Melt-blown fibers generally have diameters in the range of 2 to 7 μm, although they may be as small as 0.1 μm and as large as 30 μm. Due to the large fiber surface area of the melt-blown fabrics, they are used in filtration, insulation and liquid absorption applications. Because of the simplicity of the process, any thermoplastic fiber can be melt blown. However, the polymer should have very low melt viscosity, and it is an energy consuming process. Just like the spun laid process, although melt-blowing uses thermoplastic polymers, composite structures containing cotton fibers can be produced to accomplish unique combination of properties suitable for certain applications.

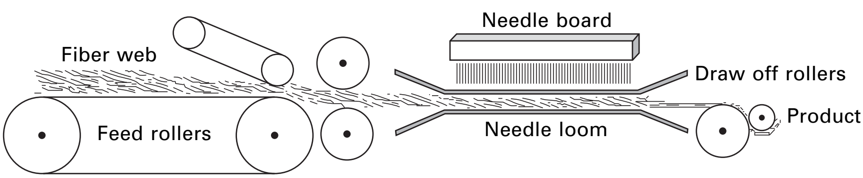
16.2.2 Web-bonding techniques

The web-bonding techniques can be generally classified into three categories, mechanical, chemical, and thermal bonding, depending on the ultimate fabric applications and/or on the web formation method. Sometimes, in order to achieve products with certain properties, a combination of different bonding methods is applied.

Mechanical bonding

Mechanical bonding can be further classified as needle punching, stitching, and spunlacing (hydroentangling). Needle punching is a process of bonding nonwoven web structures by mechanically interlocking the fibers through the web via the barbed needles. A schematic of the needlepunching process is shown in Fig. 16.4. As the unbonded web moves through the needle loom, the web is consolidated and becomes stronger because of fiber interlocking. The level of consolidation is controlled by the needle density. It is the only bonding method suitable for heavyweight nonwoven fabrics. The needle-punched fabrics are extensible, bulky, conformable, distortable and extremely absorbent. Both dry laid and polymer laid webs can be needle punched. Needle-punched fabrics have been used as carpet backing fabrics, automobile carpets and headliners, blankets, and geotextile fabrics.

Stitch bonding is the process of bonding a web by using stitching yarns, filaments, fibers, or just the stitching needles themselves to do the bonding.



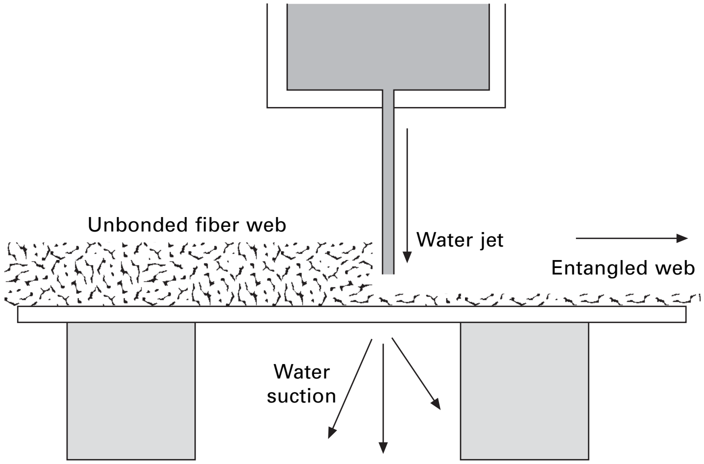
16.4 Schematic of the needle punching process (from ref. 4, with permission from INDA).

Stitch-bonded fabrics have taken the place of woven goods in many applications such as decorative fabrics for home furnishing, shoe fabrics, backing fabrics for artificial leather, etc.

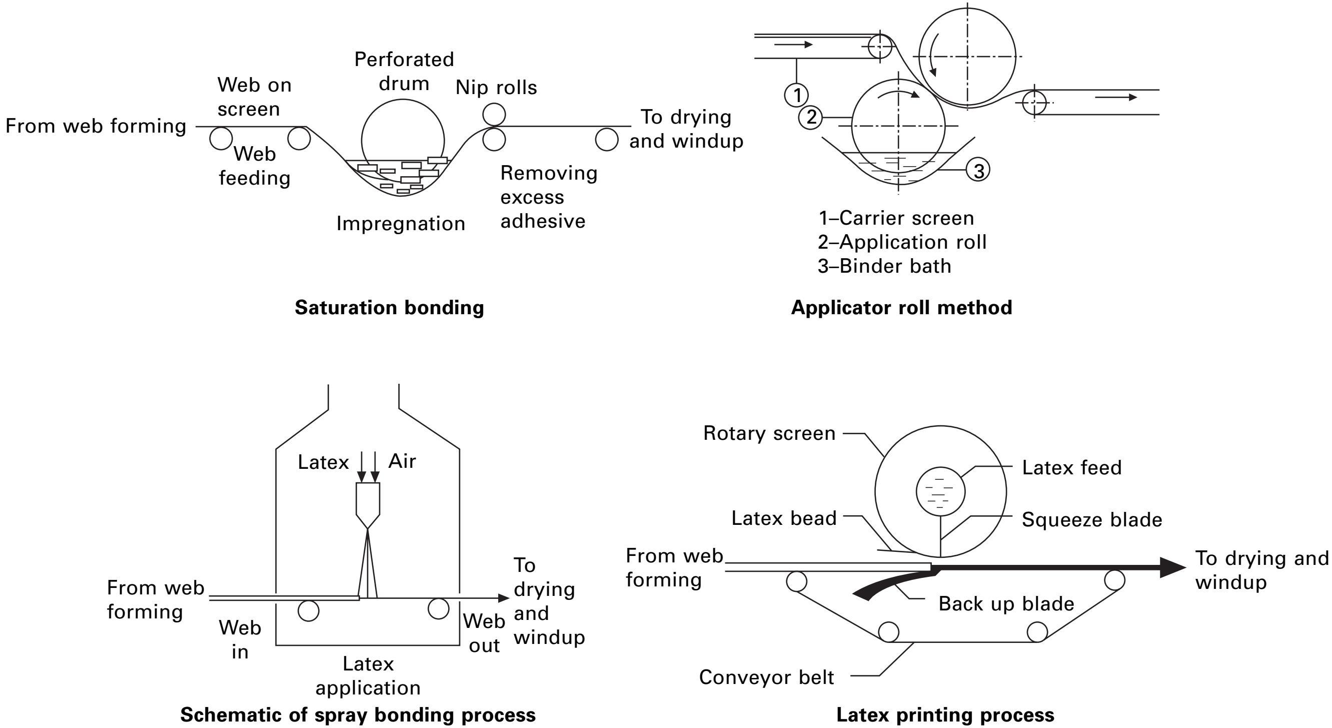
Spunlacing is a process of entangling individual fibers with each other using high-pressure water jets, which cause the fibers to migrate and entangle. As shown in the schematic (Fig. 16.5), water jets push the fibers in the web through the z-direction and the turbulence created causes enough interlocking between fibres to produce strong fabrics. The system requires a good water filtration system as clean water has to go through the fine gauge water jets. Hydroentangled fabrics have more appealing properties than the needle-punched fabrics. Spunlaced fabrics can be used as wipes, medical gowns, dust cloths, etc. Unlike needle punching the spunlace process has no reciprocating mechanical part, which allows faster production speeds to be used.

Chemical bonding

Chemical or resin bonding is a generic term for bonding fibers by the application of a chemical binder. The chemical binders most frequently used to bond fiber webs today are water-borne binders made from vinyl materials, such as polyvinyl acetate, polyvinylchloride, styrene/butadiene resin, butadiene, and polyacrylic, or their combinations. Chemical binders are applied to webs in amounts ranging from about 5% to as much as 60% by weight on fiber. The binder solution is applied to the web and then cured thermally to obtain bonding. Several methods are used to apply binders including saturation bonding, spray bonding, print bonding, and foam bonding, etc. (Fig. 16.6).



16.5 Schematic of the hydroentangling process.



16.6 Various chemical bonding processes (from ref. 4, with permission from INDA).

The type of bonding used depends on the web as well as the type of binder used.

Chemical bonded fabrics have been widely used as wipes and towels, apparel interlinings, automotive trim, filter media, etc. Use of the right chemical binder depending on the fiber and the intended application is important since the binder stays in the fabric. Also, environmental issues while applying or curing of the binders also need to be considered. Chemical bonding allows more room for fabric designs and fiber selections. On the environmental front, increasingly strict regulations and guidelines are driving a trend towards alternative products and technologies. Manufacturers and end-product suppliers alike are seeking ultra-low or formaldehyde-free binders.

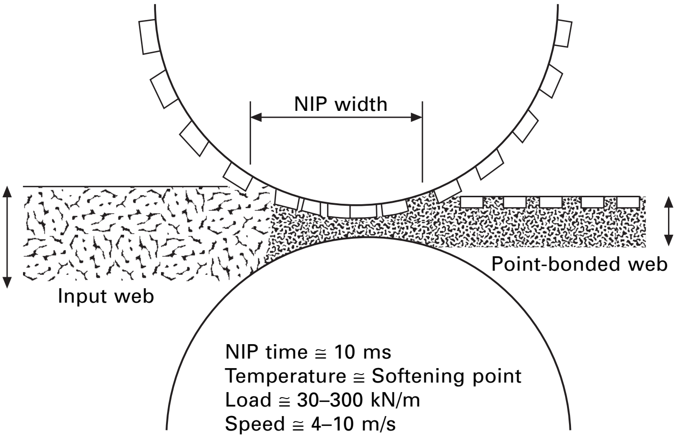
Thermal bonding

Thermal bonding is the process of using heat to bond or stabilize a web structure that contains a thermoplastic binder. It is the most popular method of bonding used in nonwovens, because of the favorable process economics, the absence of chemical binders (that is, environmentally friendly), the availability of new fibers and machinery, and process and product enhancement. The bonding is achieved by the direct action of heat and pressure by a calender, an oven, a radiant heat source, or an ultrasonic wave source. The thermoplastic binder can be in the form of fiber, web, or powder. There are four methods of thermal bonding. They are hot calendering, oven bonding, ultrasonic bonding, and radiant heat bonding. Hot calendering can be further classified as area or point bond hot calendering, and embossing hot calendering.

Among the various types of thermal bonding methods, point bonding using embossing rolls is the most desired method since this produces fabrics with desirable properties at very high speeds. A schematic diagram of the point bonding process is shown in Fig. 16.7. The process employs direct contact, with heat and pressure, to produce localized bonding in a nonwoven. Fabrics have additional softness and flexibility compared with fabrics produced using smooth rolls in area bond hot calendering.

16.2.3 Technology and relative production rate

One of the reasons for the continuing growth of nonwovens is the high production rates that are possible with the new technologies. Typical production rates are listed in Table 16.2. Compared to only a few meters per minute possible with the woven or knitted fabrics, nonwovens can be produced at the rate of a few hundred to thousand meters per minute. This high production rate combined with the fact that the intermediate yarn formation is eliminated helps in keeping the cost of nonwovens very low. This low cost of roll goods production has helped in the tremendous growth of nonwoven products.



16.7 Thermal point bonding process.

Table 16.2 Production rates of different fabric formation processes

Fabric formation process	Production rate, m/min
Weaving	1–6
Knitting	3–16
Nonwovens – web forming:	
• Carding	120–400
• Spunbond	200–2000
• Wet-laid	2000
Nonwovens – bonding	
• Stitchbonding	40
• Needling	30–500
• Calendering	2000
• Hot air bonding	5000

16.3 Fibers used in nonwovens

Manufacturers of nonwoven products can make use of almost any kind of fibers. These include traditional textile fibers, as well as recently developed hi-tech fibers. The selection of raw fibers, to a considerable degree, determines the properties of the final nonwoven products. The selection of fibers also depends on customer requirement, cost, processability, and change of properties because of web formation and consolidation. The fibers can be in the form of filament, staple fiber or even yarn.

Many different fiber types are used in the formation of nonwovens. These include traditional textile fibers such as polyester, polyolefin (PP/PE), nylon, cotton, rayon, wool, lyocell, modacrylic; and advanced fibers, such as aramid (Nomex/Kevlar); conductive nylon; bicomponents (side-by-side, sheath-core, segmented pie, and islands-in-the-sea); melamine (heat and flame resistant); hollow fibers (polyetherketone, polyaniline); Spandex fibers (polyether): fusible co-PET fiber; nylon 6 support/matrix fiber; glass micro-fiber; chlorofibre; antibacterial fiber; stainless steel; rubber thread; poly(tetrafluoroethylene) (PTFE); electrospun polymeric nanofibers.

16.3.1 Cotton fibers for nonwovens

The share of cotton in the nonwoven staple fibre market at present time is insignificant, although the potential for growth is very high. Just about everyone can recognize cotton as a durable, breathable and soft fiber. Whether it is a cotton ball or hand wipe or favorite cotton T-shirt, cotton is well recognized and widely accepted by consumers. Some of the advantages of cotton as well as issues with nonwovens are listed in Table 16.3.[9] A Cotton Incorporated, report, *Cotton Nonwovens: Innovations & Solutions*, sheds light on how powerful the name cotton has become.[10] In 2000, the global nonwovens market used the equivalent of 14.7 million bales of fibers. From 1996–2005, global consumption of bleached cotton fiber rose to 6% of total fiber used in nonwovens, while cotton's current share of the nonwovens market is 7.8% globally and 2.9% in North America. In major consumer markets of North America, Western Europe and Japan, growth of cotton usage in nonwovens is projected to be 3–6% per year for the next few years.

A study,[9] conducted by Cotton Incorporated in six cities across the USA, tested consumers' perceptions of fiber content in nonwoven products and how these perceptions affected purchasing preferences. The study was focused with four product categories: feminine napkins, tampons, baby wipes and disposable diapers. In each category, the Cotton Seal significantly influenced consumers' purchasing preference. Moreover, 66% of consumers perceived personal care products with the cotton seal to be of higher quality. To use the

Table 16.3 Cotton for nonwovens – advantages and issues

Advantages of Cotton	Issues with cotton
• Softness	• Cost
• Absorbency	• Trash content
• Excellent wicking	• Color variations
• Breathability	• Fiber length variations
• Comfort	• Dusting and linting
• Biodegradability	• Nep formation
• Higher wet strength	
• Low static potential	
• Dyeable/printable	
• Chemically modifiable	
• Sterilizable by all industrial methods	

cotton seal, products must have a minimum cotton content of 15% in some products and a higher level in some other products.

Many of the cotton absorbent products such as surgical sponges, sanitary napkins, tampons and cosmetic pads and puffs can be satisfactorily made from by-product cotton fiber, i.e., gin motes, comber noils and other mill waste. Most of these products use bleached cotton coil (an oversized sliver) that needs little integrity (fiber-to-fiber cohesion). However, roll goods from lightweight webs made by carding or air forming require textile grade fiber. Recommended fiber properties according to Cotton Incorporated and suggested methods of testing are:[11]

- micronaire: greater than or = 4.9
- length: greater than or = 0.95 inches
- uniformity: greater than or = 81.0 percent
- strength: greater than or = 23.0 g/tex
- non-lint content 0.8% maximum (MDTA-3)
- fiber-to-fiber cohesion, 1700 g force maximum (ICI Fiber Cohesion Test)
- fiber openness equal to 100 cc/gram minimum (ITT Test Method)

Fiber length and strength are important in the manufacture of lightweight nonwovens. However, good fabric appearance is more important than fabric strength in certain nonwoven products, and fiber micronaire plays a major role in these items. Nep content is an undesirable component. High micronaire cotton tends to have lower nep content after ginning and is less prone to form additional neps in subsequent processing. A careful investigation[10] of the effect of micronaire showed that substantial increases in neps were noted for the low micronaire cotton during bleaching and nonwoven web formation. There was a dramatic improvement in properties on using higher (> 4.5) micronaire cotton.

Bleached cotton

Many of the cotton nonwoven products that go into hygiene applications require bleached cotton. There is growing capacity to produce bleached fibers targeting nonwovens, due to increasing interest in bleached fibers, among nonwoven manufacturers. Cotton, when bleached, is also more aesthetically pleasing to consumers who appreciate the snow-white quality of bleached cotton. Also, when a natural fiber such as cotton is dyed, the colors tend to be softer and pastel, unlike synthetic fibers that produce much shinier and usually glare-like effects. Cotton fibers give nonwoven fabrics unique characteristics that synthetic fibers cannot duplicate easily. Synthetic fibers are currently being used more in nonwoven fabrics than cotton because of misconceptions regarding cotton's processability. With improved bleaching techniques and the development of new finish applications, cotton can be processed at speeds comparable to that used with synthetics while providing the superior attributes of cotton to the nonwoven.

Colored cotton

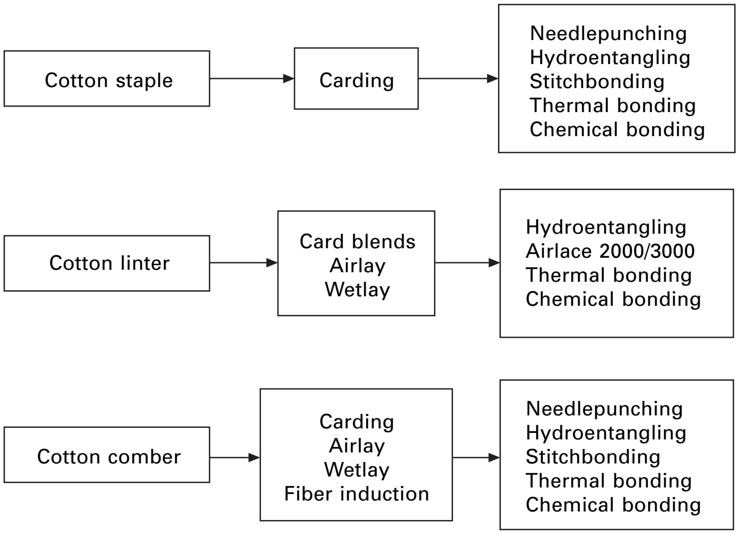
Cotton fiber is often dyed in order to obtain a wide range of colors. Chemical dyes and their finishing demand large amounts of water – so does scouring and bleaching – in turn when these wastes are disposed of they cause soil and water pollution. The negative effects of dyeing can be reduced by naturally colored cotton. Research conducted at USDA has shown that naturally colored cotton performs very well in a needlepunching process.[12] Because naturally colored cotton fibers are shorter and weaker than regular cotton, they do not perform well in spinning, but produce better quality nonwovens than the white cotton, because the nonwoven formation processes are less demanding compared to the conventional textile processes.

Other natural fibers

During the past several years, natural fibers have established a positive and highly regarded name for themselves in numerous nonwoven markets because of their reputation for being soft, durable, breathable, biodegradable and coming from renewable resources.[13] These days, traditional natural fibers, including cotton, hemp, flax and jute have been seeing more demand internationally, while other fibers such as hemp and milkweed are starting to emerge into more nonwovens areas, especially due to their natural origin and biodegradability. Many manufacturers predict that the use of these fibers will grow, as consumers become more aware of their advantages. Obviously cotton is the most used fiber, again due to its popularity in apparel and other fabrics. Jute, kenaf and flax come next, with the rest of the fibers having only a small share. Although cotton is the most attractive fiber for many applications, cost has limited some of its growth, since other manufactured fibers have been cheaper, and for many consumer products cost is a bigger issue. In many cases, blending cotton with other fibers is the best way to achieve good performance per cost.

16.3.2 Processing cotton nonwovens

Processing of cotton into nonwovens follows the general scheme discussed earlier, which involves web formation by carding or air laying and then bonding. Some of the possible production routes suitable for converting cotton fiber into nonwoven goods are shown in Fig. 16.8. As shown, different types/grades of cotton fibers require different processing combinations.[14] Cotton staple fiber, linter and comber, all have differences in length and



16.8 Processing schemes for different cotton fibers.

fineness, which means they cannot be processed using the same set of equipment. Also, properties of cotton fibers grown in different regions have differences in properties, requiring selection of different combination of processing equipment. A few specifics related to processing cotton nonwovens are discussed in this section.

Hydroentanglement

The spunlace, or hydroentanglement, method of web consolidation is highly attractive with cotton because it preserves the pure fiber condition which is conducive to making products with high absorbency. Hydroentangled fabrics have many characteristics that are similar to woven cotton fabrics, i.e., they are easily dyed and finished using conventional textile methods because they have good strength characteristics.[11] To manufacture soft loose nonwovens, partially entangled webs are produced by subjecting cotton webs to low water jet pressures (approx. 300–500 psi). These types of webs can be wet processed in a pad/batch state. Recent introduction of the Jetlace 3000, a spunlace machine by Rieter Perfojet, is a significant advancement over the previous industry standard the Jetlace 2000.[15] It is claimed the Jetlace 3000 will help save energy, reduce cost and is flexible enough to bond wide range of fibers and fiber mixtures and to produce patterns.

The main reason for cotton being suitable for spunlacing is the low wet modulus of the fiber allowing it to easily respond to water jets. Also, the non-round cross-section of cotton fibers results in additional frictional resistance leading to better adhesion and entanglement. There are also advantages in using unbleached cotton as it is cheaper and water jets can remove some of the oils or wax from the fiber. However, the drawback is the need for a better water filtration system.

Needle punching

Needle-punched cotton provides a highly efficient filter media based on the irregular fiber shape and absorption properties. Increased tenacity in the wet condition can be an important advantage for cotton filters. To build strength, scrim materials can be needle punched and used in bed blankets and industrial fabrics. Needles of 36–42 gauges have been found appropriate for the production of cotton needle-punched nonwovens. For very heavy fabrics, use is made of gauge 32 and for finer fabrics 40–42 gauge needles are used. Needle fineness has probably the most effect on fabric properties. Generally with finer needles there is an increase in web density and reduction in air permeability.

Regular length staple cotton should be considered for needle punching since longer fibers perform better. Good length uniformity in a cotton sample provides enough long fiber to form strong fabrics. Fiber finish is critical in needling. Bleached cotton with good lubricity is needed to prevent fiber damage and needle breakage. Raw cotton (unbleached) also needles extremely well with proper needle selection. As discussed earlier, choosing a fiber with a high micronaire allows the production of a stronger needle-punched fabric, providing all other factors remain equal. Recent studies have shown that the H1 needle technology with changes in needle zone contours and profiles help improve the structural features of cotton nonwovens.[16] In addition to the fact that this development allows the production of superior quality nonwovens with relatively less needling, processing speed can be increased resulting in lower production cost.

Stitch bonded nonwovens

Cotton web is stitched as in sewing and the product performance depends on web weight, stitch/cm and type of sewing thread. Arachne and Maliwatt type warp knit machines are used to produce stitchbonded nonwovens. Typically, a filament type yarn is used for stitching purposes, but it has been demonstrated that cotton yarn in counts from 18 to 30 Ne (295–177 denier) are suitable for stitching a cotton web. As with some of the other bonded webs, stitchbonded cotton can be wet processed in fabric form much like conventional textiles.[10]

Chemical bonding

Cotton webs can be bonded using aqueous binders that may be applied by spraying, foaming, gravure roll padding or printing. A wide range of chemical binders are available. Printed patterns provide fabric integrity without imparting objectionable stiffness to the bonded material. Nonwovens for wipes are produced using the print bonding technique.[10]

Thermal bonding

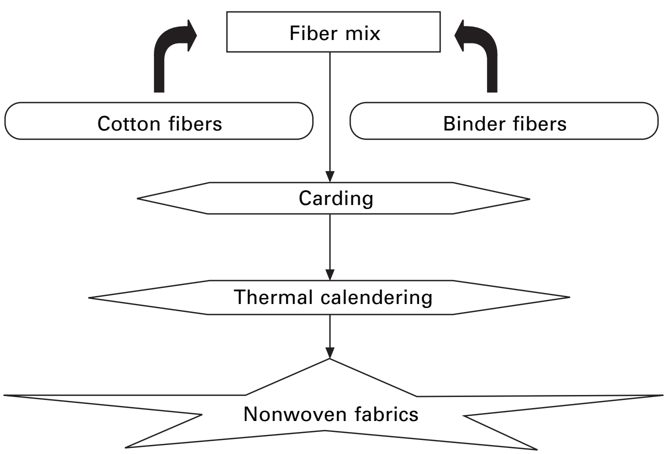
In this process cotton webs with blends of thermoplastic fibers are passed between two hot rollers (calender rollers). The thermoplastic fiber softens/melts and bonds the web. Lightweight fabrics suitable for coverstock, fabric used as a diaper top sheet, can be made by blending cotton with polyolefin, polyester or bicomponent fibers then subjecting the web to heat and pressure using heated calender rolls. The exact bonding conditions are dependent on the melting temperature of the binder fiber and the weight of the web. The calender pressure is increased with fabric weight to get efficient heat transfer. The calender temperatures are close to the melting temperature of the binder fiber. When sheath-core bicomponent binder fibers are used, the temperature is above the melting temperature of the sheath, but well below that of the core polymer. Typically a bonding temperature of about 160 °C is used with polypropylene binder fiber and about 130 °C, for a sheath core fiber with polyethylene sheath. In all the cases, the contact time is in the order of milliseconds, with production speeds of hundreds of m/min.

The strength of the webs varies with the binder fiber composition, as binder fibers are generally stronger and with more binders, there is sufficient to cause melting and flow to form good bond points. Typically 30 to 50% binder fibers with rest cotton produce stronger webs. Whereas a bond area of about 15% is used for the majority of thermoplastic fiber nonwovens, an embossed calender roll with about 30% contact area is needed for blends of cotton and thermoplastic binder fibers to achieve good tensile properties.[10] Alternatively, one can use through air bonding, where the web containing thermoplastic binder is passed through an oven. Here residence time will be in the order of several seconds to minutes for achieving good bonding due to the melting and flow of the binder around the cotton fibers.

Research on cotton-based nonwovens has been carried out at The University of Tennessee, Knoxville (UTK) using different kinds of biodegradable thermoplastic binder fibers through carding and thermal calendering processes.[17–20] The main objective is to have fully biodegradable components in the fiber mixtures, thus producing compostable products. Five different kinds of biodegradable binder fibers were used. Cotton fiber was the base fiber, and binder fibers were, ordinary cellulose acetate (OCA), plasticized cellulose acetate (PCA), Eastar *Bio*® copolyester unicomponent (Eastar), and Eastar *Bio*® copolyester bicomponent (Eastar/PP) and polylactic acid (PLA) fibers. These binder fibers have different melting temperatures, resulting in the use of different optimum bonding temperatures, ranging from 110 °C for the copolyester fiber to 230 °C for OCA. All these fibers showed good bonding with cotton. The nonwoven fabrics in this research were produced by first carding of cotton and the binder fiber and then thermally bonding the carded webs, as shown in Fig. 16.9.

The tensile strength of the nonwoven fabric made with a cotton/cellulose acetate nonwoven blend is quite low and is not suitable for consumer applications when it is processed at the temperatures associated with cellulose acetate's softening temperature (180–205 °C). Solvent treatment has been introduced in order to modify the softening temperature of cellulose acetate fiber and to lower the calendering temperature, while maintaining enhanced tensile properties. The results showed that these solvent treatments can decrease the softening temperature of cellulose acetate fiber and produce comparatively stronger webs.

From the point of energy concern, it is better to make the whole process as simple as possible. So a plasticized cellulose acetate fiber, wherein an internal plasticizer was added during fiber manufacture to lower the softening temperature of ordinary cellulose acetate and further lower the bonding temperature during the thermal calendering process was investigated. It was clearly seen that fabric strength was improved by using PCA instead of OCA. A newly introduced Eastar *Bio* GP copolyester unicomponent (Eastar) fiber, which has a relatively low softening temperature (~80 °C), was further selected as a binder fiber instead of cellulose acetate fiber.[21–22] Because of the low softening temperature of the binder fiber (T_s: ~80 °C), the bonding temperatures used are lower.

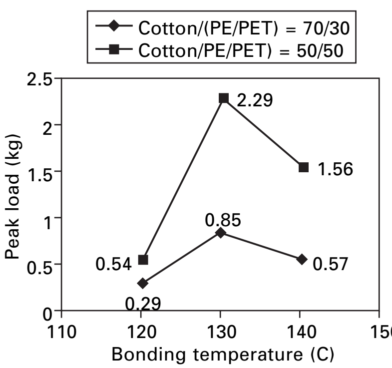


16.9 Production scheme for cotton-based thermal bonded nonwovens.

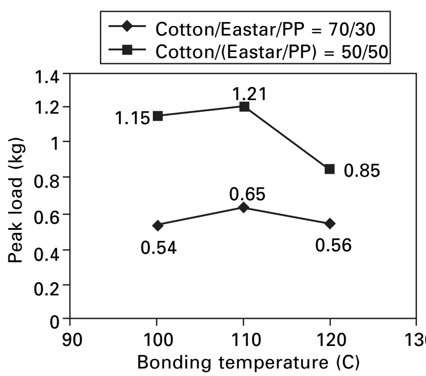
The tensile properties of cotton and two different bicomponent binder fibers with temperature and binder composition are shown in Fig. 16.10. Both the biodegradable (Eastar/PP) and the PET/PP bicomponent binder fibers show the trend of tensile strength initially increasing with bonding temperature and then dropping off after an optimum value. Actual strength values were much higher for the PET/PP bicomponent fiber compared to Eastar/PP. The SEM photographs of bond points of both blends are shown in Fig. 16.11. This indicates that bonding is comparable with both the binders, but the strength difference is due to the strength values of the binder fibers. Also, the bonding area, where there is contact between the embossed roll and the smooth roll of the calenders, in this study was only 15% compared to the 25 to 30% area that is desirable for cotton-based nonwovens. Further studies have shown that PLA can be a very good binder for cotton-based nonwovens. With the production of PLA in large volumes, the cost is supposed to come down and it is supposed to be comparable to that of or cheaper than bleached cotton, making it an attractive binder fiber. Additional advantages of PLA are that it is from a renewable resource, and is biodegradable.

16.3.3 Laminated cotton nonwovens

Cotton surfaced and cotton core nonwovens with polypropylene spunbonded fabrics have been produced with cotton content varying from 40 to 75%.[23,24] A schematic showing the introduction of a cotton/PP carded web with a spun laid fabric to produce thermally bonded composite webs during the thermal bonding process is shown in Fig. 16.12. For achieving cotton surface on both sides, another carded web is introduced from below, and for cotton core nonwovens, another spun laid web is combined from the top. The thermally bonded two or three layered laminates are soft but strong, and have a hand

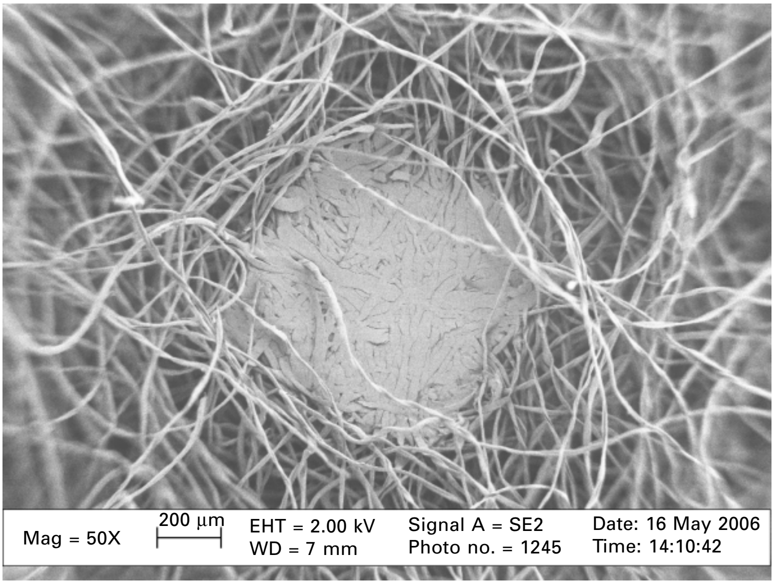


(a) Cotton/(PE/PET) nonwovens

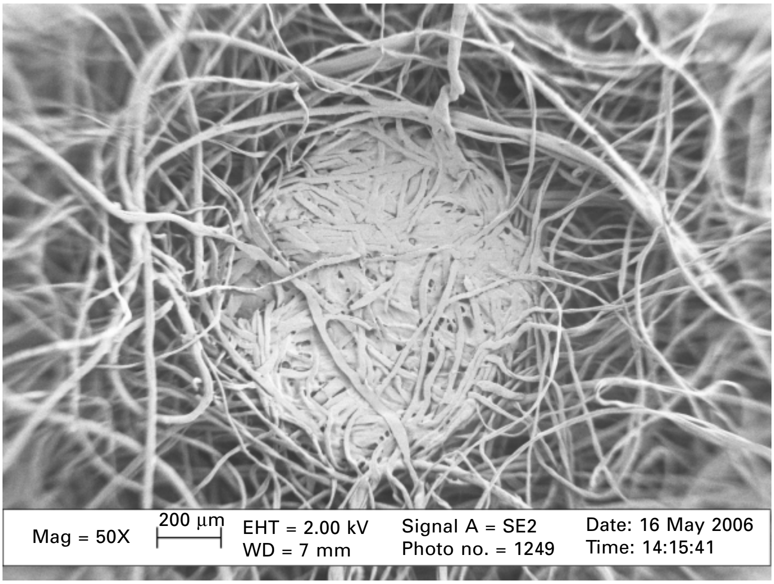


(b) Cotton/(Eastar/PP) nonwoven

16.10 Effect of bonding temperature on (MD) strength of cotton-based nonwovens.



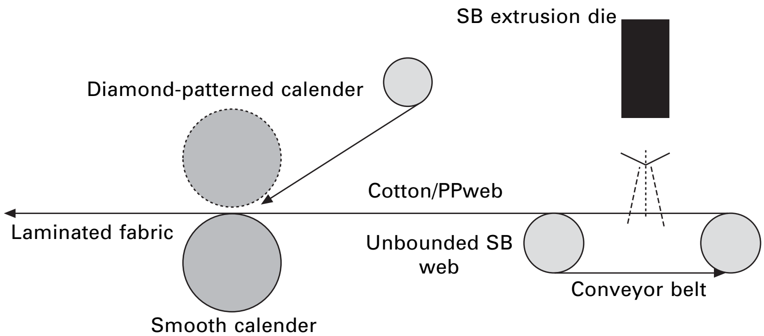
(a)



(b)

16.11 SEM photograph of bond points of thermal bonded cotton nonwovens; (a) (cotton – PE/PET), (b) (cotton-Eastar/PP).

similar to that of cotton knits or hydroentangled fabrics. The fabrics also have excellent wetting, wicking rates, water absorption and water retention properties. Most of these properties come close to that of traditionally used woven fabrics, but provide better production and are produced at a much



16.12 Cotton surface nonwoven formation using a spunbonding machine (from ref. 23, with permission from INDA).

lower cost. These fabrics exhibit minimum linting characteristics, and can be finished to impart stretchability. This study shows how cotton fibers/webs can be combined with other synthetic fiber webs to produce nonwovens with a unique combination of properties.

16.3.4 Cotton containing nonwovens for molded products

The natural feel of cotton, biodegradability and good adhesion to binder fibers, makes it a suitable candidate for molded composites. Molding of preformed nonwoven web simply using heat and pressure is a simple and practical approach to produce shaped products. Natural fiber composites containing flax/kenaf are extensively used for many automotive molded products. These show good thermal and acoustical insulation properties as well. Cotton has properties comparable to these fibers and is a suitable candidate except for its relatively high price. Recent studies by Kamath *et al.*[25–26] have shown that cotton when combined with flax or kenaf produces good molded products that have acceptable physical properties and acoustical insulation properties. In these studies waste or low quality cotton was used, and there was no need for bleaching, thus keeping the fiber cost low. Also, this is another good outlet for low-quality cotton fibers. Another advantage was that using suitable biodegradable thermoplastic binders such as PLA, fully biodegradable/compostable products could be produced. Also, these can be fabricated with other fibers without need for any modification of the process. These molded composites can be good insulating materials in automobiles as well as appliances. The acoustic measurements have demonstrated that natural fiber-based nonwoven composites contribute to the absorptive properties of the components, and are effective for noise reduction.[27–28]

16.4 Finishing and treatment of cotton nonwovens

Finishing of nonwoven bonded fabrics can be classified in different ways, such as chemical, mechanical, or thermal-mechanical. Chemical finishing involves the application of chemical agents such as coatings to fabric surfaces or the impregnation of fabrics with chemical additives or fillers. Mechanical finishing involves altering the texture of fabric surfaces by physically reorienting or shaping fibers on or near the fabric surface. Thermal-mechanical finishing involves altering fabric dimensions or physical properties using heat and pressure. Generally, finishing of nonwoven bonded fabrics is classified as dry finishing or wet finishing. The majority of finishing operations are applicable to nonwovens. Some of the possible treatments given to cotton nonwovens to enhance their performance are:

- flame resistance
- antibacterial
- water repellency
- resistance to biodegradation
- dyeing/printing
- cross linking for durability to washing
- increased resiliency.

Cotton nonwovens can be treated like other cotton fabrics for many applications to achieve desired properties or to enhance performance. The nonwoven fabric finishing is carried out either in tandem with web formation and consolidation or off-line as a separate operation. There are many examples of particular methods and types of finishing equipment being used for both kinds of fabrics. Nonwovens may be given one or more of a variety of finishing processes as a means of enhancing fabric performance or aesthetic properties. Performance properties include functional characteristics such as moisture regain and transport, absorbency, or repellency; flame retardancy; electrical response; resistance; and frictional behavior. Aesthetic properties include various attributes such as appearance, surface texture, color, and odor. The specific property requirement is dependent on the application as they vary widely from one product to another.

A significant amount of research on nonwoven fabric finishes is being conducted at USDA laboratory in New Orleans, LA.[29] One such example of the research was to carry out single-bath chemical finishing of perpendicular-laid (P-laid) high lofts to afford the composites' improved flame resistance (FR) and physical resiliency. High loft nonwovens are low density fabrics characterized by a high ratio of thickness to weight per unit area, which means that high lofts contain considerable void volume. They are usually made of synthetic fibers. The major problems with using cotton in high lofts are cotton's high flammability and lack of resiliency. Parikh *et al.* have developed finishing formulations containing the flame retardants (i) diammonium phosphate (DAP)/urea, and (ii) DAP and cyclic phosphonate ester along with the crosslinking agent dimethyloldihydroxyethyleneurea DMDHEU.[30] Both the formulations imparted flame resistance to the highly flammable high lofts, protecting them completely. However, the formulation containing DAP/urea is preferred because it is of lower cost. The crosslinking agent was effective in improving compressional resistance and recovery. So, the finishing treatment produced P-laid cotton blend highlofts that were both FR and resilient. This is important for cotton fibers that are used in mattresses that have good resiliency as well as flame retardancy to resist the open flame.

For many wound dressings, there is a need for high absorbency and ability to retain moisture. Carboxy methylation was shown to be very effective in producing a highly swellable, water retentive cotton fiber without any strength loss. The carboxymethylation was accomplished by treating the nonwoven in alcoholic caustic and monochloroacetic acid using 90/10 ethanol water. Such a treated cotton nonwoven product is sterilizable and suitable for moist dressings, especially on burn wounds. Such a product is cheaper and competitive with the traditionally used calcium/sodium alginate dressing. Also, cotton dressings can be easily modified to improve healing of chronic wounds.[31] In addition to some of these finishings, cotton nonwovens can be used as substrates for coated/laminated products as well.

Another category of finishing is the conversion of roll goods into final products. This involves cutting, slitting, folding, application of various chemicals/agents, and packaging. Some of the conversions can include thermal fusing, welding and sewing. For some products, such as premoistened wipes, nonwovens are impregnated with lotions after folding in packaging. Medical and surgical products are sterilized after the conversion of products. The sterilization could be radiation type or the one using ethylene oxide and steam. Unlike many other types of nonwovens, cotton nonwovens are easy to handle in many finishing operations.

16.5 Future trends

Cotton fiber nonwovens are already used in a variety of applications, but the potential for growth is very high. Consumer demands for cotton are well documented, but because nonwovens are not required to list fiber content in products, consumers often do not know what they are purchasing. There is definitely an opportunity to increase market share by adding cotton to the fiber content since there is a consumer preference for cotton-containing products.[11] Some of the recent developments leading to increased use of cotton in nonwovens are:

- Cotton linters replacing the traditional 100% wood pulp fibers for producing absorbent cores for disposable diapers and famine pads, as this improves some properties as well as consumer appeal.[32]

- Cotton is being blended with kenaf fibers to improve the softness and hand.[33]
- Buckeye Technologies has developed 100% natural cotton for tampon manufacture.[34]
- Development of a 'flexible cotton decontamination wipe' for human and sensitive equipment decontamination at Texas Tech University.[35] The purpose here is to use the natural fiber that is comfortable to use on the body, but at the same time can be incorporated with decontaminant additives such as activated carbon and metal oxides.

Wipes are one of the largest application areas for cotton nonwovens. Because of its high absorbency, a good fabric-like structure, low linting tendency and high wet strength, spunlaced cotton nonwovens are highly suitable for hospital, medical, consumer, cosmetic and wet wipes. These are also suitable for special applications in the computer industry for cleaning lithographic plates, etc.

Spunlaced cottons are also used as semi-durable bed sheets, napkins and table cloths. These can be washed 6–8 times without any problem.[36] The products obtained have the appearance and feel of linen and can be dyed and printed for special effects. Cotton blankets, carpets and rugs also have been produced from needlepunched nonwovens. Thermal bonded nonwovens are suitable for cover stock and other healthcare products therefore cotton nonwovens find application in many areas. The challenge is to make them economically competitive by appropriate selection of fibers and manufacturing methods.

16.6 Conclusions

Although the current share of cotton in nonwovens is small, cotton has a bright future in this growing sector of fabrics. Hygiene and other absorbent products are the major markets for bleached cotton fibers. Raw cotton can be used for many products such as moldable composites, furniture and bedding pads, and for several products produced through the hydroentangling process. Absorbency, wet strength and breathability of cotton give natural advantages to many products. The biodegradability of the fiber as well as its renewable resource makes it an environmentally safe product to use. Cotton nonwovens can be recycled, reused or disposed of by natural degradation conditions. Cotton is a readily renewable resource with long-term supply assurance. Extensive research to improve the bleaching process and nonwoven fabrication processes such as needling and hydroentangling make cotton nonwovens more economical. The share of cotton in nonwovens will continue to increase as cotton-containing items are preferred by consumers. Innovation is the key to produce competitive products with superior performance to increase the share of cotton in the growing nonwovens industry.

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