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Engineering apparel fabrics and garments

J. Fan and L. Hunter

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Engineering apparel fabrics and garments

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Preface

Globally, textiles represent the fourth largest manufacturing industry, with the apparel sector forming the most valuable component of this industry. Global textile fibre production or consumption is presently some 80 million tonnes, 48% of which (about 38 million tonnes) are for the apparel sector with a value of some 8000 million US dollars at the factory level. The fibre production and consumption are increasing annually owing to population growth, increasing per capita fibre consumption with increasing prosperity and the ever increasing new applications being found for textiles.

Engineering apparel fabrics and garments means that they are so designed and manufactured that they meet the performance requirements and specifications appropriate to their specific end-uses. Compared to other products, such as electronics, automobiles, etc., engineering apparel fabrics and garments represents a much greater challenge, owing to the long manufacturing and complex pipeline which is often difficult to control within the narrow tolerances required. Furthermore, there has also been a lack of precise relationships between the large number of variables, some difficult to measure and control, and the various fabric and garment performance measures and requirements for the diverse end-uses. Engineering apparel fabrics and garments has therefore been the subject of considerable research effort by textile and clothing scientists and technologists from different parts of the world and for many decades.

Engineering apparel fabrics and garments to produce the correct quality, first time and consistently, becomes imperative as globalisation proceeds and global competition intensifies, which increases pressure on the entire textile and clothing pipeline, from fibre to garment, in terms of quality, performance, cost, innovation and environmental impact. Added to this are increasing consumer demands and expectations in terms of multi-functionality, comfort, appearance, novelty, wear performance (quality), design, style and fit. Thus for example, consumers expect their clothing to perform to their satisfaction in terms of handle, appearance, fit and comfort, when new and for an acceptable wear period thereafter. Clothing manufacturers require that the fabric is easy to make-up, passes through the garment manufacturing process easily and without undue problems and that the finished garment has a good appearance and wear performance. In the final analysis, the fabric manufacturer has to meet the technical and other expectations of the garment manufacturer at an acceptable cost, while the garment manufacturer needs to meet similar requirements from the retailer and ultimately those from the consumer.

In the light of these developments and pressures, it becomes imperative that fabric and garment manufacturers are able to engineer fabrics and garments, respectively, to meet those technical performance and other characteristics required for the specific end-use for which they are destined. In so doing, rejects, waste and complaints, together with the associated costs, can be minimised.

This book addresses performance-related issues in apparel fabrics and garments, including methods of measuring the various performance characteristics, the influence of factors, such as fibre, yarn, fabric and clothing parameters, on the various performance characteristics, and ways in which these parameters can be selected to achieve specific performance requirements.

The book is divided into chapters, with Chapter 1 dealing with Handle and Making-up Performance while Chapters 2, 3 and 4 cover wear appearance issues, such as Wrinkling, Pilling and Bagging, respectively. Chapter 5 addresses Fabric and Garment Drape, while Appearance Issues in Garment Processing, including seams, fusing and pressing are dealt with in Chapter 6. Chapter 7 deals with durability-related issues, including abrasion resistance and bursting, tensile and tear strength. Physiological and Psychological Comfort, including tactile, thermophysiological, thermal insulation, moisture transport and ease of movement and pressure comfort, are covered by Chapters 8 and 9. Chapter 10 covers Fire Retardancy and Flammability and Chapter 11 addresses Waterproofing and Breathability. The Ultraviolet Protection of fabrics and garments is discussed in Chapter 12 while Chapter 13 deals with Laundry Performance. The Application of Artificial Intelligence in Fabric and Garment Engineering is covered in the final Chapter, namely Chapter 14. All chapters include References for further reading.

It is important to remember, however, that in many cases it is necessary to compromise and optimise when engineering performance, since frequently trade-offs are necessary when improving a particular property (e.g. softness) at the expense of another property (e.g. pilling and abrasion resistance).

J. Fan and L. Hunter

1

Handle and making-up performance of fabrics and garments

L. HUNTER and E. L. HUNTER

Abstract: This chapter focuses on the use of Fabric Objective Measurement (FOM) in characterising fabric handle and garment making-up performance. It discusses the development of FOM and the influence of changes in fibre, yarn and fabric properties, as well as that of dyeing and finishing on handle and making-up performance. Reference and benchmark values for the various parameters are also given.

Key words: Fabric Objective Measurement (FOM), fabric handle, garment making-up performance, Kawabata system, FAST system.

1.1 Introduction

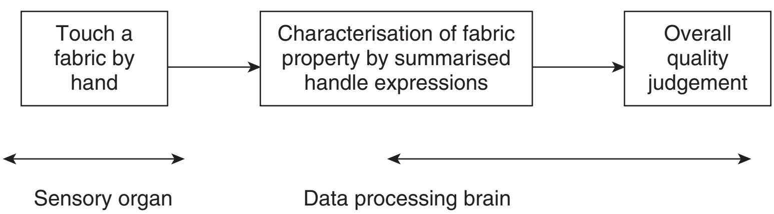
Handle and making-up performance (tailorability) are interrelated and represent key quality parameters for clothing manufacturers and consumers, handle (or hand) being defined[1] as 'the subjective assessment of a textile material obtained from the sense of touch'. Consumers expect their clothing to perform to their satisfaction in terms of handle (feel), appearance, fit and comfort, when new and for an acceptable wear period thereafter. Clothing manufacturers require 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 (see Table 1.1[2]).

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 (also referred to as fabric hand), by experts in the clothing industry (see Fig. 1.1[3]). In assessing the fabric, 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 handle and garment making-up and appearance during wear. Such experts, who were frequently highly skilled, assessed the fabrics using their hands to perform certain physical actions on the fabric, such as rubbing, bending, shearing and extension

Table 1.1 Assessment of fabric performance in apparel. Source: Hearle, 1993[2]

For consumer		
Aesthetic impression	Visual	colour and pattern *drape
	Tactile	*feel
	Audible	rustle etc.
Cover	Light transmission *body shape (obscure or enhance)	
Comfort	Permeability	heat, moisture, air
	Skin contact	*feel (local and distributed)
Strength and durability	Breakage and loss of fibre *damage-prone sharp folds	
Appearance retention	*Wrinkling and creasing change of aesthetics ease-of-care	
For clothing manufacturer		
Handling characteristics	*Laying down, cutting, *transporting, *sewing manipulation, needle and stitch action, *forming and pressing	

*All involve complex buckling of fabrics related to fabric hand



1.1 Process used by experts in the subjective evaluation of fabric handle. Source: Kawabata, 2000[3]

(stretching). They expressed what they felt (i.e. their perceptions) in terms of subjective sensations, such as stiffness, limpness, hardness, softness, fullness, smoothness and roughness, which then formed the basis for the fabric selection.[4] Because of the way this 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 (sense of touch) 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

Table 1.2 Fabric properties that are related to tailoring performance, appearance in wear, and handle. Source: De Boos, 1997[5]

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

+ Important;
– Less important

the fabric, including garment making-up, comfort, aesthetics, appearance and other functional characteristics (see Table 1.2). Nevertheless, although such experts were highly skilled and their judgements 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 based) 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 process, and removed much of the guesswork from garment manufacturing. In certain cases, dimensional stability and crease related parameters have been included in FOM.

Kawabata and Niwa[6] have illustrated the development in textile science and engineering, including fabric objective measurement and the engineering of fabric quality and properties, during the past century. This chapter focuses on the use of fabric objective measurement (FOM) in characterising fabric handle and garment making-up performance, and the influence of fibre, yarn and fabric properties and finishing on FOM properties.

According to Wemyss and de Boos,[7] the more important fabric properties in producing suits and tailored garments with good appearance and stability are fabric weight, bending, shear and tensile properties; longitudinal compressibility; dimensional stability; and possibly surface frictional characteristics. Data charts define the region in which fabrics would be expected to have good tailoring performance and handle, the details of the charts depending upon the end-use requirements of the fabric (e.g. men's suiting or ladies' wear).[7] Tailorability (making-up) performance is affected by a number of fabric properties, such as bending, longitudinal compression, tensile and shear,[7] with finishing playing a very important role in its affect on fabric properties, such as bending and shear stiffness. Highly sett fabrics are more affected by finishing than more loosely sett fabrics, with fabric construction having a greater effect on highly finished fabrics.

Figure 1.2[8] summarises the approach involved in developing an 'ideal' fabric, having good handle, and good garment appearance and garment comfort.

1.2 Fabric Objective Measurement (FOM) of fabric handle and making-up performance

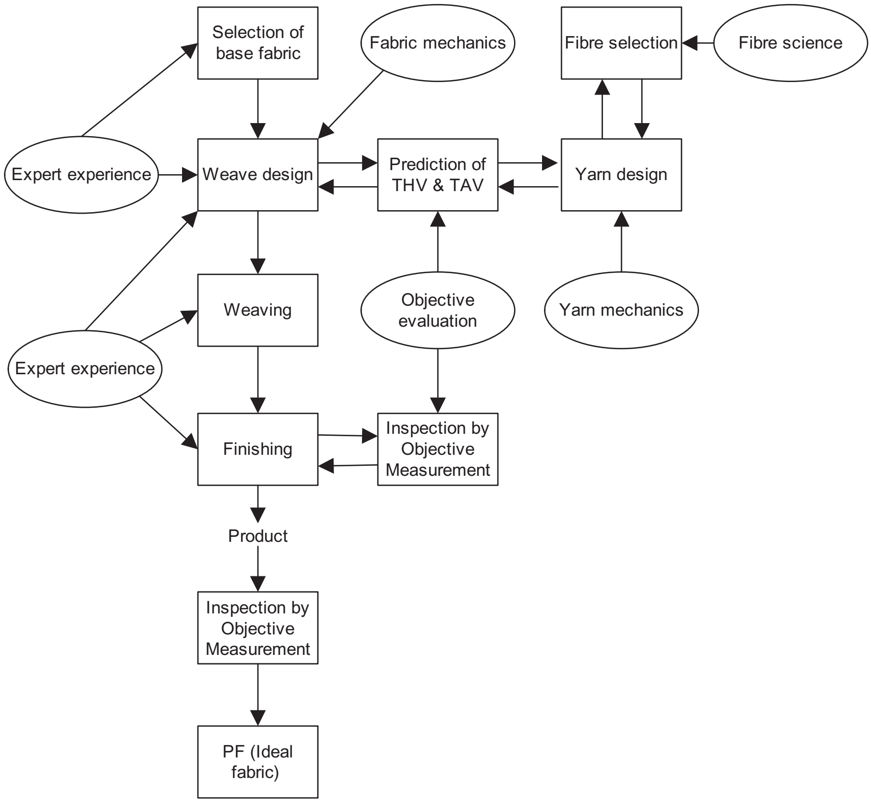
1.2.1 Background of FOM

Fabric objective measurement (FOM) provides a scientific means of quantifying the quality and performance characteristics of fabrics. Although originally developed for men's suiting fabrics, FOM has also been extended to non-woven fabrics,[9–11] men's shirts,[12,13] and diapers.[14] According to Niwa[8,15] there are three criteria for the objective evaluation of fabric performance – good handle, good garment appearance (Chapter 6) and good garment comfort (Chapter 8) – and an ideal fabric should satisfy all three criteria (see Fig. 1.3).

Lee[16] proposed a new database management system for improved clothing manufacturing and presented an excellent table (Table 1.3)[16] listing the controllable parameters in the tailoring process.

Tests for the objective measurement of fabrics may be broadly classified as follows:[4]

- High-stress mechanical tests to measure properties such as tensile strength, tear strength and abrasion, such tests normally being con-

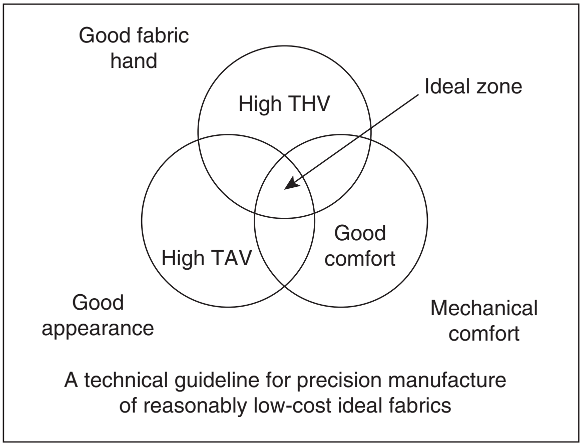


1.2 Summary of the approach involved in developing an 'ideal' fabric, having good handle, good garment appearance and garment comfort. Source: Niwa, 2001[8]

ducted until the fabric fails (these are dealt with in other chapters of this book).

- Low-stress mechanical tests which reflect the range of stresses a fabric undergoes during normal use and which determine fabric handle (as well as making-up performance and garment appearance).

At the present time, and as used here, FOM refers to the instrumental measurement of those fabric properties which affect the tactile, making-up/tailorability and appearance-related properties of fabrics in garment applications, and generally involves small-scale deformation characteristics (bending, shear, compression and extension) as well as dimensional stability-related characteristics, such as hygral expansion and relaxation shrinkage.



1.3 The ideal fabric concept. THV = Total handle value, TAV = Total appearance value. Source: Niwa, 2001[8]

In its broadest sense, FOM of finished fabric has three main uses for quality control:[5]

- To ensure that fabrics are easy to tailor
- To ensure that garments keep their shape during wear
- To provide information on fabric handle.

The above factors are interrelated and, in many cases, are dependent upon the same, or similar, fabric properties (see Table 1.2). Tables 1.2 and 1.4 contain lists of fabric properties that are believed to be related to these quality-control objectives. Test methods related to the fabric properties are also listed. The tests have been rated according to their importance for assessing the relevant property.

Based upon extensive research, it has been well established that the garment quality and appearance and its making-up processing and performance are determined by the fabric mechanical and surface properties.[4,17] The quality of fabrics, their tailorability, and the subsequent appearance and performance of garments can, in fact, be related to six basic fabric mechanical properties, as shown in Table 1.4 with the quality and mechanical performance characteristics to which they relate,[18,19] together with the fabric dimensional properties.

FOM also establishes an objective basis and language for communication between researchers, industry sectors (notably between fabric and garment manufacturers) and traders in fabrics and garments. Table 1.5 lists the various areas of application of FOM.

Table 1.3 Controllable data in tailoring process. Source: Lee, 2002[16]

Materials
- Fibres
  - physical and chemical structure
  - fibre fineness and shape
- Yarns
  - single yarn (number, diameter, No. of twist)
  - folded or cabled structure
  - blended ratio
- Fabrics
  - width and thickness
  - weight per unit area
  - colour, colourfastness
  - finishing information (dimensional stability, pilling resistance,laundering properties, wetting resistance . . .)
  - mechanical properties (Instron, KES, FAST . . .)
  - drapery-wrinkle resistance-defects (slubs, knots, streaks)
- Subsidiary materials
  - information on sewing thread
  - specifications of interlining
  - zippers and buttons

Tailoring process variables
- Pattern
  - making
  - grading
  - marker marking
- Spreading and cutting
  - spreading count
  - cutting speed
- Sewing process
  - sewing speed
  - thickness of needle
  - pressure of presser foot
  - yarn tension
  - stitch type
  - stitch length
- Press
  - temperature
  - time
  - pressure

Garment
- Aesthetic quality
  - colour
  - style
  - drape
  - hand
  - fitness, consistency in sizing
- Functional quality
  - comfort
  - freedom for movement
  - appropriateness of garment for purpose
- Standard or inspection
- Quality levels
  - adequate
  - competitive
  - superior

Table 1.4 Basic fabric mechanical properties and related quality and performance attributes of fabrics and garments. Source: Postle, 1983[19] and Harlock, 1989[18]

Fabric mechanical properties	Quality and mechanical performance
Uniaxial and biaxial tension	Fabric handle and drape Fabric formability and tailoring properties
Shear under tension	Garment appearance and seam pucker
Pure bending	Mechanical stability and shape retention
Lateral compression	Relaxation shrinkage, dimensional stability and hygral expansion
Longitudinal compression and buckling	Wrinkle recovery and crease retention abrasion and pilling
Surface roughness and friction	Mechanical and physiological comfort

Table 1.5 Application of fabric objective measurement technology. Source: Postle, 1983, 1989[17,19]

1.	Objective measurement of fabric quality and handle and their primary components for various textile products
2.	Design and production of a diverse range of high quality yarns and fabrics using objective mechanical and surface-property data
3.	Objective evaluation and control of textile processing and finishing sequences for the production of high quality yarns and fabrics
4.	Objective evaluation of fabric tailorability and finished garment quality and appearance
5.	Objective specifications by tailoring companies for fabric selection, production planning, process control and quality assurance, using fabric mechanical and dimensional property data
6.	Measurement and control of the comfort, performance and stability of fabrics and clothing during use
7.*	Evaluation of the effect of changes in fabric finishing routines, including decatising, on fabric tailorability

* Author's addition

The ground-breaking work of Peirce[20] on the objective measurement of fabric mechanical properties was followed by pioneering work relating fabric low-stress mechanical properties to tailorability (making-up) carried out at TEFO in the 1950s and 1960s.[21–24] The next, and probably the most important, advance in the objective or quantitative assessment of fabric 'handle' and quality occurred early in the 1970s when Kawabata and Niwa organised the Hand Evaluation and Standardisation Committee in 1972[25] as a research committee of the Textile Machinery Society in Japan, and when the objective method of evaluation of fabric handle was developed by Kawabata and Niwa. Through extensive research, involving experts from the clothing industry, the committee selected and defined the 'primary fabric handle' expressions and related these to the mechanical properties of the fabric.[26] An integrated system of FOM, the Kawabata Evaluation System for Fabrics (KES-F, later to become the KES-FB system), was the most important outcome of this work. This pioneering work laid a solid foundation for the accurate and routine measurement of those fabric properties that determine fabric handle and garment making-up and appearance. Along similar but greatly simplified lines, the CSIRO in Australia developed the FAST (Fabric Assurance by Simple Testing) system many years later, for measuring the main fabric properties affecting garment making.

The Kawabata and FAST systems measure similar low-stress fabric mechanical properties (compression, bending, extension and shear), although they differ somewhat in the measurement principles that they use, there being good correlation between similar parameters measured on the two systems and also on other systems. The results obtained on the two systems are plotted on control charts, sometimes called 'fingerprints', and comparisons between fabrics, as well as diagnosis of tailoring problems, can be made more easily when information is presented in this way. Originally, the Kawabata system was essentially aimed at predicting the feel, handle and appearance of fabrics, whereas the FAST system was essentially aimed at predicting fabric tailorability.[27] Sule and Bardhan[27] have summarised the differences between the two systems with respect to predicting tailorability as follows: the KES-FB system does not include the measurement of relaxation shrinkage and hygral expansion, which are important to tailorability, while the FAST system does not measure the linearity of tensile properties as well as tensile, bending and shear hysteresis, to which the Kawabata system attaches considerable importance.

The following fabric properties are commonly measured by FOM systems:

Compression: Fabric compression normally refers to the difference in fabric thickness under different loads, also termed the 'thickness of the surface layer', and provides a measure of fabric softness or fullness.[28] The surface-released thickness, i.e. difference between the surface layer thickness before and after steaming, provides a measure of how *stable* the fabric finish is. Fabric hardness is affected by the fabric compression and recovery properties.

Dimensional stability: Generally there are the following three main types of dimensional change resulting from changes in the environment[5] (excluding felting shrinkage):

- Relaxation
- Hygral
- Thermal.

The stability tests provide a measure of the potential change in fabric and garment dimensions when exposed to changes in moisture, and normally only the first two are considered important and are measured, namely relaxation shrinkage and hygral expansion.[28] During finishing, most fabrics are dried under tension, which is not released until the fabric is exposed to moisture, typically during final pressing, at which stage the fabric undergoes relaxation and returns to its original dimensions, this being termed relaxation shrinkage. Some relaxation shrinkage is beneficial to avoid bubbling in the pleat formation process and to shrink out any residual fullness in the garment during final pressing,[28] while excessive shrinkage creates problems which will be discussed later.

Hygral expansion refers to reversible changes in fabric dimensions when the fabric is exposed to changing moisture, and excessive hygral expansion results in a change in appearance, seam pucker, bubbling and even delamination of fused panels. Excessive hygral expansion can also cause problems in pleating.[28] Problems relating to hygral expansion typically occur when the garments are made under low humidity conditions and are afterwards exposed to conditions of high humidity.[28]

Together with relaxation shrinkage, hygral expansion can cause problems with sizing, seam appearance, waviness and pucker, pattern matching at seams and the balance or appearance of the finished garment after making-up and during wear.[29]

Tensile and shear: Fabric tensile properties, and sometimes also recovery and hysteresis (energy loss), are measured under low deformation forces, these also being used to calculate properties such as deformability.

Low fabric extensibility can lead to difficulties in producing overfeed seams, leading to problems in moulding and seam pucker.[28] High extensibility can lead to the fabric being stretched during laying-up, causing the cut panels to shrink when they are removed from the cutting table, this often being mistaken for relaxation shrinkage. Fusible tape can be used to stabilise fabrics with excessive extensibility. Shear rigidity can be calculated from the bias extensibility, while formability is calculated from the extension at 5 gf/cm and 20 gf/cm, together with fabric bending rigidity, being the product of fabric bending rigidity and initial fabric extensibility.[28] Inadequate warp formability necessitates refinishing of the fabric to increase warp extensibility. For wool fabrics, hygral expansion, relaxation shrinkage and extensibility are often related.

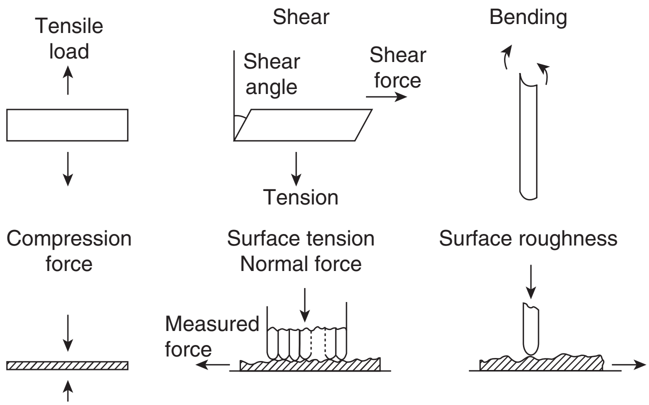
Friction and roughness: An estimation of fabric friction and roughness can be obtained by measuring either fabric-against-fabric or fabric-against-metal static and dynamic friction.[28] This property is related to fabric handle. A greater difference between the static and dynamic friction is required for a scroopy handle, a negative value producing a soft and slippery handle.[30] It was also found[30] that the higher the compression, the greater the difference between the static and dynamic friction tends to be. Bertaux *et al*.[31] found that fabric properties, such as bending, thickness and compressibility, affected the relationship between fabric surface friction and subjectively assessed handle (touch). Das *et al*.[32] found fabric kinetic friction to be always lower than static friction. Fabric-to-metal friction was found to be much less sensitive to fabric roughness and direction of rubbing than fabric-to-fabric friction, the latter being affected by many factors, such as fibre and blend type, yarn and fabric structure, crimp and compressibility.

Bending rigidity: Fabric bending length is generally measured and used to calculate the fabric rigidity. Fabrics with relatively high values of bending rigidity will feel stiffer but will not generally cause problems in making-up. Low values can lead to problems during making-up, for example, distortion during cutting, as well as seam pucker during sewing.[28]

1.2.2 Kawabata system

A detailed description of the Kawabata system and instruments is given elsewhere.[33] The Kawabata System for Fabrics (KES-F, later renamed as the KES-FB) uses the following four instruments[4] (see Figure 1.4 and Table 1.6).

(i) **Tensile and shear tester (KES-FB1).** A tensile test is conducted by clamping the sample between chucks. A higher tensile resilience (RT), for example, indicates a better resilience (i.e. recovery from tensile deformation). A shear test is conducted under a constant tension; opposing forces are applied in parallel to the fabric plane.



1.4 Principles used in the KES-F instruments for the objective measurement of fabric mechanical and surface properties. Source: Postle, 1983, 1989[18,19]

Table 1.6 The parameters describing fabric mechanical and surface properties. Source: Postle, 1983[19] and Harlock, 1989[18]

Tensile	(KES-FB1)	LT	Linearity of load/extension curve
		WT	Tensile energy in N/m (gf.cm/cm^2)
		RT	Tensile resilience (%)
		EM	Extensibility, strain at 500 N.m/degree tensile load (%)
Shear	(KES-FB1)	G	Shear rigidity in N.m/degree (gf.cm/deg)
		2HG	Hysteresis of shear force at 0.5° shear angle (gf/cm)
		2HG5	Hysteresis of shear force at 5° shear angle (gf/cm)
Bending	(KES-FB2)	B	Bending rigidity in 10^{-4} N.m (gf.cm^2 /cm)
		2HB	Hysteresis of bending moment in 10^{-2} N (gf.cm/cm)
Lateral compression	(KES-FB3)	LC	Linearity of compression/thickness curve
		WC	Compressional energy in N.m (gf.cm/cm^2)
		RC	Compressional resilience (%)
Surface characteristics	(KES-FB4)	MIU	Coefficient of friction
		MMD	Mean deviation of MIU
		SMD	Geometrical roughness (μm)
Fabric construction		W	Fabric weight per unit area (mg/cm^2)
		T	Fabric thickness (mm)

A higher shear stiffness (G) indicates a greater resistance to shearing and therefore a higher drape coefficient. Collier[34] found that the shear hysteresis at 5° explained over 70% of the variation in drape values of woven fabrics.

(ii) **Bending tester (KES-FB2).** A fabric sample is mounted in a vertical plane and a pure curvature is applied to record moment–curvature relationships, a higher value for bending rigidity (B) indicating a stiffer fabric.

(iii) **Compression tester (KES-FB3).** A fabric sample is compressed in its thickness (lateral) direction, using a compression head, and the load–deformation curve is recorded. A higher compressional resilience (RC) value indicates a better recovery from compression.

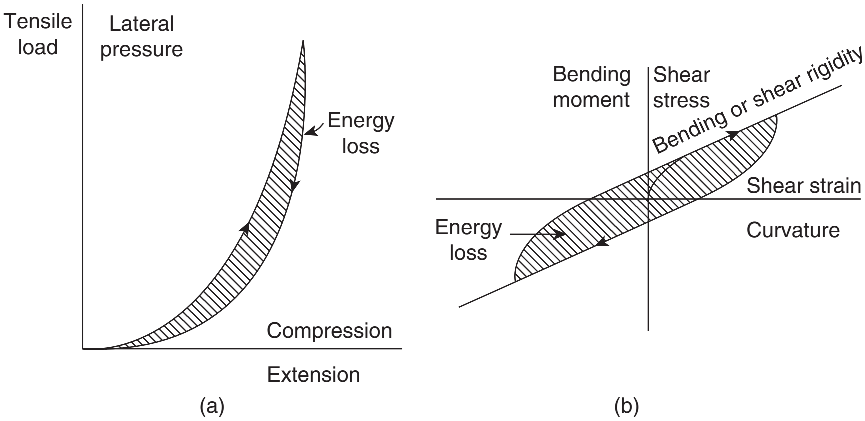
(iv) **Surface tester (KES-FB4).** Surface roughness and the coefficient of friction are measured using two contact sensors, one for measuring thickness variation and the other for measuring frictional force. The fabric sample is moved, relative to the sensors, under a constant tension. A higher coefficient of friction (MIU) value represents a higher fabric friction, while a higher geometrical roughness (SMD) value indicates a rougher (i.e. less smooth) fabric surface.

These instruments can test fabrics automatically and provide continuous stress–strain curves. Load and deformation are measured using sensors and recorded using an *X–Y* plotter.

An automatic version of the Kawabata system, called KES-FB AUTO, is also available.

Figure 1.4 shows the principles used in the measurement of fabric properties by the four KES-FB instruments.[18,19] Figure 1.5[19] shows typical graphical outputs (deformation–recovery curves) of the instruments, which illustrate the non-linearity and hysteresis of the curves, and the need to select the maximum values for the recovery part of the cycle in accordance with the values experienced in the performance of the garment. The hysteresis (losses) of the curves are due to inter-fibre friction and the visco-elastic properties of the fibres.[18] Typical bending/shear deformations are reversible, i.e. they can be deformed in either direction to give positive or negative curvatures. Tensile deformations are not reversible since the fabric tends to buckle under longitudinal compressive loads. For small deformations, the shear and bending rigidities, as defined by the gradients of the graphs, are linear,[18] these, together with hysteresis, being important in determining the ease with which fabrics drape and can be forced into complex three-dimensional shapes without puckering. Hysteresis behaviour is important in terms of fabric resilience or springiness.

The three Primary Handle Values (PHV) arrived at were Koshi (stiffness), Numeri (smoothness) and Fukurami (fullness) and were related to



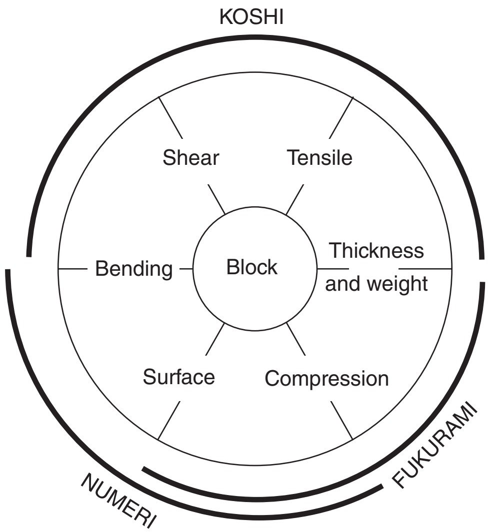
1.5 Typical deformation-recovery curves for (a) fabric extension or lateral compression, and (b) fabric bending or shear, showing the energy loss during a complete cycle as the shaded area. Source: Postle, 1983[19]

the KES-FB measured fabric properties as illustrated in Fig. 1.6, using elaborate statistical analysis. Further handle values, Shari (crispness) and Hari ('anti-drape stiffness'), were added for men's summer suitings and women's fabrics (see Table 1.7). Each of the Primary Handle Values ranks from 1 to 10.

An outcome of the above development is that fabric handle can be objectively graded in terms of the 'Total Handle Value' (THV), and garment (suit) appearance in terms of the Total Appearance Value (TAV),[3] both on a scale of 1 to 5. THV is a combined measure of smoothness, softness and stiffness. Table 1.7[2] gives the interpretation of these values, TAV providing a measure of tailorability and drape/suit appearance.

1.2.3 Interrelationship between KES-FB measured fabric properties and fabric handle and making-up performance

The test results from the Kawabata system, although primarily aimed at defining handle, can show which fabrics will go through a clothing factory easily and efficiently, which ones will need special care (with indicated adjustments of machine settings) and which will cause serious problems. As already mentioned, Kawabata and Niwa[6] stated that an ideal suiting fabric should satisfy the following three conditions:



1.6 Relationship between the three primary hands and the mechanical properties. The related properties are covered by a line of the corresponding hand. Source: Hand Evaluation and Standardisation Committee, 1972–1975[25]

Table 1.7 Primary hands. Source: Hearle, 1993[2]

KOSHI	'Stiffness'	A measure of crispness in bending; springy flexural rigidity
NUMERI	'Smoothness'	A measure of smooth, supple and soft feel
FUKURAMI	'Fullness and softness'	A measure of bulk, with springiness in comparison; rich and warm
SHARI	'Crispness'	A measure of a crisp rigid fabric surface, with a cool feel
HARI	'Antidrape stiffness'	A measure of flare, the opposite of limp conformability

(i) Good handle (high THV)
(ii) Good suit appearance (high TAV)
(iii) Mechanical comfort conditions (shaded zone on control chart)

Experience over many years has suggested that the KES-FB measurements may be standardised in terms of the parameters listed in Table 1.6.[19] In the Kawabata system, the quality, tailoring and appearance performance of fabrics can be related to six basic fabric mechanical properties[35,37] (see Table 1.4). The relationship between KES-FB measured properties and tailorability and appearance is illustrated in Tables 1.8 to 1.11.[38]

Table 1.8 Influence of measured parameters on PHV. Source: Sule and Bardhan, 1999[36,39]

PHV	Measurable parameter
Smoothness (NUMERI)	Surface, compression and shear
Stiffness (KOSHI)	Bending rigidity, weight, thickness, shear and surface
Fullness and softness	Compression surface, thickness and shear
Crispness (SHARI)	Surface, bending and tensile
Antidrape/spread (HARI)	Shear, surface and bending

Table 1.9 The desirable range of mechanical properties for high-quality suit production. Source: Kawabata and Niwa, 1989[38]

Mechanical parameter	Range for good appearance and good tailorability	Range for especially good appearance
EMI (%)	4–6	4–6
EM2/EM1 (%)	>1	>2
RT (%)	65–76	72–78
G (gf.cm/deg)	0.5–0.7	0.5–0.7
2HG5 (gf/cm)	0.8–1.7	0.6–1.5

Table 1.10 The range of mechanical properties for fabric to be rejected. Source: Kawabata and Niwa, 1989[38]

Mechanical parameter	Range for rejection
EMI (%)	>9 or <3
EM2 (%)	<4
2HG5 (gf/cm)	<4

Table 1.11 Interrelation between difficulties in sewing process and ranges of mechanical parameters. Source: Kawabata and Niwa, 1989[38]

Range of parameters	Difficulty predicted in:
LT < 0.55 or >0.7	Overfeed operations
RT > 70	Cutting process
RT < 55	Steam-press operations
LT < 0.55 and RT > 73 or LT < 0.55 and RT < 55	Especially difficult in overfeed operations
EMI < 1 or > 8	Overfeed operations
EMI > 5	Cutting operations
EM2 < 4	Overfeed operations
EM2/EM1 > 3	Sewing operations and steam-press operations
G < 0.6 or > 0.95	Overfeed operations
2HG5 > 3	Overfeed operations

It is also necessary to measure steam press shrinkage and recovery, this being done by the HESC-FT-103A testing method,[40] which also provides a measure of hygral expansion, a 'fingerprint' chart being used to determine whether a fabric is ready for tailoring after sponging. The relaxation shrinkage should fall below 1.5% (preferably below 1%).

Behera and Mishra[41] found TAV to be negatively correlated with the fabric crease recovery angle, there being a limiting crease recovery angle above which the fabric exhibits a poor appearance, the limiting angle being lower for lightweight than for heavy fabrics. They also observed a negative correlation between drape coefficient and TAV, with a drape coefficient between 35 and 40% being considered optimum for the worsted fabrics studied. TAV was positively correlated with formability, a value of 0.4 to 0.6 being optimum for warp formability[41] for worsted suiting fabrics. Values of THV and TAV above 4 (on a scale of from 1 to 5) constitute a perfect winter suiting fabric while a THV above 3.5 and TAV above 4 are required for a perfect summer suiting fabric.[42] Behera and Mishra[43] found that, of all the wool and wool blend fabrics tested, wool/linen blend fabrics had the highest winter THV (of 4.34) and wool/tussah silk fabrics had the highest THV for summer suitings.

Postle[44] stated that fabrics having the most sought-after handle have very high ratings of both sleekness and fullness (≈9 on a scale of 1 to 10) and moderate values of fabric firmness (ratings of 5 to 6).

Mahar *et al.*[45] found that the shear rigidity (G) of men's suitings fabrics lie between 67 gf/cm and 91 gf/cm, their shear hysteresis (2HG5) between 1.43 gf/cm and 2.11 gf/cm, warp extensibility (ε_{M1}) > 3.5 and weft extensibility (ε_{M2}) > 4.0%. Fabric formability (F = E × B, where B is pure bending rigidity, $E = \frac{\varepsilon_{20}}{100} \times \frac{1}{20}$) should be less than 20 mm^2 × 10^{-4} in both warp and weft directions. They concluded that fabric extensibility (at 500 gf/cm) discriminated better between 'good' and 'poor' appearance fabrics, using values of $\varepsilon_{M1} = 3.5\%$ and $\varepsilon_{M2} = 4.0\%$, than fabric formability. It has also been mentioned that warp and weft extension at a load of 500 gf/cm should preferably be 4% or higher for wool fabrics.

For winter suitings (≈>220 g/m^2), a soft handle, such as is obtained with cashmere or superfine wool, is considered ideal in Western Europe and Japan.[46] For summer suitings (≈160 to 220 g/m^2) in Japan, the preferred menswear fabrics are crisp to the touch (linen like) with a surface clear of fibres,[46] relatively stiff, particularly in the weft direction, and light and porous. The best such suitings are typically made of mohair and wool. Such fabrics should ideally have little contact with the skin and not cling. Mori[47] mentioned that desirable subjective-handle fabric can have low THV, and that a high THV may not be compatible with high dimensional stability.

Mori[47] lists the following requirements for apparel fabrics:

- Relaxation shrinkage of fabric must be less than 2% and hygral expansion less than 7% for both warp and weft directions. If hygral expansion exceeds 4%, pressing (e.g. wool cycle) should be applied. Specifications for steam-press shrinkage have been formulated.
- Extensibility of polyester/wool/mohair blended fabrics for summer suits should be greater than 4% (KES-FB, standard testing condition) in the weft direction ($EM_2 > 4\%$).
- Extensibility of wool gabardine, polyester/wool/tussah and polyester/wool tropical must be between 4% and 8% in the warp direction ($4\% < EM_1 < 8\%$), preferably between 4 and 5%.
- Shear hysteresis (at shear angle 5°) must be less than 2.5 gf/cm (KES-FB, standard testing condition) for suit and jacket fabrics (2HG5 < 2.5 gf/cm).

Carnaby *et al.*[48] described the development of tropical fabrics of good KOSHI, SHARI and HARI handle properties, with some 50% of relatively coarse (≈35 μm) New Zealand wool in the weft.

Fujiwara,[49] in designing good quality mohair/wool blend suiting fabrics, found that for good making-up properties, such fabrics had to have large weft elongation, soft shearing, good elasticity, high weft bending rigidity and high surface roughness as based on the Kawabata KES-FB system:

- Weft elongation > 7%
- Shearing $0.6 \geq G \geq 0.4$
  $1.0 \geq 2HG5 \geq 0.5$
- Weft bending rigidity ≥ 0.2
- High coefficient of surface friction (μ)
- Comparatively high compression (WC)

Such fabrics have good HARI, KOSHI and SHARI.

Table 1.12 gives the proposed criteria that a fabric needs to satisfy if it is to be considered a 'perfect' or 'ideal' fabric.[6]

Sewability (S_k) according to Kawabata can be calculated as follows:[50]

$$S_k = 500\,G.LT/2HG5.W.EMT$$

and formability (F), according to Lindberg, as follows:

$$F = B_\varepsilon/49.5$$

Niwa *et al.*[51] derived the following equation for formability (*F*):

$$F = \frac{EM.B.G}{F_{max}.LT.2HG5} \qquad [1.1]$$

Table 1.12 The criteria for an ideal fabric. Source: Kawabata and Niwa, 1998[6]

	Type of suiting		Remarks
	Winter–autumn	Mid-summer	
1. Total Hand Value (THV)	THV > 4.0	THV > 3.5	THV 1(poor)–5(excellent)
2. Total Appearance Value (TAV)	TAV > 4.0	TAV > 4.0	TAV 1(poor)–5(excellent)
3. Mechanical comfort (must be inside the snake zone)	0.58 > LT > 0.50 78 > RT > 73 5.1 > EM1 > 4.3 18 > EM2 > 7.5 3.0 > EM2/EM1 > 1.3 0.65 > G > 0.50 1.5 > 2HG5 > 0.8	0.60 > LT > 0.50 78 > RT > 73 5.1 > EM_1 > 4.3 18 > EM_2 > 7.5 3.0 > EM2/EM1 > 1.3 0.65 > G > 0.50 1.5 > 2HG5 > 0.8	LT: Average of LT_1 and LT_2 RT: Average of RT_1 and RT_2

Subscript/suffix: 1, warp direction; 2, weft direction

If EM2 > 9 and RT2 ≈ 55 to 65 or EM2 > 12 and RT2 ≈ 70 to 80, particular care during the sewing operation is required.[52]

Uemura[53] gives the following values for 'excellent' men's suitings fabric:

- ((Koshi + Hari)/13) × 100% >70
- Formability >5
- Sewability >4 and <8
- EM1 + EM2 (%) >7.5
- MEV >1.35
- Form stability >3
- EM2 >4.5
- EM2/EM1 (%) >0.9

Inextensible and highly elastic (high RT), stiff and inelastic (in bending and shearing), and lightweight fabrics often lead to seam puckering problems.[52] For the 2HG5 values, the following applies:[52]

- 2HG5 > 3.5: Possible problems with wrinkling
- 3.0 ≈ 2.5: Upper limits of acceptability for apparel manufacturers
- 0.5 ≈ 1.3: Potential problems with seam puckering, but if this is avoided then it will be an excellent suit
- 2HG5/G > 1.8: The appearance of suits from such fabrics will become poor

Shishoo[54] also presented a table indicating the relationship between KES measured mechanical properties and tailoring properties. The KES system is also able to distinguish differences in finish, for example differences between classes of silicone finishes[55] on polyester/cotton fabrics, and has been applied to evaluating the quality of ladies' garments.[56] A new tailorability function, namely LT × log(B × EMT/2HG5), was proposed by Shishoo.[57]

Vohs *et al.*[58] derived the following best fit regression equation, relating subjectively assessed fabric handle to KES-FB measured fabric properties for fabrics produced from air-jet and ring-spun yarns.

$$\begin{aligned}\text{Handle} &= -2.51 + 4.34(\log WT) - 1.15(\log MMD) \\ &\quad + 1.31(\log SMD) - 2.68(\log W)\end{aligned} \qquad [1.2]$$

$R^2 = 0.976$

where:

WT = Tensile energy (gf.cm/cm^2)
MMD = Mean deviation of MIU
SMD = Geometrical roughness (μm)
W = Weight per unit area (mg/cm^2)
MIU = Coefficient of friction

Frydrych and Matusiak[59] showed that less complicated tests (involving 10 fabric parameters in all), done on an Instron tensile tester (as proposed by Pan *et al.*[60]) could replace the more complex and expensive tests (Kawabata and FAST) for predicting a General Hand Factor (GHF), which was the reciprocal of the General Quality Factor (GQF). They derived the following equation for cotton and cotton/polyester fabrics woven from 20 tex yarns and differing in finishing treatments and structural parameters (e.g. ring versus rotor yarns, weave structure, sett):

$$\begin{aligned}1/GHF_{in} = GQF_{in} = 6.3\frac{WT}{WT_{\max}} + 6.3\frac{HG}{HG_{\max}} \\ + 15.6\frac{HB}{HB_{\max}} - 9.4\frac{LC}{LC_{\max}} \\ + 15.6\frac{RC}{RC_{\max}} + 15.6\frac{\mu_S}{\mu_{S\max}} \\ + 15.6\frac{\mu_k}{\mu_{k\max}}\end{aligned} \quad [1.3]$$

where:

WT = Tensile loading energy
HG = Shearing hysteresis
HB = Bending hysteresis
LC = Compression linearity
WC = Energy of compression
RC = Compression resilience
μ_S = Coefficient of static friction
μ_k = Coefficient of kinetic friction.

Tensile linearity (LT) and tensile resilience (RT) did not contribute to GHF.

1.2.4 FAST system

The Fabric Assurance by Simple Testing (FAST) system was developed in the 1980s by the CSIRO Division of Wool Technology, Australia, as a simpler alternative to the more sophisticated Kawabata system, and uses three individual instruments (FAST-1, FAST-2 and FAST-3)[4] as well as a test method (FAST-4). They essentially measure the resistance of fabrics to deformation and not their recovery from deformation. The FAST instruments are similar in operation to conventional measuring instruments, except that measurement is carried out using sensors, and the test results are displayed digitally. The FAST system measures the mechanical, dimensional and pressing performance related propensities of fabrics and is used to assess the fabric making-up (tailorability), appearance and handle properties.

FAST-1: Compression meter (FAST-1) measures:

- fabric thickness (T)
- fabric surface thickness ($ST = T_2 - T_{100}$)
- released (relaxed) surface thickness.

The compression meter[61] measures the thickness of fabrics at two loads, namely 2 gf/cm^2 (0.196 kPa) and 100 gf/cm^2 (9.81 kPa). This allows the calculation of the fabric surface thickness, the difference in thickness between the two loads, which is a measure of the amount of compressible fibre or pile on the surface of the fabric and can be used to ascertain the extent and consistency of fabric surface processes, such as singeing, cropping, raising, and pressing. A further measurement of the fabric surface thickness, after release in steam (or even water), provides a measure of the stability of the finish of the fabric; the larger the difference, the less stable the finish. This measurement is important in determining the extent of subsequent changes in appearance and handle of the fabric after garment pressing and can indicate the potential re-emergence of such things as running marks.[61]

FAST-2: Bending meter (FAST-2) measures:

- bending length (BL in mm – measured at an angle of 41.5°)
- bending rigidity (BR in μN.m) = $9.8 \times 10^{-6}\ W\ (BL)^3$

(where: W = fabric weight (g/m^2)).

The bending meter measures[61] the bending length of fabric, from which the bending rigidity can be calculated. This is an important property for the handle of the fabric and also influences the cutting and sewing performance and the ease with which the fabric can be processed by automated handling equipment.[61] Too stiff a fabric can lead to problems in moulding the fabric, whereas too limp a fabric can be difficult to cut as it will easily distort and can also lead to seam pucker.

FAST-3: Extension meter (FAST-3), measures:

- warp extensibility
- weft extensibility

- bias (45°) extensibility
- shear rigidity (N/m) = 123/EB5 (% bias extension).

The extension meter[61] measures the extensibility of the fabric at three loads, 5 gf/cm (4.9 N/m), 20 gf/cm (19.6 N/m) and 100 gf/cm (98.1 N/m) in the warp and weft direction to indicate potential problems in the laying up of the fabric and in seams that require overfeed. This information is also combined with the bending rigidity to determine the fabric 'formability' which is a measure of the fabric's propensity to pucker when it is compressed along the seams, a possibility along with seam blowing when formability is low. The extensibility is also measured on samples that are cut on the bias (45° to the warp) to determine fabric shear rigidity. This measurement indicates potential problems in laying up and in the fabric's ability to form smooth three-dimensional shapes, such as are needed around the sleeve head and shoulder region in a structured jacket.[61] Low shear rigidity indicates that the fabric will be easily distorted in laying up, marking and cutting, whereas a high value indicates that the fabric will be difficult to form into smooth three-dimensional shapes, causing problems in moulding and sleeve insertion. Too low a shear rigidity could indicate that the fabric will be difficult to lay up and may require pinning, whereas too high a value could indicate problems with moulding the fabric and inserting sleeves. Low extensibility can lead to difficulties in producing overfeed seams, problems in moulding, and seam pucker. High extensibility can lead to the fabric being stretched during laying-up, causing the fabric panels to shrink when removed from the cutting table. Low warp extensibility often leads to seam pucker problems; increasing the warp crimp during finishing (e.g. reduce warp stretching and then pressure-decatising, to 'set' the higher crimp) can avoid, or at least minimise, this problem.

FAST-4: Dimensional stability test method (FAST-4), measures:

- relaxation shrinkage (RS) = $(L_o - L_D)/L_o$
- hygral expansion (HE) = $(L_w - L_D)/L_D$

where L_o = the original length, L_D = the dried length, and L_w = the relaxed length in water.

The dimensional stability test enables both the relaxation shrinkage and the hygral expansion of the fabric to be determined.[61] Relaxation shrinkage is the once only change in fabric dimensions associated with the release of strains set up in the fabric as a result of spinning, weaving and finishing (e.g. if a fabric is dried under a high tension during finishing). This change can be brought on by exposure of the fabric to steam, water or high humidity. Depending upon which stage during garment manufacture that this change manifests itself, the problem can range from one of incorrect sizing to poor appearance on and around fusibles and seams. This is also a critical fabric property for processes, such as pleating, where there are certain minimum requirements for sharp, smooth pleats.

Hygral expansion is the reversible change in fabric dimensions associated with the absorption and desorption of moisture by hygroscopic fibres such as wool. The appearance of garments can deteriorate (e.g. seam puckering and bubbling) when exposed to high humidity if the hygral expansion is high, especially those that were made up under conditions of low relative humidity.[61] Steam and chemical settings of wool fabrics increase hygral expansion, the latter being related to the degree of fibre swelling during setting.[57]

1.2.5 Interrelationship between FAST measured fabric properties and fabric and garment making-up performance

From the above measured properties, other properties, such as 'formability' and 'finish stability', can be calculated. For example, if the ratio of surface thickness after and before relaxation is over 2.0, it indicates improper finishing or 'definishing'.[40] Tailorability is dependent mainly upon fabric formability (bending rigidity × low stress extensibility).[41] Formability (compressibility × bending rigidity or extensibility at low loads × bending rigidity ($F\ (mm^2) = BR\ (E20 - E5)/14.7$)), the latter being used on the FAST, is a measure of the ability of fabric to accommodate 'in-plane' compression without buckling, such as that encountered during tailoring, and is a direct measure of seam puckering, low formability indicating a tendency to pucker.

Table 1.13[39] provides a summary of the FAST system. Table 1.14 summarises the FAST fabric properties associated with problems in garment making[62] while Table 1.15 lists those FAST fabric properties associated with potentially poor garment appearance.[62] Figure 1.7 shows the FAST control chart on which measured fabric properties are plotted as a 'fingerprint', for easy diagnosis and corrective action.

Finish Stability (i.e. ratio in percent of surface thickness after and before steaming) should preferably be above 75%.[63] Formability (F), particularly that in the warp direction, is important in predicting garment seam behaviour, and should preferably be higher than 0.25.[63]

In addition to the above properties, 'seam pressing performance' (PP) can also be predicted, using the crease pressing performance test, which involves inserting a crease in a sample and then measuring the recovery of

Table 1.13 Summary of CSIRO's FAST system. Source: Sule and Bardhan, 1999[39]

Instrument and test	Measures	Predicts problems in:
FAST-1	Thickness Compression	Pressing Finish stability
FAST-2	Bending	Cutting, automated handling
FAST-3	Extensibility	Laying up, pattern matching, overfed seams, moulding
	Shear	Laying up, moulding, sleeve insertion
FAST-2 and 3	Formability	Seam pucker
FAST-4	Relaxation shrinkage Hygral expansion	Size, seam pucker and pleating Looks, pleating

Table 1.14 Fabric properties associated with problems in garment making. Source: Anon[62]

Property	Potential problem
Low relaxation shrinkage	Bubbling of fused panels Delamination of fused panels Bubbling in pleating Difficulty shrinking out fullness
High relaxation shrinkage	Excessive fusing press shrinkage Excessive steam press shrinkage Variation in size of cut panels
Excessive hygral expansion	Excessive shrinkage during manufacture Bubbling of fused panels Bubbling of pleated panels
Low formability	Difficulty in sleeve setting
Low extensibility	Difficulty with sewing overfed seam Difficulty in pressing Difficulty shrinking out fullness
High extensibility	Difficulty matching checks Difficulty sewing unsupported seams (Warp) Easy to stretch in laying up, leading to shrinkage problems
Low bending rigidity	Difficult to cut and sew Automated handling problems
High bending rigidity	Difficult to mould and press
Low shear rigidity	Easy to distort in laying up, marking and cutting
High shear rigidity	Difficulty in garment moulding Difficult to form smooth 3D shapes

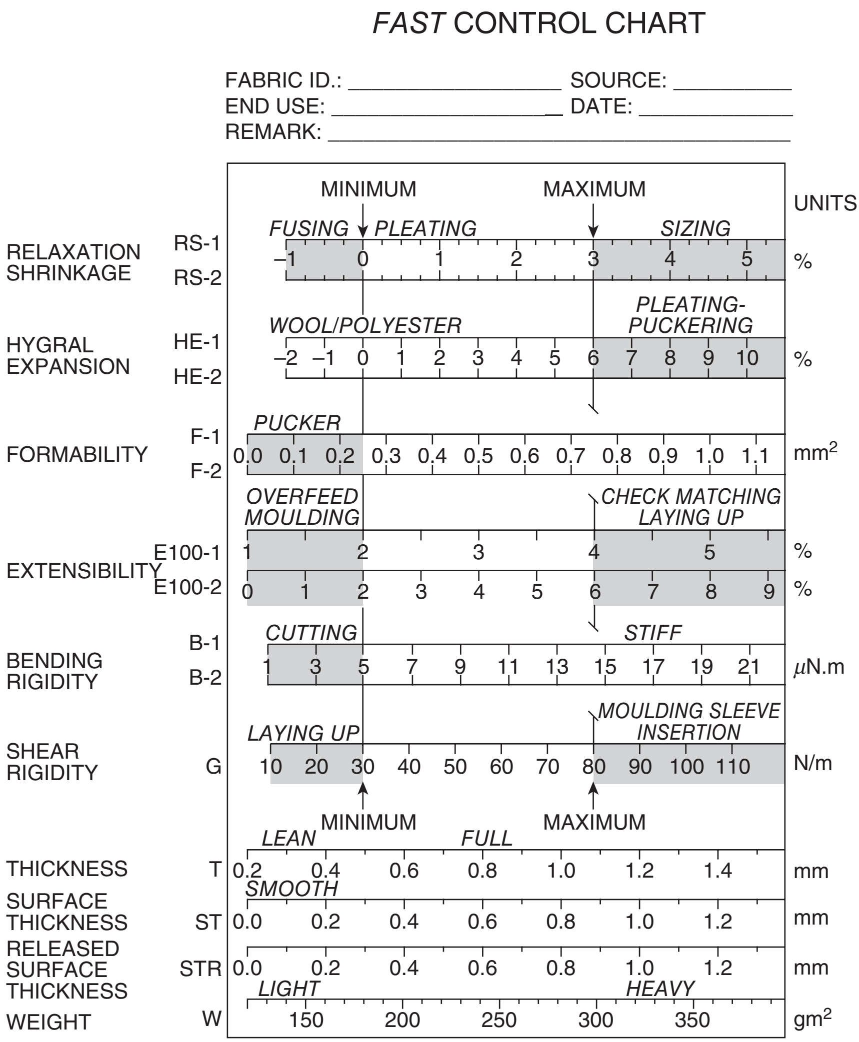
Table 1.15 Fabric properties associated with potential poor garment appearance in wear. Source: Anon[62]

Property	Potential problem
Low relaxation shrinkage	Bubbling/waviness in fused panels Delamination of fused panels Seam pucker
High relaxation shrinkage	Size variation Seam pucker
Excessive hygral expansion	Bubbling/waviness in fused panels Poor shape retention Seam pucker
Low formability	Puckering of seams Difficulty in pressing
Low bending rigidity	Poor shape retention Soft drape of sleeves
Low shear rigidity	Poor garment shape retention Soft drape of sleeves
Excessive increase in surface thickness	Poor appearance retention (fabric) Re-emergence of running marks or cracking and distortion of fabric

the crease under standard atmospheric conditions. It enables the propensity of a fabric to produce blown seams (i.e. seams which do not remain flat) after pressing to be predicted.[65] The Press Test Angle (PTA) relates to the ability to maintain flat pressed seams in the garment. The weft value is generally the more important one, and the lower the PTA value the better, preferably lower than 30 degrees.[63]

An upper limit of about 15° is required for the crease angle of lightweight (140–180 g/m^2) wool fabrics.[66] Generally values below 20° should give good pressing performance, with values above 30° indicating poor pressing performance. Tailorability Index (TI) may also be calculated from the ratio of the warp formability and the weft PTA,[63] the higher the value the better.

Shirting fabrics have been found to be more difficult to rate for handle than suiting fabrics,[67] with shear rigidity, formability and bending rigidity having the main effect on their handle. Yick *et al.*[12] have established FAST control charts for shirting material, based on 104 commercial shirting materials ranging in weight from 93 to 258 g/m^2, high correlations being found between FAST and Kawabata results for fabric formability, bending rigidity and shear rigidity.



1.7 The FAST control chart for light-weight suiting fabrics. Source: Anon[64]

1.3 Other methods

Although the Kawabata and FAST systems dominate the fabric objective measurement market, various alternative or complementary systems have been developed,[6,68] such as a portable system,[68] universal tensile testers[60,69–74] and LSU[75] tensile tester, a polymeric human finger sensor (artificial finger),[76,77] pressure sensitive glove,[78] measuring the force required to pull a fabric through a ring or nozzle[79–86] or pins[87], as well as a system of on-line measurement of fabric compressional behaviour.[88] Bereck *et al.*[71] found that, using an Instron tensile tester, the hysteresis at 75% of maximum extension correlated well with subjectively assessed softness of fabrics given different dyeing, finishing and softening treatments. Work is also under way to develop a haptic simulation model of fabric forces on the fingers and hand associated with feeling a fabric via highly sensitive touch response transducers,[89] enabling users to evaluate fabric handle without actually touching the fabric. Recently, Breugnot *et al.*[90] used the tactile difference messages elicited by the cutaneous mechanoreceptors of the skin to tactile stimuli, as recorded by the micro-neurography, to modify mechanical measurement of 'touch' or handle.

1.4 Effects of fibre properties

The fibre mechanical properties (e.g. bending and tensile) are generally related directly to the corresponding yarn and fabric mechanical properties, but the precise relationship is affected by the yarn and fabric structures, notably those that affect the freedom of movement and alignment of the fibres within the yarns, and the freedom of movement of the yarn within the fabric.

Of the various fibre properties, bending stiffness (flexural rigidity) has by far the most important effect on fabric and garment handle, torsional rigidity also being important. Bending stiffness, in turn, is a function of fibre bending modulus, diameter (to the fourth power) and cross-sectional shape, as illustrated in the following equation:

$$\text{Flexural rigidity} = \frac{\eta E T^2}{4\pi\rho} \qquad [1.4]$$

Morton and Hearle[91] provide tables of values (*their* Tables 17.1 and 17.2) for η and E for different fibres.

Note: E = specific modulus in N.kg^{-1}.m
T = fibre linear density in kg.m^{-1}
η = fibre shape factor (= 1 for a circular fibre)
ρ = fibre density in kg.m^{-3}

In practical units, the equation becomes:

$$\text{Flexural rigidity} = \frac{\eta E T^2}{4\pi\rho} \times 10^{-3}\,\text{N.mm}^2 \qquad [1.5]$$

where E is in N/tex, T is in tex and ρ is in g/cm^3.

For a fibre of unit tex (i.e. eliminating fibre fineness) this equation becomes:

$$\text{Specific fibre flexural rigidity} = \frac{\eta E}{4\pi\rho} \times 10^{-3}\,\text{N.mm}^2/\text{tex}^2 \qquad [1.6]$$

Therefore, for a specific type of fibre, diameter is the main parameter affecting handle. The greater the fibre diameter (i.e. the coarser the fibre), the stiffer, harsher and crisper (harder) the handle becomes, and the rougher (harsher) the fabric surface. For summer suiting fabrics to be worn under high temperature and humidity conditions, the fabric should be light, crisp, porous and stiff, so that contact with the skin and clinginess are minimised. To achieve such a fabric, relatively coarse fibres (e.g. mohair) are required, particularly in the weft direction (e.g. mohair or New Zealand wool tropicals[46] of 170–180 g/m^2).

Increasing fibre diameter also increases the sensation of scratchiness and prickliness (dealt with in Chapter 8). In the case of wool it is the fibres coarser than 30 μm that are mainly responsible for the sensations of prickliness and scratchiness. Research has indicated that as long as the percentage of fibres coarser than 30 μm is lower than 5%, the level of prickliness will normally not be unacceptable, although certain persons are more sensitive to fibre/fabric prickliness. Micro-fibre fabrics will tend to be very soft and smooth, even limp.

The effect of fibre shape is due to its effect on the fibre flexural rigidity and this is illustrated in Equation 1.4. Fibre bending modulus is mainly dependent upon the type of fibre (see Tables 17.1 and 17.2 of Morton and Hearle[91]) and to a lesser extent on chemical (softening) treatments applied to the fibre and fabric. Chemical treatments can change Young's modulus, and through that the handle and making-up properties. Nevertheless, the dependence of fibre stiffness on diameter to the fourth power (linear density squared) means that changing fibre diameter is the easiest and most practical way of changing fabric handle. The fibre torsional modulus is also related to the diameter to the fourth power. Therefore, in essence, fibre diameter changes will have the greatest effect on fabric stiffness and therefore on all handle and related making-up properties, followed in importance by the fibre Young's modulus (E), with fibre shape (η) also important.

Hunter *et al.*[92] found mean fibre diameter to have the main influence on the primary handle values, the latter generally increasing with increasing mean fibre diameter. An increase in fibre crimp was found to increase shear stiffness and hysteresis. Such fabrics also generally have good tailorability. An increase in fibre crimp generally produces an increase in fabric fullness and softness.[93] Matsudaira and Kawabata[94] found higher fibre crimp to produce a more deformable fabric in both tension and compression which correlates well with a high fabric quality or FUKURAMI.

Dhingra *et al.*[95] found increased fibre staple crimp to be associated with increased fabric hygral expansion, the latter depending mainly on weave crimp, with the effect of weave structure being relatively small, as also that of fibre diameter. The effect of staple crimp was attributed to its effect on weave crimp.

Fibre friction affects the fabric smoothness and therefore fabric handle, as well as the ease with which the fibres slide over each other in the fabric, which in turn can be reflected in the bending and shear stiffness and hysteresis properties.

1.5 Effects of yarn properties

The effect of yarn properties on fabric handle and making-up are heavily dependent upon the properties of the constituent fibres, with yarn structure and twist also playing a role. The most important fibre properties in this respect are diameter, cross-sectional shape, modulus, length and crimp, particularly the first two mentioned. The fibre entanglement, orientation and compactness will also all play a role. Bulky and soft-twist yarn will produce a soft and compressible fabric and handle, with fabric shear stiffness depending mainly upon the relative movement of yarns.

If the fibres in a yarn can bend independently, which is largely the case in practice, the bending rigidity of a yarn (G) is given by:[96]

$$G = CTD^2\left[1+6\left(\frac{V}{100}\right)^2\right] \Big/ \left[1+\left(\frac{V}{100}\right)^2\right] \qquad [1.7]$$

which can be approximated by:

$$G = CTD^2\left[1+5\left(\frac{V}{100}\right)^2\right] \qquad [1.8]$$

when:

$\left(\frac{V}{100}\right)$ is much smaller than 1

where:

C = a constant
T = yarn linear density (tex)
D = fibre diameter (μm)
V = coefficient of variation of fibre diameter (%).

The yarn structure, surface and compressional properties will affect fabric handle, yarn twist playing a major role in this respect. As twist is increased, so the fibre mobility, yarn diameter, surface roughness, friction and yarn compressibility decrease, while yarn stiffness, harshness, inter-fibre frictional forces and smoothness increase. Nevertheless, Mori[47] found the effect of weft yarn twist to be small on KES and FAST properties in practice. Finer yarns will tend to produce smoother and softer fabrics,[93] provided twist factor is constant.

Wrapper fibres, such as are present to a lesser or greater extent in rotor-spun (OE) and air-jet spun yarns (MJS) will restrict fibre freedom of movement and increase yarn stiffness and roughness. Air-jet yarns tend to have a greater surface roughness, resistance to compression and bending stiffness than ring-spun yarns. Behera *et al.*[97] found that, from a tactile comfort point of view, ring-spun cotton yarns were superior to rotor-spun and friction-spun yarns. Vohs *et al.*[58] compared ring-spun and air-jet 65 polyester/35 cotton yarn and fabric (twill and plain weave) properties, tested by means of the Kawabata KES-FB range of instruments. The fabrics produced from the air-jet yarns were stiffer, thicker, rougher, harsher and less compressible and had higher contact friction than those produced from ring-spun yarns, these properties mostly reflecting corresponding differences in the two types of yarns. Differences between the two types of yarns were greatly affected by fabric structure and could be reduced by selecting weave structures that promoted yarn mobility, such as twill and satin weaves. Fabric shear stiffness was, however, more affected by fabric structure (weave, sett, etc.). Twill weave fabrics tended to be regarded as softer and more flexible, with a more desirable handle than plain weave fabrics. They concluded that the type of yarn had a smaller effect on fabric handle and the primary hand components than fabric weave.

Lord *et al.*[70] studied the handle of plain and 3/1 twill weave fabrics containing ring, rotor (OE) and friction-spun cotton yarns. They concluded that the plain weave structure is more sensitive than the twill weave to changes in yarn structure, with the fabrics containing friction-spun yarns rated the smoothest and those containing rotor-spun yarns the roughest.

Behera and Mishra[43] found that singles wool and wool blend yarns had higher THV than 2-ply yarns for both winter and summer applications, due to lower (easier) compressibility and bending rigidity giving higher softness and fullness.

1.6 Effects of fabric properties

Essentially, the handle of a fabric is related to its bending, shear stiffness, bulk compressibility and surface friction properties while its prickliness is mainly a function of the fibre buckling force (a function of fibre bending stiffness and length, see Chapter 8), with surface friction of secondary importance. In the main, lighter fabrics, particularly knitted fabrics, are considered to have a better handle.

It has been found that the bending hysteresis curve of a woven fabric can be approximated by the following equation:[98]

$$M = \pm H_F + K_F k \qquad [1.9]$$

where:

M = bending moment and
k = curvature of the bent yarn
with $H_F = H_Y + H_I$
$K_F = K_Y + K_I$

The subscripts, $_F$, $_Y$ and $_I$ denote the fabric, yarn and inter-yarn effects, respectively.

Matsuo and Suresh[98] also presented the following equation for the slope K_Y of the bending hysteresis curve of a woven fabric:

$$K_Y = \{tw/(1+C)\}N_Y N_S N_S \quad [1.10]$$

where:

N_Y = yarn (thread) linear density
N_S = number of fibres in the yarn cross-section
K_S = single fibre stiffness
C = crimp ratio of a yarn within the fabric
tw = fibre length of a helical coil of a twisted yarn/yarn length.

The parameters H_I and K_I are reduced by several finishing treatments,[98] such as desizing, heat-setting, relaxation, lubrication, sericin removal and peeling. Fibre swelling also increases as H_I.

Vohs *et al.*[58] concluded that fabric weave had a greater influence on subjectively assessed handle and the primary hand components than the type of yarn,[58,99] with weaves having fewer yarn interlacings (e.g. twills) improving the relatively poor handle of fabrics containing air-jet yarns (see also Section 1.5).

Fabric cover factor is an important parameter. Fabrics with low cover factor have low shear rigidity. Fabric bending rigidity depends upon fabric compactness ratio (ratio of cover factor to theoretical maximum cover factor). In general, looser fabrics have a higher (better) General Hand Factor (GHF); adding polyester to cotton fabrics has a slightly adverse effect on GHF; and finishing has a major beneficial effect.[59]

Choi and Ashdown,[100] using the KES-FB system, found that, for a large number of knitted cotton fabrics of various structures and in terms of the primary hand values, an increased knit density (tightness or cover factor) was associated with increased fabric stiffness, fullness and softness, and decreased smoothness. The Total Hand Values tended to increase with increased knit density: the double knit fabrics exhibited higher THVs than the single knit structure fabrics, with the half-Milano rib and cross-miss interlock having the highest values. In terms of good dimensional stability and softness, fabrics combining miss and tuck stitches were best.

Hygral expansion increases with fabric weave crimp, the relationship being affected by fabric cover factor. The following relationship has been found:[7]

$$\text{Hygral expansion (dry–wet)} = 0.38 \text{ weave crimp} - 1.30 \text{ shear hysteresis} + 1.6 \quad [1.11]$$

Fabrics with insufficient weft crimp, and consequently low weft-wise extensibility, tend to pucker around the shoulder seam and at other seams where there is significant overfeed during sewing.[46]

1.7 Effects of dyeing and finishing (chemical and mechanical) treatments

The effects of dyeing and finishing on FOM measured properties and handle have been reviewed.[101,102]

1.7.1 Chemical (wet) treatments

Fabric dyeing and finishing, notably the latter, have a major effect on fabric handle and making-up performance, the effect being most apparent in the fabric shear rigidity and hysteresis. Fabric dyeing and finishing generally effect large reductions in fabric bending, and shear rigidity and hysteresis, with concomitant changes in fabric handle and making-up (tailorability), this often being a major consequence of dyeing and finishing.

Any fabric or garment dyeing and finishing procedure which reduces fibre-to-fibre and yarn-to-yarn friction, bends and flexes (mechanically manipulates) the fabric, induces relaxation, and increases fabric surface hairiness (i.e. brushed effect) will increase fabric softness. Any chemical finish which increases inter-fibre friction and/or bonding (spot welding) will increase fabric stiffness. Finishes which reduced the energy to deform the fabric and increased fabric smoothness have been found to improve the handle of fabrics containing air-jet yarn.

For conventional fabric (piece) dyeing, the major impact on fabric handle is due to the way the fabric is handled during dyeing (i.e. dyeing conditions), rather than on the type and depth of dye and dyeing auxiliaries used.[101] This is attributed to the relaxation of internal stresses and the ease with which the yarns can move relative to each other within the fabric structure. In pigment dyeing or printing, however, the binder stiffens the fabric and therefore the fabric handle,[101] although the fabric type (e.g. knitted versus woven) has a greater effect than the pigment dyeing. Furthermore, beck dyeing of polyester gives a softer handle than thermosol dyeing, because of differences in the dyeing process and conditions. Piece-dyeing is an effective way of producing fabrics with a high THV.

Fabric finishing processes, notably decatising (steaming fabric between two layers of fabric, usually cotton-press cloth),[102] correctly undertaken, generally have a favourable effect on fabric formability and making-up (tailorability) in general, although care needs to be taken not to impart excessive extensibility and hygral expansion to the fabric, which could lead to puckering in the garment.[102,103]

Two categories of functional finishes, namely softness and hand builders, are specifically aimed at modifying fabric handle.[101]

Cross-linking finishes, e.g. wrinkle-free finishes, tend to stiffen the fibres and fabrics.[101]

Durable press resins, based upon formaldehyde derivatives, generally increase fabric stiffness and reduce fabric extensibility, with an associated effect on fabric handle,[104] and softeners are generally applied with the resin to reduce these effects of the resins.

The effect of shrink-resist treatment of wool fabrics on handle and tailorability depends, amongst other things, upon the hardness (flexibility) of the polymer and the formation of inter-fibre bonds;[105] these effects can be reduced by subsequent finishing processes, such as laundering and tumble drying (which break the bonds), semi- or pressure-decatising and applying a softener. Shrink-resist treatments can affect fibre friction and therefore fabric handle, corona discharge and chlorine treatments increasing friction while permanganate-based treatments reduce friction. Resin (polymer) treatments affect stiffness and surface smoothness, silicone-based treatments tending to give a smoother and kinder handle than more inflexible resins, such as polyurethane-based treatments.[106] Silicone-based finishes improve the handle of most types of fabrics.[107] It has been shown that the effect of cationic surfactants on Hercosett®-treated wool can be assessed through changes in the hysteresis.[108]

Fluoro-chemicals, because of their low add-on levels, are less likely to affect fabric handle than silicone finishes, which generally impart a slippery handle.[101] Soil release finishes available for DP finishes, involving co-polymers of methacrylic acid and ethylacrylate, applied together with a DP resin, can cause the fabric handle to become stiff and boardlike.[101] Soil release finishes available for DP finishes, which involve a block copolymer containing fluoro-chemical blocks and hydrophilic blocks along the polymer backbone (combining oil repellency and soil release) have a negligible effect on fabric handle, because of the low add-on levels required and the greater flexibility of the cured polymer.[101] Soil release finishes which have a lubricating effect can produce a slightly softer fabric handle.[101]

Most flame retardant finishes increase the fabric stiffness,[101] more particularly because of the high levels which generally need to be applied to achieve adequate flame retarding.[101]

Softeners (e.g. non-polar compounds, such as hydrocarbons and silicones), being lubricants, provide functional properties (e.g. reduced friction and improved sewability, tear strength and abrasion) as well as modifying fabric handle. Chen *et al.*[75] used a new instrumental method to illustrate the effect of softeners on fabric softness. Surfactants (e.g. cationic surfactant softeners) can increase fabric and yarn bulkiness and compressibility and therefore fabric handle (softness) but have a relatively small effect on fabric surface characteristics (MIU, MMD, SMD), pressing having a much greater effect.[109]

Crabbing under warp tension can provide fabrics with the required weft crimp to avoid seam pucker.

Chemical setting of wool fabrics tends to reduce bending and shear hysteresis, which often results in a limp handle that can be minimised by changing the fabric structure.[110] It also increases hygral expansion. Hygral expansion increases with the degree of fabric setting imparted during dyeing and finishing. The stiffness of tightly woven fabrics tends to be more affected than that of looser fabrics by finishing, including chemical setting.

According to Tomasino,[101] hand modifiers, such as softeners and hand builders incorporated in the final finish bath, have the greatest effect on fabric handle and can be used to great effect by finishers to modify handle, softeners being included in most finish formulations. Hand builders (film forming polymers), which can be either durable or not, are generally applied to limp or fragile fabrics, adding weight, softness and body, thereby enabling fabrics to be more easily handled during cutting and sewing,[101] their effect depending upon the stiffness of the polymer. Normally, hand builders are divided into two main groups, the one adding fullness (increased bulk) and the other adding stiffness. Durable hand builders can be either thermosetting (e.g. melamine) or thermoplastic (latex) polymers, the effect of the latter depending upon the Tg of the polymer, the higher the Tg the stiffer the fabric generally. Non-durable ones are generally water soluble, such as starch, carboxymethyl cellulose and PVAlc.[101] Increased stiffness can adversely affect tear strength, due to a lack of mobility of the yarns when the fabric is torn.

Na and Kim[111] stated that silk fabrics degummed *after* weaving had a soft and bulky touch, excellent resilience and good drape, whereas those made from degummed yarns were stiff and thin.

The controlled hydrolysis (e.g. in hot caustic solutions) of polyester fabrics can make the fibres finer and less stiff (i.e. more flexible) with a corresponding effect on fabric stiffness and handle.[101] Caustic-reduced polyester fabrics exhibit strong silk-like characteristics except for their surface properties.[112]

Table 1.16 Effect of finishing operations on the properties of wool fabric. Source: De Boos and Tester, 1994[115]

Operation	Fabric property					
	Relaxation shrinkage	Hygral expansion	Extension	Bending	Shear	Compression
Wet setting	X	X		X	X	X
Scouring	M	M	M	M	M	M
Milling	X	X	M-X	X	X	X
Dyeing	X	X	X	X	X	M-X
Drying	X		X			
Cropping	M		M			M
Singeing						M
Damping						M
Relaxing	X		X			X
Pressing	M-X		M-X	M	M	X
Decatising	X	X	X	X	X	X
Sponging	X		X			M

Note: X indicates a large effect; M indicates a small but significant effect; M-X indicates that, while the effect is normally small, under the appropriate conditions the effect can be large.

Treatments of cotton fabrics with enzymes (e.g. cellulase)[113] can reduce friction and stiffness and therefore increase fabric smoothness and softness.[114] They also decrease shear hysteresis and rigidity.[101]

Milling will tend to produce a softer fabric. De Boos and Tester[115] give a table to illustrate the effect of finishing on the properties of wool fabrics (Table 1.16).

1.7.2 Mechanical (dry) finishing

Mechanical finishing generally produces a softer fabric handle. Where wet (or chemical) finishing or processing of fabric (i.e. preparation, dyeing and finishing) generally involves subjecting the fabric to a chemical reaction or treatment in a solution (e.g. water or solvent), mechanical finishing (dry finishing) involves subjecting the fabric to a mechanical or physical action (manipulation) such as surface finishing (brushing, raising, napping, sueding, sanding, shearing/cropping), compaction (e.g. Sanforising), calendaring (Schreinering), setting and pressing. Surface finishing, such as brushing, raising, sueding, sanding and napping, creates a pile or a more hairy (fibrous) fabric surface which generally produces a softer and warm handle (soft texture). Sanding, also referred to as sueding or emerising, generally involves passing the fabric over a series of rollers usually covered in emery paper (or sand paper or diamond dust) which rub (abrade and break) the surface fibres to create a soft and pleasant handle. Brushing, also referred to as raising or napping, involves raising and breaking the surface fibres by means of sharp hooks (e.g. wire teeth) to create a nap or pile.

Fabric drying and heat setting can also affect fabric handle. Any drying action (e.g. tumble drying) which relaxes the fabric and bends and flexes the fabric will increase fabric softness, whereas drying or heat setting under tension will tend to increase fabric stiffness.

Decatising tends to produce a soft and smooth handle.[102] Semi-decatising (blowing), full decatising and pressing, particularly paper pressing, produces a smooth surface, particularly if pressing is followed by full decatising at high wrapper tension.[106] Pressing can increase both fabric smoothness and stiffness.[106] Wet flat setting has a beneficial effect on handle. Intensive setting during dry finishing can increase hygral expansion significantly, a machine for reducing the problem having been developed.[116] Cafaggi[63] found that post-KD finish decatising improved wool fabric properties related to tailorability, notably formability and Press Test Angle. Fabric pressing will decrease fabric thickness, compressibility, specific volume and surface roughness.

Sponging (releasing strains by water or steam) generally reduces subsequent relaxation shrinkage and improves the fabric dimensional stability and minimises adverse changes due to the tailoring process.[117] Ito[118] established the optimum conditions of sponging automatically, using a computer, by measuring the tensile, shear and shrinkage properties of fabrics, using the KESF-1 Auto and KESF-6 Auto (fabric shrink test) instruments.

1.7.3 Effect of garment refurbishing

Garment refurbishing generally refers to the care and maintenance treatments applied to the garment during its use or wear life. It includes laundering (domestic and commercial in aqueous media), dry-cleaning (in solvent media), pressing and ironing.[104] Dry-cleaning changes various fabric mechanical properties, which are related to fabric handle, largely as a result of it changing fabric structure.[119] By and large, dry-cleaning improves the handle of wool fabrics, the fabric becoming more supple, fuller and smoother,[104] with increased extensibility and resilience, and decreased bending, shear stiffness and hysteresis. Nevertheless, the effect will depend upon the dry-cleaning conditions (e.g. solvent and water load used, temperature, mechanical action, pressing, etc.) as well as upon fabric type, history and properties.

Laundering generally tends to increase cotton fabric shear and bending stiffness and hysteresis, and to decrease fabric extensibility, causing a deterioration (increased harshness) in fabric handle,[104] whereas, up to a point, the opposite may be true for acrylic knitwear. Provided the wool does not felt (i.e. has been shrink-resist treated), laundering tends to soften wool fabrics, reducing bending shear stiffness, although this effect may be reversed upon prolonged laundering.

After-wash rinse aids or softeners (mostly cationic surfactants) tend to reduce fabric shear hysteresis (a good measure of the softener effectiveness and durability);[105] the effect depends upon the type of softener, resiliency during compressional deformation being a good indicator of fabric softness.[104]

1.8 General points

Chen and Leaf[120] developed a software program (MECH FAB) to optimise woven fabric structural parameters based on the specifications of the eight most commonly used physical and mechanical properties, including tensile, bending and shear moduli.

Discriminant[121] fuzzy logic[122] and neural network analyses,[123] utilising KES-FB and FAST fabric measurements, have been used to develop models to classify and predict the handle of cotton, linen, wool and silk fabrics. Lam and Postle[124] used stepwise regression analysis to identify two mechanical blocks, viz. surface and compression, which are needed to explain 99% of the total handle value of winter suiting fabrics in terms of smoothness/sleekness and fullness/softness. For summer suiting fabrics, three mechanical blocks are sufficient to explain the primary hand values of crispness, hardness and fullness/softness; the three fabric mechanical blocks are surface properties, tensile properties and bending properties. Park *et al.*[125] found that fuzzy and neural network-transformed overall hand values based upon the KES-FB measured mechanical properties (tensile recovery (CRT), maximum tensile elongation (FMT), compressional recovery (RC), bending rigidity (B), shear hysteresis of 0.5° (2HG), surface roughness (SMD) and weight (W)) agreed better with the subjective test results and the KES-FB values for knitted fabrics. Park and Hwang[126] developed an alternative simplified fuzzy total hand value, based on seven principal KES-FB physical and mechanical properties (EMT, RT, RC, B, 2HG, W and MIU) for double jersey knitted fabrics. Hui *et al.*[127] proposed a novel approach for predicting sensory handle based on fabric properties, using a resilient back-propagation network. They implemented a fuzzy fabric predictor to predict customers' favourable response using 14 subjective handle ratings. Chen *et al.*[128] used a method of fuzzy comprehensive evaluation to solve the problem of grading fabric softness as a measure on the Kawabata KES-FB instruments. Also based upon the KES-FB measurements, Chen *et al.*[129] proposed a neural network computing technique

Table 1.17 Interrelationship between handle characteristics and fabric properties. Source: Ganssauge *et al.*, 1998[138]

No.	Then direction	Property		Code	Units	If . . . increases	Weight [g/m²]	Weave (float length)	Finish (density) mech. addition	% wool	Yarn/sl dyed (wool)	55/45 wool/PES (piece-dyed)
1	FAST	tensile	extension at 5 N/cm	E5	[%]	warp	↗ ? S	↗ ?				
2					[%]	weft	↘ ? M					S > M
3				EB5	[%]	diagonal	↘ ? M		↘			
4			extension at 20 N/cm	E20	[%]	warp	↗ ? S	↗ ?				
5					[%]	weft	↘ ? M					S > M
6			extension at 100 N/cm	E100	[%]	warp	↗ ? S	↗ ?				
7					[%]	weft	↘ ? M					S > M
8	KES-F		max. extension	EMT	[%]	warp	↗ ? S	↗ ?				
9					[%]	weft	↘ ? M					S > M
10			extension energy	WT	[J/m²]	warp	↗ ? S	↗ ?				
11					[J/m²]	weft	↘					
12			recovery power	RT	[%]	warp		↘	↘		G < S	S > M
13					[%]	weft		↘	↘		G < S	S > M
14			linearity	LT	[–]	warp			↗			
15					[–]	weft			↗			
16	FAST	shear	resistance	G	[N/m]		↗ G M	↘	↗			
17	KES-F		resistance	G	[N/m·rad]	warp	↗ G M	↘	↗			
18					[N/m·rad]	weft	↗ G M	↘	↗			
19			hysteresis at 0.5°	2HG	[N/m]	warp	↗		↗		G > S	S < M

Table 1.17 Continued

No.	Then direction	Property		Code	Units	If . . . increases	Weight [g/m^2]	Weave (float length)	Finish (density) mech. addition	% wool	Yarn/sl dyed (wool)	55/45 wool/PES (piece-dyed)
20					[N/m]	weft	↗		↗		G > S	S < M
21			hysteresis at 5°	2HG 5	[N/m]	warp	↗		↗		G > S	S < M
22					[N/m]	weft	↗		↗		G > S	S < M
23	FAST	bending	length	C	[mm]	warp	↗		↗		G > S	
24					[mm]	weft	↗				G > S	
25			resistance	BS	[μNm]	warp	↗				G > S	
26					[μNm]	weft	↗				G > S	
27	KES-F		resistance	B	[μNm^2/m]	warp	↗				G > S	
28					[μNm^2/m]	weft	↗				G > S	
29			hysteresis	2HB	[μNm^2/m]	warp	↗	↗	↗		G > S	S < M
30					[μNm^2/m]	weft	↗	↗	↗		G > S	S < M
31	FAST	compression	compressibility	ST	[mm]		↗				G > S	
32			fabric thickness at 2 cN/cm^2	T 2	[mm]		↗	↗			G > S	
33			fabric thickness at 100 cN/cm^2	T 100	[mm]		↗	↗			G > S	
34	KES-F	compression	compressibility	EMC	[%]		↗				G > S	
35			fabric thickness at 0.5 cN/cm^2	T 0	[mm]		↗	↗			G > S	
36			fabric thickness at 20 cN/cm^2	T 20	[mm]		↗	↗			G > S	

37			energy	WC	[J/m²]					G > S	
			recovery power	RC	[%]		↘	(↘)			S > M
38			linearity	LC	[–]						
39											
40	KES-F	surface	friction coefficient	MIU	[–]	warp			↘	G > S	
41						weft			(↘)		S < M
42			mean variation from MM	MMD	[–]	warp		↘	(↘)		
43					[–]	weft			(↘)		
44			profile	SMD	[µm]	warp			(↘)		
45					[µm]	weft			↘		
46	KES-F	handle rating	rigidity+ elasticity	Koshi	[–]		↗				
47			soft smooth-ness	Numeri	[–]			↗			
48			bulk and softness	Fukurami	[–]			↗	↗	G > S	
49			soft handle	Sofutosa	[–]			↗	↗		
50	FAST	mouldability		F	[mm²]	warp	↗	↗	↘		
51					[mm²]	weft	↗ G				S > M
52	KES-F	bulk	relative density	SPV	[cm²/g]					G > S	
53		weight	fabric weight	W	[g/m²]			↗			

↗ statistically significant increase, (↗) tending to increase, ↘ statistically significant decline, (↘) tending to decline, G applicable only to yarn-dyed and slubbing-dyed, S applicable only to piece-dyed all-wool, M applicable only to piece-dyed 55/45 polyester/wool, ? relationship appears to be not necessarily valid to predict fabric end use. Fan and Hunter[130] used an artificial neural network model for predicting worsted fabric properties from fibre, yarn and fabric parameters.

Behera and Muttagi[131–133] used artificial neural network (ANN) systems to engineer woven fabrics to achieve the desired physical properties. They concluded[134] that ANN models produced the least errors compared to mathematical and empirical modelling. Wong *et al.*[135] concluded that hybrid models, incorporating traditional statistics and neural networks and fuzzy logic, best predicted overall clothing comfort, including tactile comfort.

Lai and Lin[136] used ten FAST-based physical properties to characterise the generic handle of cotton, linen, wool and silk woven fabrics by means of discriminant analysis and neural networks. Cotton type polyester, linen-textured rayon, wool type polyester and silk-like polyester fabrics could be classified accurately by the neural network method. A similar approach has also been successfully applied using sixteen KES-FB based parameters.[137]

Ganssauge *et al.*[138] gave a table (Table 1.17) to illustrate the relationship between fabric handle and fabric properties.

1.9 Sources of further information and advice

There are various reviews on the topic covered by this chapter, as well as related topics. These include the following:

- The design logic of textile products[98]
- Clothing, textiles and human performance[139]
- Science of clothing comfort[2]
- Fabric objective measurement[17,18,27,36,39,40,44,107,127,140–157,163]
- Fabric handle[44,115,127,140–163]
- Modelling fabric mechanics[157,164]
- Advances in apparel production.[165]

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2
Wrinkling of fabrics and garments

L. HUNTER

Abstract: The various methods of measuring wrinkling performance and crease recovery, particularly recent developments in quantifying the severity of wrinkling, are discussed in this chapter. The influence of fibre, yarn, fabric and dyeing and finishing parameters on wrinkling, and ways in which wrinkling performance can be improved, are treated in detail. Attention is given to the particular role and importance of the fibre visco-elastic and inter-fibre frictional properties in wrinkling.

Key words: wrinkling, crease recovery, fibre visco-elastic properties, frictional couple.

2.1 Introduction

Wrinkling may be defined as the unwanted residual bending deformation, largely random in nature, which occurs during wear and which does not disappear spontaneously, resulting in wrinkles or creases which can make the fabric appear unsightly.[1] All textile apparel fabrics bend and fold with remarkable ease during wear and laundering,[2] often to relatively high curvatures. This pliability, so important in wear, comfort and aesthetics and garment construction and shape (form), leads to wrinkling. This tendency for a fabric or garment to wrinkle or crease when subjected to sharp folds (bends, creases or wrinkles) under pressure (load) during wear or laundering also has a bearing on 'ease-of-care' related properties (durable press, easy-care, minimum-iron, after wash appearance, etc.).

Two types of wrinkles usually occur in garments during wear, viz. pressure (sharp) wrinkles and movement (rounded) wrinkles[2] (Table 2.1). They are normally confined to small areas and specific locations in the garment. A distinction can be made between sharp compressive wrinkles, typical on trouser and skirt seat areas (this category includes the wrinkles formed at the back of knees while sitting), and the more rounded low-density wrinkles caused by repeated flexing, typical of the sleeves of coats, laps of trousers and at the back of shoulders. The pressure wrinkles are usually produced when the wearer sits and creases the fabrics, and are sharp and *numerous*.[1] The movement wrinkles are produced when the wearer bends and are

Table 2.1 General details of wrinkles that occur in wear. Source: Smuts, 1989[2]

Type of wrinkle	Wrinkle forming mechanism	Nature of wrinkles	Location and orientation of wrinkle w.r.t. fabric direction
Compressional wrinkles	Fabric is compressed between body and another surface or between two different parts of the body. Pressure relatively high	Sharp, high frequency	Back of blouse – random. Trouser seat – bias and across warp. Skirt seat, trouser crotch, skirt tail – random. Trouser behind the knee – across warp.
Movement wrinkles	Repeated flexing	Rounded, low frequency	Generally found in coat sleeves, skirt laps, trouser knees and trouser lap (front). Generally horizontal and perpendicular to axis of bending and therefore across warp yarns.

frequently accompanied by bagging. These wrinkles are formed in those areas where the fabric is compressed between two parts of the body as a result of body movement.[1] An essential difference between the two main types of wrinkles is that on a pair of normally-worn trousers, the sharp wrinkles predominate at the back of the trousers, while the rounded type predominate at the front of the trousers. The sharper types of wrinkles are probably the most bothersome and are the ones usually simulated in laboratory tests.

In effect, it is not so much the ability of the fabric to withstand creasing or wrinkling which is important in appearance, but rather its ability to regain its original shape and smooth appearance from such creases and wrinkles, i.e. its wrinkle or crease recovery, which is important. Therefore, in testing 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, time, temperature, humidity and moisture content, 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 untreated cellulosic fibres, such as linen and cotton, and considerable research and development work over many decades has been directed towards developing chemical treatments which improve this property without an unacceptable loss in other desirable properties, such as softness, comfort and durability.

2.2 The measurement of wrinkle and crease recovery

In most cases, it is wrinkle or crease recovery which is measured rather than wrinkle resistance. There are various test methods for measuring fabric wrinkle and crease recovery,[3] it being possible to divide these into two broad categories, namely those which involve the insertion of a single sharp crease (fixed deformation) and those which insert a family of largely random creases or wrinkles (random deformation) 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 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. Wear trials represent a third category of assessing wrinkling performance. It is important to mention that the results generated by the different test methods are often not very highly correlated.

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 largely random wrinkles are induced in the fabric under standard atmospheric conditions using a standard wrinkling device under a predetermined load for a prescribed period of time. The specimen is then re-conditioned and rated for appearance by comparing it with three-dimensional reference standards (AATCC Wrinkle Recovery Replicas). The same method has been adopted by Japanese industry and the International Organisation of Standardisation. Nevertheless, the method suffers from the disadvantage that it is subjective and that fabric colour and pattern have a significant effect on the perception of wrinkles; in fact, Qiu and Yang[4] recommended that this test method be revised. Considerable research has led to the development of objective assessment techniques, including computer vision (photometric stereo technology combined with ANFIS-adaptive neural fuzzy inference systems), for evaluating the fabric wrinkle grade objectively. Fan *et al.*[3] and Hunter[5] 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 this, the load is removed and the specimen allowed to recover, once again under specified conditions and times (e.g. 5 min), and the recovery angle (crease recovery angle) is measured. Test methods include AATCC 66, BS EN 22313 and ISO 2313. This test is frequently used to assess durable-press and easy-care related properties of treated cotton fabrics.

Yang and Huang[6] and Kang *et al.*[7] reviewed objective methods for evaluating fabric wrinkling and reported on a photometric stereo method and a wavelet-fractal method, respectively, which they proposed.

2.3 Surface smoothness after repeated laundering[3,5]

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.

2.4 Factors affecting fabric wrinkling and recovery

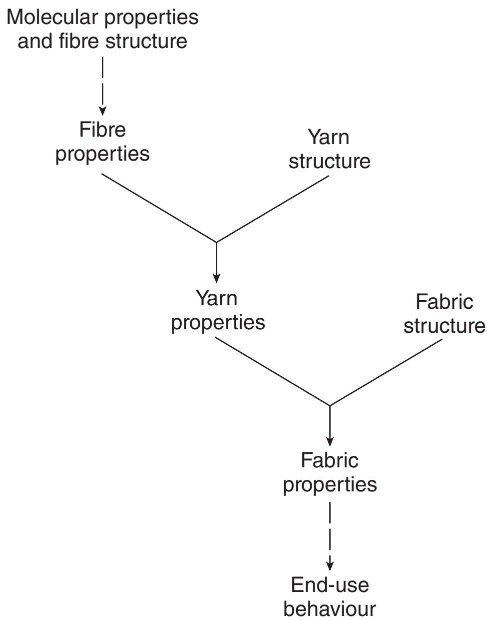
Figure 2.1[8] illustrates the interrelationship between fibre, yarn and fabric properties, while Table 2.2[9,10] lists the various fibre, yarn and fabric parameters that play a role in wrinkling and wrinkle recovery. This will be dealt with in detail in the following sections.

Essentially, the wrinkle recovery properties of a garment can be improved in two ways:[2]

- Micro level: by modification of the fibre at molecular level, for example by changing fibre type and chemical/amorphous structure and by chemical treatment; also by annealing, in the case of fibres such as wool.
- Macro level: by constructing the yarn, fabric and garment in such a way that either the strains imposed during bending (use) or the interactions between fibres and yarns, or both, are minimised.

Behera and Mishra[11] reported on the various fibre, yarn and fabric parameters influencing fabric appearance, including wrinkling.

Simply stated, the yarn and fabric construction largely affect the frictional couple, and to some extent the nature and severity of the fibre deformations when the fabric is deformed during use.



2.1 Interrelationship between fibre, yarn and fabric structure and fabric properties. Source: Hearle *et al.*, 1969[8]

Table 2.2 Fibre, yarn and fabric parameters that influence wrinkling. Source: Leeder, 1976, 1977[9,10]

Fibre	Yarn	Fabric
Type	Type	–
Visco-elastic bending parameters	Ply and twist level	Weave structure and crimp
	Twist direction	Mass per unit area
Visco-elastic torsional parameters	Crimp	Thickness
	Cross-sectional shape	Surface hairiness
Cross-sectional shape	Linear density	State of relaxation (i.e. energy state)
Crimp	Diameter	
Diameter	Lateral pressures	Sett
Diameter distribution	Construction	Compactness
Friction	(e.g. woollen-spun,	Mechanical finishing
Chemical or physical treatment	worsted-spun, friction-spun, etc.)	

2.5 Factors affecting wrinkling during wear[2,12]

The most important wear related factors that influence the wrinkling (including type of wrinkles formed) of fabrics or garments during wear are as follows,[2] the importance and magnitude depending upon various other factors, notably the fibre type:

(i) The temperature of the fabric in contact with the body.
(ii) The moisture content of the fabric in contact with the body.
(iii) The pressure which deforms the fabric and the sharpness of the wrinkle or crease inserted by the applied pressure.
(iv) The time the fabric is deformed, and the time of recovery, wrinkling being worse when subsequent recovery is at a lower RH and temperature.
(v) The time the fabric is in a particular atmosphere before wrinkling commences.
(vi) The number of times the fabric is deformed (bent or creased) in the same locations (regions).
(vii) The actual changes in atmospheric conditions (or in the fibre regain and temperature) and associated de-ageing effects, as well as the aged state of the fabric, relative to the conditions prevailing during wrinkling. These are important considerations, more particularly for wool and other animal fibres.
(viii) The conditions during wear – this pertains to environmental conditions before, during and after creasing. Ageing/de-ageing phenomena can also be included, particularly for fabrics containing animal fibres, such as wool and mohair.
(ix) Factors relating to the wearer, e.g. activity, size and shape of the wearer.
(x) Wearer and garment interactions, e.g. garment fit, cut, style, activity of the wearer, etc. In other words, the nature of the garment– wearer system. The fact that some people are ‘more severe’ wrinkles than others simply means that they get their garments over the threshold above which wrinkling is noticeable more easily. Leeder[9,10] stated that this must be accepted as part of the phenomenon of wrinkling, and attempts must be made to produce fabrics having a higher threshold level, so that all wearers will notice the improvement.

Chapman and Hearle[13] have subdivided the mechanical deformations in fabrics that lead to wrinkling into the following three types:

- Pure bending
- Creasing
- Buckling.

When the fibres in a folded or bent fabric are subjected to pressure (strain) during wear or laundering, particularly in the presence of moisture and heat for prolonged periods, they invariably retain a certain degree of residual deformation after removal of the deforming forces. The residual deformation largely depends upon the fibre visco-elastic properties and to a lesser extent on the frictional couple or coercive couple (M). In addition, it is greatly dependent upon the degree (severity) and duration of the original deformation and the conditions of temperature and moisture prevailing during and after the actual deformation. This residual (unrecovered) deformation which occurs during garment wear and use, and which is generally of a random nature, is termed wrinkling. The most severe form of wrinkling generally occurs under conditions of sharp deformation (bends and creases), for a prolonged time and under conditions of high humidity and temperature. Wrinkling occurs because the deformation forces imposed during wear generally far exceed the resistance of the fabric to bending, and the subsequent recovery forces are generally inadequate to overcome the forces opposing complete recovery (i.e. return to the undeformed state).

Fibres cannot be regarded as perfectly elastic: during bending (or stretching) they undergo stress-relaxation; when allowed to recover they show an instantaneous partial recovery followed by a slow time-dependent recovery, the latter being characteristic of visco-elastic materials. The greater the stress-relaxation is, the poorer the wrinkle-recovery.

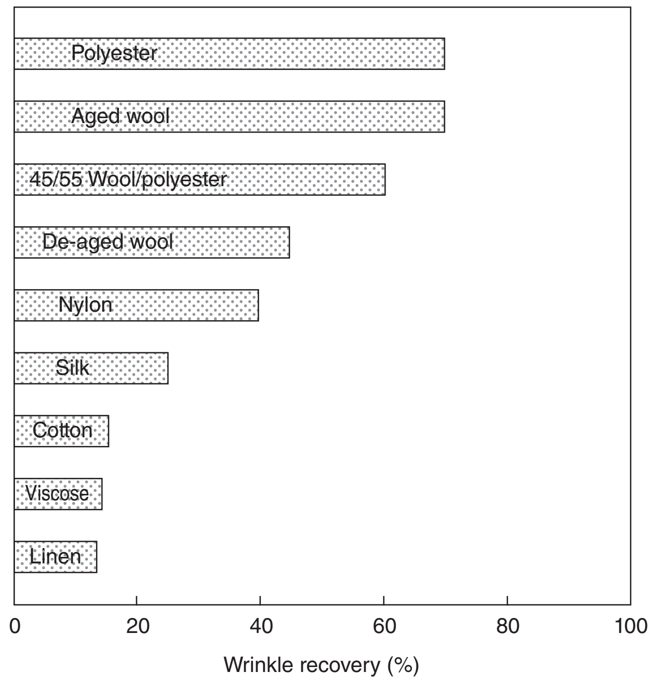
2.6 Effects of fibre properties

Fibres undergo complex deformation during wrinkling, involving bending, twisting, extension and compression, although single fibre bending is considered to be the main factor in wrinkling.

Fibre type, in terms of its visco-elastic properties, which can be affected by ageing, annealing and glass transition temperature (Tg) versus humidity and temperature relationships and chemical modification has a major effect on fabric wrinkling. Wrinkling is closely related to fibre mechanical properties, such as resilience and elastic recovery, essentially as manifested in the visco-elastic (rheological, elasto-viscous, etc.) nature of the fibres.

Figure 2.2[9] and Table 2.3[14] show the relative wrinkling properties of different fibre types. The ideal fibre, in terms of good wrinkling performance, should have the following properties:

- Good elasticity and elastic recovery
- High resilience
- Good flexibility
- High glass transition temperature (Tg), also under moist and wet conditions.

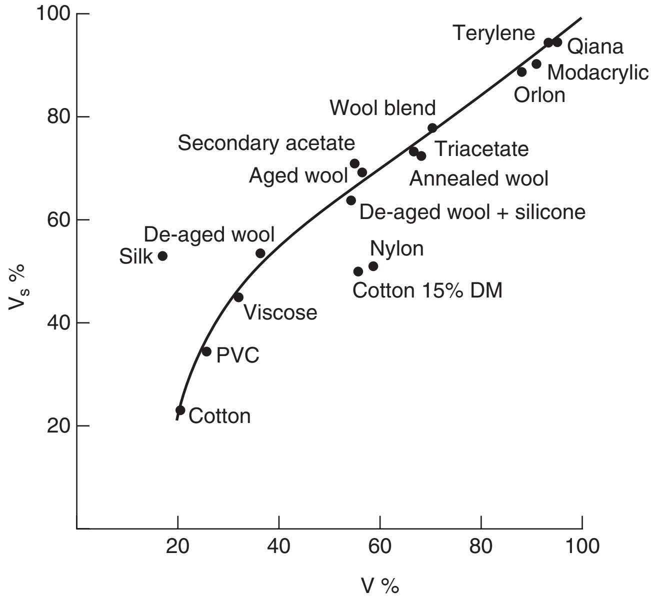


2.2 Relative wrinkle recovery of fabrics made from different fibre types. Source: Leeder, 1976[9]

Table 2.3 Rating of fibres in respect of recovery from dry creasing. Source: Taylor, 1972[14]

Poor	Fair	Good	Very good
Acetate	Silk (tussah)	Acrylic	Polyester
Cotton	Triacetate	Modacrylic	Regenerated protein
Rayon	Polyvinyl chloride	Nylon polypropylene	Wool
		Silk (Bombyx)	

The wrinkle recovery of untreated cellulosic fabrics is poor due to the disruption of inter- and intra-chain hydrogen bonds by moisture,[15] which reform to stabilise the wrinkled (creased) state. Sarvani and Balakrishnaiah[16] stated that the creasing behaviour of cellulosic fabric may be directly linked to the ability of the free hydroxyl groups in the amorphous region to get bound to each other. Wrinkle resistance is generally achieved[17] by cross-linking adjoining cellulose polymer chains, which increases flexibility and resilience.



2.3 Visco-elastic component obtained by a shortened test (V_s) plotted against the visco-elastic component (V) obtained in the conventional way. Source: Chapman, 1976[18]

As already mentioned, the visco-elastic properties of the fibres have the greatest effect on the wrinkling behaviour of a fabric. The relative performance of various fibre types (in terms of their visco-elasticity) is illustrated in Fig. 2.3.[18] The glass transition temperature (Tg) of a fibre plays an important role in wrinkling, since it is at this temperature that the behaviour of an amorphous polymer changes from 'glass-like' to 'rubber-like', and changes quite drastically when subjected to bending and other deformations. The higher the Tg, also under conditions of high humidity or moisture content, the better in terms of wrinkling performance. The Tg values of various fibres under different conditions are given in Table 2.4.[19]

It is important to note, however, that the visco-elastic component combines with the frictional component to give the coercive couple just defined. For a well relaxed fabric comprising highly wrinkle-resistant fibres, the frictional couple is small and does not play nearly as an important a role in wrinkling as the fibre visco-elastic properties. This is not the case for fibres with a low resilience (recovery). Table 2.5[18] illustrates this for different fibres and fabrics. F is the 'pure' frictional component of fabric recovery and V the visco-elastic component of recovery of the fabric, it being better to express fabric wrinkling in terms of the two separate components rather

Table 2.4 Glass transition temperatures of various fibres. Source: Fuzek, reprinted with permission from 'Water in Polymers', ACS Symp. Series 127, Copyright 1980 American Chemical Society[19]

Fibre	Transition temperature Tg,°C			Difference in Tg between conditioned and wet
	Dry	Conditioned	Wet	
Polyester (PET)	73	71	57	14
Nylon 6.6	59	40	29	11
Nylon 6	–	41	28	13
'Qiana' nylon	175	150	90	60
'Orlon' acrylic	–	97	30	67
'Verel' modacrylic	–	59	38	21
Acetate	118	84	30	54
Silk	197	108	30	78
Wool	165	60	≈0	60

Table 2.5 Frictional (F) and visco-elastic (V) components of wrinkle recovery. Source: Chapman, 1976[18]

	Long test		Short test		
Fabric type	V %	CV %	V %	CV %	F %
(1) Wool (aged)	57.3	4.3	70.1	4.6	3.6
(2) (De-aged)	36.7	2.6	54.0	2.1	3.6
(3) Silicone treated (de-aged)	55.0	4.3	64.2	2.9	1.8
(4) (Annealed)	68.2	1.4	73.7	2.5	3.3
(5) Terylene (polyester)	93.8	1.0	95.3	0.3	4.2
(6) 55% wool/45% Terylene blend (de-aged)	71.5	1.7	78.5	1.4	7.6
(7) Nylon	59.3	2.5	51.9	1.2	13.8
(8) Cotton	20.8	6.5	23.5	4.1	12.9
(9) Cotton (+15% DMDHEU)	56.4	5.1	50.2	2.1	14.3
(10) Silk	17.8	37.5	53.7	6.0	9.0
(11) PVC	26.1	9.2	34.6	5.2	12.5
(12) Viscose	32.2	6.9	45.2	2.9	6.9
(13) Qiana	95.6	0.7	95.1	0.7	12.5
(14) Orlon	88.6	1.4	89.9	1.0	8.8
(15) Secondary cellulose acetate	55.7	4.7	71.5	2.2	8.2
(16) Modacrylic	91.8	0.9	90.9	1.4	21.8
(17) Triacetate	67.5	3.0	74.0	1.3	7.0

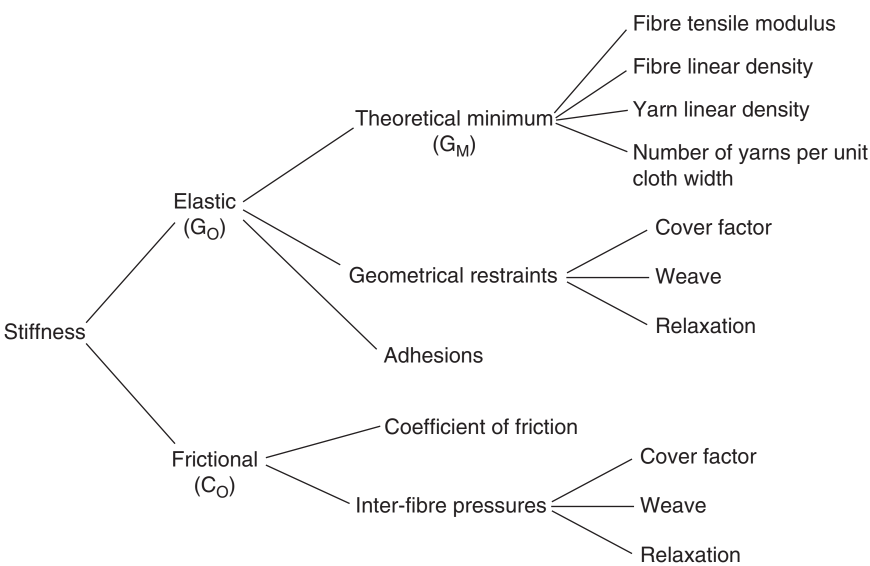
CV = Coefficient of variation

than in terms of a combined component, such as R = V − F, termed the 'wrinkle recovery'. For optimum wrinkling properties, V should be at a maximum and F at a minimum. The factor F/V, called the frictional residue,[20] determines the frictional recovery of the fabric and is considered as important as either V or F since it and V set an upper bound limit beyond which a fabric can never recover. The visco-elastic behaviour of materials can be described in terms of two basic elements, namely a spring (i.e. elastic) and a dash-pot (i.e. viscous).

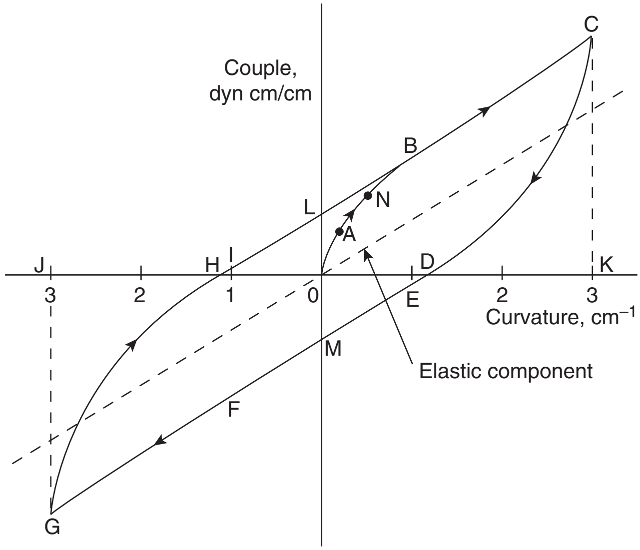
Silicone treatment represents a good example of a way to reduce F, but proper fabric relaxation and setting are still considered to be the best ways and most practical to reduce F and thereby improve wrinkling performance.

2.7 Effects of yarn and fabric parameters

In the main, yarn and fabric parameters affect wrinkling in as much as they affect (i) the freedom of fibre movement, (ii) inter-fibre frictional forces (frictional coercive couple), both within the yarn and within the fabric and (iii) the degree of fibre deformation during the fabric deformation occurring during wrinkling. These are related to the factors affecting fabric bending stiffness, illustrated in Fig. 2.4.[21] In essence, therefore, fabric wrin-



2.4 Factors contributing to fabric stiffness and coercive couple. Source: Owen, 1968[21]



2.5 Typical bending-hysteresis curve for woven fabric. Source: Owen, 1968[21]

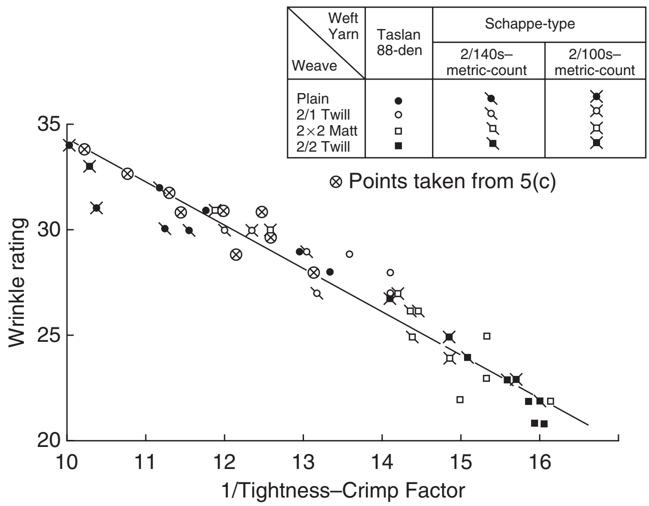
kling can be reduced by reducing the frictional (coercive) couple, represented by LM/2 in Fig. 2.5,[21] which shows a typical bending-hysteresis curve for a woven fabric.

The effect of yarn twist on wrinkle recovery is not clear cut, contradictory results having been reported in the literature.[2] It therefore appears that changing the yarn twist is not an effective way to improve wrinkling, although very high twist levels are believed to effect some improvement in wrinkling. Similar considerations apply to yarn linear density, although, if fabric mass is kept constant, coarse yarn should improve wrinkling because of the associated increase in fabric thickness and decrease in fabric tightness.

The frictional resistance in a fabric is determined by:[22]

- The ratio of the relative fibre and yarn movement to the fabric deformation (determined by yarn and fabric geometry).
- The forces between fibres and yarns at intersections (largely determined by the state of relaxation of the fabric).
- The coefficient of friction between fibres and between yarns (determined by the fibre type and surface characteristics, as well as by the presence of softening agents and lubricants).

Probably, the state of relaxation (i.e. stress relaxation) of the fabric and freedom of yarn movement (mobility) are the two main fabric parameters



2.6 Effect of tightness-crimp factor on wrinkle rating of woven nylon shirtings. Source: Sudnik, 1966[23]

affecting fabric wrinkling performance, their effect depending upon the recovery properties of the fibres. All other factors being constant, fabric wrinkling improves with an increase in fabric mass, fabric thickness and relaxation, and with an increase in yarn mobility, the last being related to fabric tightness (cover factor) and yarn float length (number of yarn intersections per unit area). It appears that fabric wrinkle recovery increases as sett, and therefore fabric tightness, decreases, up to a certain point of approximately 10% below maximum sett, after which it levels off or disappears. The effect of fabric weave structure on wrinkling depends upon fabric tightness and float length, twill weaves being better than plain weave, for example.

An increase in weave crimp accompanied by a decrease in interstitial pressures decrease shear modulus, resulting in a concomitant improvement in wrinkling. The relationship between wrinkle rating and fabric tightness and crimp is illustrated in Fig. 2.6 for nylon shirting fabrics of different weave structures.[23]

According to the classical buckling theory[8] the wavelength (λ) of the wrinkles in a thin-walled fabric tube (such as for example a trouser leg) is related to the fabric thickness (t) and diameter (D) of the sleeve as follows:

$$\lambda = 1.7\sqrt{tD} \qquad [2.1]$$

Therefore, at a constant fabric mass, the use of coarser yarns together with the required lower sett, would provide better wrinkling performance than the use of finer yarns and higher sett. Furthermore, the use of a weave structure with fewer intersections (longer float lengths) is to be preferred in terms of wrinkling performance.

Although the variations in yarn and fabric structural variables are unlikely to effect large improvements in wrinkle recovery, it is possible to effect significant improvements by optimising them. The following lists the ways in which this can be achieved:

- Decrease cover (tightness) factor, up to a certain point
- Increase float length.

Zaouali *et al*.[24] investigated the effects of various parameters on the wrinkling of fifty different fabrics, concluding that the fibre composition, fabric weight, weave, drape and warp and weft densities were important.

2.8 Effects of fibre, yarn and fabric processing parameters

2.8.1 Fibre processing parameters

Essentially, any treatment (for example cross-linking and resin) that improves the resilience (i.e. recovery from bending and torsional deformation) of the fibre has a beneficial effect on wrinkling. Relaxation of internal stresses in the fibre also improves wrinkling performance. Ultimately, to effect an improvement, the treatment (usually chemical) needs to increase the ability of the fibre to return to its undeformed state, i.e. the state prior to the wrinkling deformation. Furthermore, any treatment that makes the fibres less sensitive to the effects of heat and moisture, for example increasing the glass transition temperature (Tg), also in the presence of moisture, will have a beneficial effect on wrinkling performance.

2.8.2 Yarn processing parameters

Yarn processing parameters have limited potential in terms of changing wrinkling performance, except insofar as they affect the fibre parameters referred to above, and the inter-fibre frictional component (F). A treatment (e.g. silicone) that reduces the frictional couple (Mo or F) will have a beneficial effect on wrinkling performance. Changes in yarn twist can have a similar effect.

2.8.3 Fabric processing parameters

Ignoring for the moment those fabric processes which affect the fibre resilience *per se* (see Section 2.8.1), any process which improves the fabric relaxation, reduces the frictional couple (F) and improves the fabric elastic recovery (resilience) (for example, resin treatment) will have a beneficial effect on fabric wrinkling performance. Thus, for example, autoclave decatising of wool fabrics improves their wrinkling performance, and so does heat setting of fabrics containing thermoplastic fibres, such as polyester and nylon. Nevertheless, care must be exercised in the case of multi-component blends where certain of the blend components (e.g. natural fibres) could be damaged by the high temperatures required to set the synthetic fibre components. For example, Ranganathan[25] stated that wool/polyester blends should be heat set at 170 to 190°C for 30 seconds for good results. According to Leeder,[26] the wrinkle recovery of wool fabrics can be improved by the following general types of chemical treatments:

- Cross-linking with difunctional reagents
- Cross-linking with large amounts of poly-functional resins and polymers
- Stabilisation treatments with reactive metal salts
- Incorporation of bulky molecules which exclude water from the wool structure at high humidities.

Ageing and annealing of wool and other animal fibre fabrics, and any treatments which fix such an aged or annealed state, will have a beneficial effect on the fabric wrinkling performance.

The first recorded easy-care product was reportedly[27] a non-iron fabric finish for cotton developed in 1928 by the Tootal Broadhurst Lee Co. Ltd. in England.

Care, however, must be taken that any treatment does not too adversely affect the desirable properties of wool, notably comfort, durability and handle. The application of external polymers, such as polyurethane and silicone elastomers, can beneficially affect fabric wrinkling performance. Polymers that substantially improve wrinkle recovery generally fall into the class of elastomers, having high elastic recovery, high glass-transition temperatures and low permanent set.[28] Such polymers can improve wrinkling performance by reducing inter-fibre frictional forces (i.e. F) and by the introduction of elastic polymer-bonds between fibres which do not stress-relax, thereby assisting recovery after deformation. Such surface polymers can also impede the flow of moisture in and out of the fibre[29] and add an elastic (resilient) component to the fabric (elastic cover/sheath to the fibre and/or elastic inter-fibre bonds). Various other authors have discussed chemical treatments to improve the wrinkling performance of fabrics,

Table 2.6 Ways of improving fabric wrinkling performance

Parameter	
Fibre	
Type	Use resilient fibres (e.g. polyester, nylon, wool) which are insensitive to temperature and moisture.
Fineness	Coarser fibres preferable (small effect).
Glass trans. temp. (Tg)	Higher Tg, also under high moisture conditions, advantageous.
Visco-elasticity (V)	Good visco-elastic properties are critical.
Inter-fibre friction	Reduce inter-fibre friction, particularly for fibres with relatively poor visco-elastic properties.
Yarn	
Construction	Select constructional parameters so as to reduce inter-fibre frictional forces (small beneficial effect).
Linear density	Coarser yarns slightly better.
Twist	Effect of twist unclear, very high levels sometimes considered beneficial.
Fabric	
Construction	Looser structures (lower tightness within certain limits), longer float lengths and thicker fabrics preferable.
Blend and fibre type	Judicious selection of blend components. Fibre composition critically important.
Finishing	
Frictional	Reduce inter-fibre frictional forces and/or replacing the inter-fibre frictional forces by elastic inter-fibre bonds.
Visco-elasticity	'Internal' resin and polymer treatments which, by cross-linking etc., improve the elastic recovery from deformation of the fibres. 'External' (surface) resin and polymer treatments which coat the fibres with an elastic sheath.

notably those of cotton by cross-linking,[30,31] with an increasing emphasis on formaldehyde-free treatments (e.g. ionic crosslinking[31] and citric acid), and reducing strength losses (i.e. durability).

Huang *et al.*[32] reported the use of mixed sol–gel solutions to improve the wrinkling of cotton fabrics. Yuen *et al.*[33] reviewed the evolution of the wrinkle-free finishing of cotton fabric up to the newly developed nanotechnologies.

2.9 Sources of further information and advice

Kernaghan *et al.*[15] recently reviewed the crease recovery treatment of linen fabrics, and Lo *et al.*[34,35] reviewed the basics of wrinkle formation and wrinkle resistance mechanisms for cellulosic fabrics. Hu[36] discussed modelling wrinkling properties with visco-elastic theory.

2.10 Concluding remarks

Fabric wrinkling is largely dependent upon the visco-elastic properties (V) of its component fibres, and to a lesser extent on the frictional couple (F), the former being largely a function of the fibre type and chemical treatment (e.g. resin) applied to it, and the latter, i.e. F, being largely a function of the state of relaxation of the fabric and inter-fibre frictional forces and elastic bonds. The effect of F is less for highly elastic (resilient) fibres. Table 2.6 presents a summary of the factors that affect wrinkling, as well as ways of improving wrinkling performance.

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3
Pilling of fabrics and garments

L. HUNTER

Abstract: This chapter deals with the pilling of fabrics and garments, and the influence that various fibre, yarn, fabric and dyeing and finishing parameters have on pilling. Developments in the testing of fabrics for pilling propensity and the quantitative evaluation of the pilled appearance of the fabric after the test are covered in detail. The effects of various chemical and mechanical treatments on pilling, as well as ways of reducing pilling, are also dealt with.

Key words: pilling, pill formation, pilling evaluation, reducing pilling, testing pilling propensity.

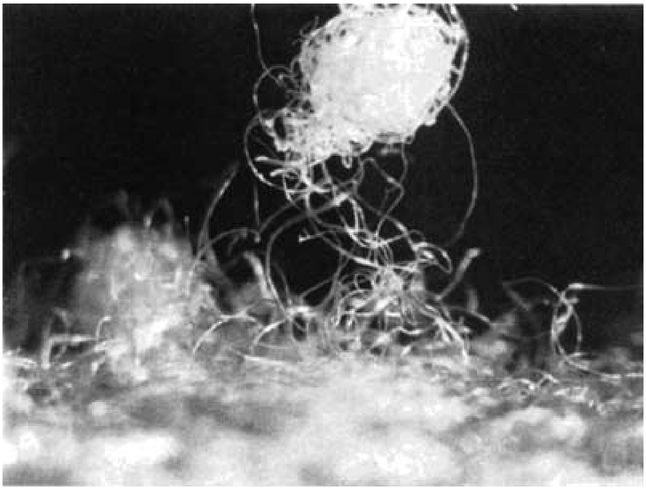
3.1 Introduction

3.1.1 Definition of pilling

Pilling is defined[1] as 'the entangling of fibres during washing, dry cleaning, testing or in wear to form balls or pills which stand proud of the surface of a fabric and which are of such density that light will not pass through them (so that they cast a shadow)'. A pill is therefore a cluster or entanglement (bundle) of fibres in the form of a ball, attached to the fabric surface by one or more 'anchor' fibres (see Fig. 3.1),[2] sometimes also incorporating lint or foreign matter. Pilling, when it occurs, represents a serious quality problem, particularly in apparel and upholstery fabrics, and can be the reason why a product becomes 'unsightly' and no longer acceptable for further use. Although pilling is an unacceptable fabric fault or weakness, it is often a necessary 'trade-off' when a high degree of softness is required, which generally comes associated with increased pilling propensity. Furthermore, when 'easy-care' is required, strong synthetic fibres with a long flex-life are often blended with weaker natural fibres, such as wool and cotton, with the synthetic fibre anchoring pills to the fabric, preventing them from wearing off.

3.1.2 Pill formation

In order for pills to form, a sufficient density (and length) of fibre ends (hairs) is required on the fabric surface so that they can entangle during mechanical

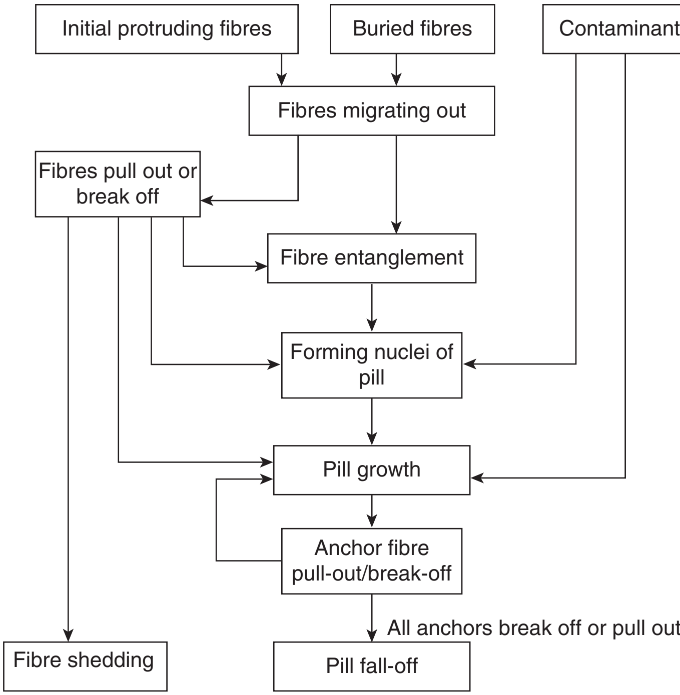


3.1 A typical pill in knitted fabric. Source: Anon., 1972[2]

action (such as rubbing) applied to the fabric surface. Therefore, pilling cannot occur where the fabric contains continuous filament yarns unless the fabric is subjected to a treatment which breaks the filaments on its surface.

Mechanical action applied to the fabric surface, for example the rubbing action during wear or cleaning, or even during dyeing and finishing, can cause the surface fibres to break and become entangled into clusters or balls (i.e. pills). The mechanical action can also cause fibres to migrate to the fabric surface (i.e. to be pulled out from the body of the fabric) and to extend further from the fabric surface until the density and length of surface fibres (fuzz or hairs) are such that further mechanical action (frictional forces) causes them to become entangled into pills which remain attached to the fabric by one or more fibres. Often loose fibres, or even contaminants, on the fabric surface form part of the pill formation process and pill. Pilling generally takes place in the following stages:

(i) Formation of fabric surface fibres (fuzz) of sufficient density and length, in most cases also involving migration of fibres from the body of the fabric to the surface.
(ii) Entanglement of the surface fibres, sometimes together with loose fibres and/or contaminants, to form fairly solid balls or clusters of fibres (pills).
(iii) Wearing-off of the pills due to continued mechanical action. Generally pills are removed during wear as a result of the anchoring fibres being pulled out of the fabric or breaking; flex-life is a critical factor in the latter case, and fibre length and binding in the former case.



3.2 The pilling process. Source: Miao, 2004[3]

All three of the above factors play an important role in determining whether a fabric is acceptable or not from a pilling perspective. For example, a fabric with a high rate of pill formation (Stage (ii)) and a rapid rate of pill wear-off (Stage (iii)), which is often the case for relatively weak natural fibres, is generally preferable to one having a slow rate of pill formation and wear-off. The latter is typically the case for strong synthetic fibres, such as polyester, nylon and acrylic. The pilling process is illustrated in Fig. 3.2.[3] The rate and severity of these stages are dependent upon a number of fibre, yarn and fabric parameters which will be discussed later.

3.1.3 Laboratory measurement of pilling

A great deal of research effort, over many decades, has gone into the laboratory evaluation of a fabric's potential to form pills, i.e. to predict or anticipate the pilling propensity during wear, and more than twenty different test methods have been developed. It has proved extremely complicated, since, in essence, tests require that the test conditions simulate the conditions prevailing during use, which are not only extremely diverse and inconsistent but also very difficult to simulate. It is therefore hardly surprising that, even today, no single pilling tester or test method is universally accepted as providing a reliable measure of the pilling propensity of a fabric in the various end-use applications. What has rather happened is that certain testing instruments and methods have received a greater acceptance than others, for a specific type of end-use and/or fabric.

Generally, there are two aspects to the laboratory measurement of pilling, namely the specific conditions required to produce or simulate those to be encountered by the fabric in use and secondly the measurement or quantifying of the severity or degree of pilling. These two aspects have been researched in great depth, often independently. Some laboratory tests measure the flex abrasion properties (over a wire) of fibres, which provides a measure of the inherent pilling propensity of the fibre.

3.1.4 Pilling test methods and instruments

A large number of pilling test instruments and associated methods (ISO EN BS12495) have been developed and these have been covered in detail elsewhere.[2–4] In brief, pilling testers utilise a rubbing/abrading action, generally flat, or a tumbling action, to develop the pills. Examples of the former include:

- Martindale Abrasion Tester
- Stoll Quartermaster Universal Wear Tester (e.g. using an elastomeric friction pad)
- Brush and Sponge Pilling Tester

Examples of pilling testers based upon a tumbling action are:

- Random Tumble Pilling Tester
- ICI Pilling-box.

Generally, the tumbling-type pilling testers are used (but not exclusively so) for knitted fabrics, and abrasion-type pilling testers for woven fabrics. Suffice it to say that the correlations between the results obtained on the different pill testers, and those between the pill testers and actual wear, as well as the corresponding ranking of fabrics, vary greatly, depending upon the fabric type and construction, and the actual testing and wear conditions involved.

3.1.5 Quantification of pilling

Traditionally, the pilling induced on the fabric sample during laboratory testing has been assessed (i.e. quantified) subjectively by a rating system, often with the aid of photographic standards. Objective methods used involve the number, size and weight of pills, for example, counting and sizing the pills, shaving them off and weighing them. Instrumental methods of quantifying the degree of pilling have received considerable attention and research, particularly over the past two decades or so. This has been reviewed by Fan *et al.*[4,5] and Ukponmwan *et al*.[6] In essence, two approaches have been used, namely laser scanning and triangulation and image processing. Analysis methods include wavelet transforms and Fourier. Commercial systems recently introduced include the Pill-Grade (Line Tech/SDL-Atlas) and the Opti-Grade SET (Roaches International/Marks and Spencer/Shenkar College). Nevertheless, as yet, no instrumental method of quantifying pilling has generally been adopted, subjective measurement still being the norm, although it is undisputed that this will change and that the use of instruments for this purpose will increase and become the norm one day.

3.1.6 Factors that affect pilling

There are many factors that affect pilling in use, including the following:

- End-use
- Wear conditions
- Washing and dry-cleaning conditions
- Fibre properties
- Yarn properties
- Fabric properties
- Fabric finishing
- Relative humidity.

The rate at which the three different stages of pilling (i.e. fuzz formation, pill formation and pill wear-off) occur depend upon fibre, yarn and fabric properties, and their interactions. These will now be discussed in turn.

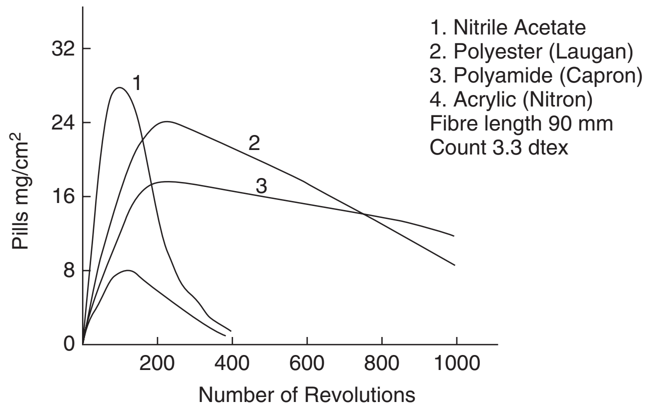
3.2 Effects of fibre composition and properties

3.2.1 General

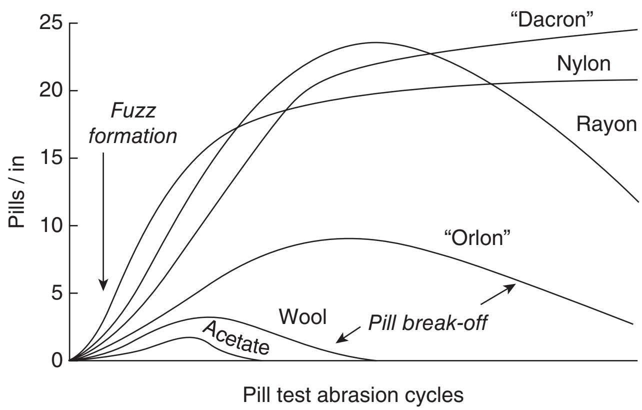
There can be little doubt that fibre composition and properties play a major role in both the formation and wear-off of pills. This is illustrated by Figs 3.3[8] and 3.4.[7]

Gintis and Mead[7] summarised the effect of fibre properties on pilling in Table 3.1.

Fibre fatigue resistance, usually a combination of bending (flexing) and torsion, plays a crucial role in pilling, being illustrated for a modified polyester in Fig. 3.5.



3.3 Test results showing maximum pilling of various fabrics. Source: Cooke, 1985[8]

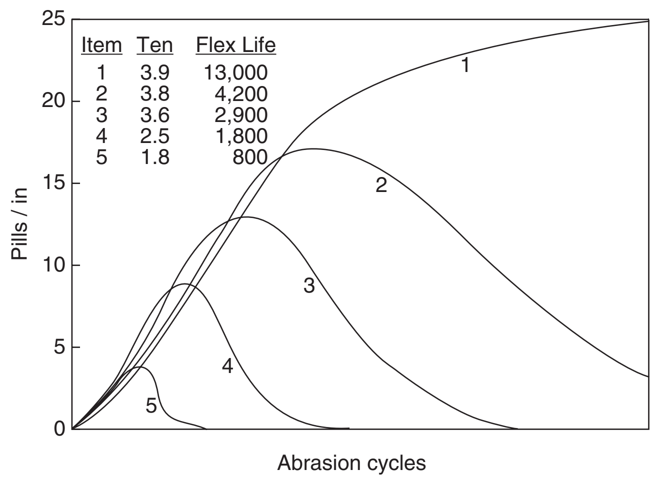


3.4 Pilling of various fabrics. Source: Gintis and Mead, 1959[7]

For pills to form, it is necessary to have a sufficient density and length of fibre ends (hairs) projecting from the fabric surface. It could be that this is already the case in the finished fabric or garment, i.e. before they are subjected to wear or testing, or else surface fibres are created during wear and testing due to fibre ends migrating to the fabric surface and the length of the surface fibres thereafter increasing as a result of a mechanical (rubbing/abrasion) action on the fabric. Most commonly, both already-existing protruding fibres and fibre migration lead to the surface fibres and fuzz, which then form pills during the next stage. Fibre properties that play a role in pilling (including surface hairs and fuzz formation) and hair effects are discussed below (see also Table 3.1).

Table 3.1 Fibre properties affecting the stages of pilling. Source: Gintis and Mead, 1959[7]

Stage			Fibre property
Fuzz formation	→	→	Friction
		→	Stiffness
		→	Breaking strength
		→	Abrasion-resistance
Entanglement	→	→	Shape
		→	Linear density
		→	Stiffness
		→	Recovery
		→	Friction
		→	Elongation
Pill wear-off	→	→	Breaking strength
		→	Flex-life



3.5 Pill curves for several modified polyester fibres. Source: Gintis and Mead, 1959[7]

3.2.2 Fibre length

Longer fibres produce fewer fibre ends (i.e. less hairiness) and also resist migration better than shorter fibres. Therefore, longer fibres should lead to lower fuzz and pill formation, but could reduce pill wear-off due to the anchoring of the pills. On balance, however, longer fibres are generally preferable in terms of pilling. Nevertheless, it is sometimes possible that longer fibres which are not securely held will form a large number of large pills.

3.2.3 Fibre diameter and stiffness

All other factors being constant, a change in fibre diameter (or fineness) is associated with a corresponding change in fibre stiffness, which is proportional to diameter to the fourth power or linear density (fineness) squared. It is therefore difficult to separate the effects of fibre diameter from those of stiffness. Nevertheless, considering the effect of fibre diameter independently from stiffness, it can be concluded that an increase in diameter (or linear density), all other factors being constant, will lead to fewer fibre surface hairs and fuzz and also to fewer pills being formed. If the effect of diameter on stiffness is considered, then coarser, and therefore stiffer, fibres should reduce pilling, since stiffer fibres are more difficult to entangle into pills.

3.2.4 Fibre friction

An increase in inter-fibre friction will generally reduce pilling, since it will reduce the tendency for fibres to migrate to the fabric surface. Inter-fibre friction is related to the fibre surface characteristics, in particular the level and nature of oils, waxes and other additives and substances on the fibre. Fibre surface treatments, such as plasma or chlorination, can also affect fibre friction, by increasing the surface roughness, thereby decreasing the pilling propensity.

3.2.5 Fibre cross-section

It is generally held that a 'non-circular' fibre cross-section, for example, tri-lobal, elliptical, irregular and flat (ribbon), is preferable from the point of view of reducing pilling, the fibre cross-section affecting both fibre friction and bending.

3.2.6 Fibre strength

Stronger and higher-elongation fibres generally lead to greater pilling; weaker and more brittle (lower elongation) fibres reduce pilling. This is due to stronger fibres and those with a long flex-life anchoring pills to the fabric, thereby resisting pill wear-off. The strength and flex-life of synthetic fibres, such as polyester, may be reduced (by, for example, reducing the average molecular weight) so as to reduce pilling propensity, particularly when used in blends with natural fibres. Such fibres are referred to as 'low-pilling'.

3.2.7 Fibre flex-life

The ability of a fibre to withstand flexing, bending and twisting, notably the first of these, plays a crucial role in the pilling propensity of a fabric. Fibres with a higher flex-life generally produce fabrics with a greater pilling propensity (see Fig. 3.5), once again because such fibres anchor pills and do not allow them to wear off. A combination (blend) of fibres with low and high flex-life (or low and high strength) is particularly bad from a pilling perspective.

3.2.8 Fibre crimp

An increase in fibre crimp is generally associated with a reduction in fabric pilling, possibly because it reduces yarn hairiness and increases inter-fibre cohesion and frictional resistance.

3.2.9 Fibre composition

Fibre composition, in terms of fibre blend composition, plays a major role in fabric pilling, the actual effect of fibre composition depending greatly upon the fibre characteristics of the blend components as well as on the proportion of each blend component. It is probably safe to say that blending of fibres differing widely in their respective properties will in most cases lead to an increase in pilling propensity. This is particularly the case where fibres with a relatively high strength and flex-life (e.g. polyester and nylon) are blended with fibres of a relatively low strength and flex-life (e.g. cotton), where the weak fibres break and form the pill while the stronger fibres with a high flex-life, anchor the pills to the fabric and reduce the wearing-off (falling-off) of pills.

3.2.10 Fibre electrostatic properties

Fibres having a greater propensity to electrostatic charge (static) will be more inclined to collect loose fibres or other contaminants which can aggravate pilling.

3.3 Effects of yarn structure and properties

3.3.1 General

The effect of the yarn properties on pilling can be ascribed largely to the yarn hairiness and the ease with which fibres can migrate to the surface of the yarn, and therefore to the surface of the fabric, which in turn are related to the yarn structure, construction and hairiness, as discussed below.

3.3.2 Yarn type and structure

Yarn type can affect pilling insofar as it has an affect on the yarn structure, particularly in terms of the arrangement (orientation) of fibres within the yarn cross-section, the ease with which fibres can migrate to the yarn surface (fibre binding), and yarn hairiness. There is some evidence that air-jet and rotor-spun yarns are better than ring-spun yarns, in terms of pilling, with compact-spun yarns superior to conventional ring-spun yarns. Nevertheless, this will greatly depend upon the conditions during spinning and how these affect the yarn structure, notably in terms of wrapping fibres and hairiness. An increase in wrapper fibres will reduce pilling due to increased fibre binding. Woollen-spun yarns are associated with a greater pilling propensity than worsted yarns.

3.3.3 Yarn linear density (count)

Although there is conflicting evidence concerning the relationship between yarn linear density and pilling propensity, the balance of evidence indicates that finer yarns should produce less pilling if all other factors are constant. This could be explained as follows: finer yarns are generally spun to higher twist factors and are converted into fabrics, both knitted and woven, with more yarn cross-over points and shorter float lengths, all factors which contribute towards a lower incidence of pilling.

3.3.4 Yarn twist factor

Pilling will decrease with an increase in twist factor, until a maximum twist level is reached, after which there is little further effect of twist on pilling. The beneficial effects of an increase in twist are largely due to the increased yarn compactness and therefore binding-in of the fibres (i.e. greater inter-fibre friction and cohesion, and reduced tendency for fibres to move to the yarn surface) and reduced yarn hairiness.

3.3.5 Yarn hairiness

An increase in yarn hairiness is generally associated with an increase in pilling, since more protruding fibres are available.

3.3.6 Yarn plying

Plying tends to bind the fibres more securely into the yarn body and to reduce yarn hairiness, both of which decrease pilling propensity. Therefore, plied yarns lead to less pilling than singles yarn, with an increase in plying twist generally reducing pilling.

3.3.7 Yarn irregularity

More irregular yarns tend to be associated with increased pilling, largely because twist runs to thinner yarn segments, leaving thicker yarn segments with a lower twist and a greater tendency to pill.

3.4 Effects of fabric structure and properties

3.4.1 General

The main effect of fabric structure and properties on pilling is due to their effect on the number of fibres on the fabric surface, and the ease with which fibres can move (migrate) from the body of the fabric to the fabric surface. Very simply stated, the fewer and shorter the surface fibres, and the more difficult it is for fibres to migrate (i.e. the more securely they are bound), the lower will be the pilling propensity. The latter factor implies that the greater the number of yarn cross-over points per unit area, the lower the yarn float lengths, the flatter the fabric surface and the more compact/dense (i.e. the higher the tightness factor) the fabric, the lower the pilling propensity should be. Fabrics with a fuzzy surface (nap) will be inclined to pill. Nevertheless, a more tightly constructed fabric could reduce the ease with which anchoring fibres can become detached from the fabric, thereby both reducing the tendency for pills to wear- off and increasing pilling.

3.4.2 Fabric tightness

As already stated, the tighter and more compact the fabric, in both knitted and woven fabrics, the lower the pilling propensity. An increase in woven fabric sett or knitted fabric stitch density will therefore reduce pilling.

3.4.3 Fabric structure

Because they are generally looser (less compact) and have a greater surface area, knitted fabrics are more prone to pilling than woven fabrics. The effect of fabric structure on pilling is largely a function of its effect on the fabric compactness, number of yarn cross-over points and float length. Therefore, plain weave fabrics are generally the least prone to pilling, while pilling increases when the density of yarn cross-over points decreases and the yarn float length increases. This applies to both woven and knitted fabrics, the latter being more prone to pilling than the former. A fabric with a flat surface, i.e. no raised or relief effects, is also less likely to pill.

3.4.4 Fabric weight

The effect of fabric weight on pilling propensity will depend upon the way the weight is changed. If the weight is increased by increasing the fabric compactness (tightness or cover factor) and/or reducing yarn float length, this will cause a reduction in pilling, but if the increase is effected by increasing the yarn linear density and at the same time reducing the yarn cross-over point density, the opposite will occur.

3.4.5 Fabric relaxation

Pilling tends to increase with a greater fabric relaxation, due to an increase in ease of fibre migration.

3.5 Effects of fibre, yarn and fabric processing parameters

3.5.1 Fibre processing parameters

Various treatments can be applied to fibres to modify their pilling propensity. These include:

- Reducing the tenacity and flex-life of synthetic fibres (e.g. low-pill polyester) and embrittling the fibre, for example by reducing the molecular weight and viscosity (IV of 0.4 to 0.5) of the polymer prior to, or even during, extrusion, or by co-polymerisation or by applying additives to the polymer.
- Increasing inter-fibre friction by, for example, fibre surface treatment (e.g. plasma) or applying a suitable additive which increases inter-fibre friction and cohesion.
- Chemical treatment to reduce the fibre mechanical properties, such as tenacity, elongation and flex-life.
- Increasing fibre crimp.

3.5.2 Yarn processing parameters

Yarn treatments to reduce pilling largely involve reducing the yarn hairiness and the ease with which fibres can move (migrate) to the yarn surface. Treatments include yarn singeing.

3.5.3 Fabric processing parameters

Various fabric chemical and mechanical finishing treatments are effective in reducing fabric pilling, these mostly operating by either reducing the surface hairs and/or ease by which fibres migrate to the fabric surface. Any treatment that decreases fibre strength and/or flex-life, i.e. embrittles the fibres, will reduce pilling propensity. Care needs to be exercised, however, that any treatment applied to the fabric does not cause an unacceptable deterioration in other desirable fabric properties, such as handle and durability. Treatments that can reduce pilling include:

- Singeing
- Shearing or cropping, preferably with prior brushing
- Heat-setting and steaming
- Shrink-proofing of wool (e.g. oxidation or chlorination, followed by resin)
- Sanding before brushing and shearing
- Hot impregnation of synthetic fibre fabrics
- Milling, depending upon its relative effect on 'fibre binding' and fabric surface hairiness
- Silicic acid treatments
- Cross-linking (e.g. acrylic)
- Latex treatments
- Certain easy-care treatments
- Oleophilic treatment of wool/polyester fabrics
- Any treatment that will increase inter-fibre friction and cohesion or that will bind the fibres more securely within the fabric
- Applying a resin, polymer or adhesive to more securely bind fibres and reduce fibre migration
- Bio-polishing of cellulosic fabrics
- Enzyme treatment of wool or cotton
- Caustic solution treatment of polyester and viscose fabrics
- Colloidal silica
- Dyeing, insofar that it weakens the fibres an/or increases inter-fibre friction
- Anti-static treatment
- Avoiding finishing treatments which reduce inter-fibre friction and binding.

3.6 Sources of further information and advice

The reader is referred to various publications[9–28] for further information.

3.7 Concluding remarks

Although it is possible to engineer a fabric with a low pilling potential, this is often at the expense of other desirable fabric properties, notably in terms of handle (softness and flexibility) and drape. Table 3.2 presents a summary

Table 3.2 Fibre, yarn, fabric and finishing parameters that can reduce fabric pilling propensity, some of which are interdependent. (Not necessarily in order of importance.)

Parameter
Fibre
Increased length
Decreased flex-life/increased brittleness
Decreased strength/tenacity
Increased stiffness/modulus
Increased diameter
Increased non-circularity
Increased fibre friction
Yarn
Decreased hairiness
Increased fibre binding
Increased twist factor
Decreased yarn linear density
Increased yarn evenness
Plying/folding
Yarn structure (e.g. compact, open-end and wrapped yarns)
Fabric
Increased compactness/tightness
Decreased yarn float length
Decreased hairiness
Increased fibre binding
Flatter surface (reduced raised effects)
Increased weight
Finishing
Removal of surface hairs (singeing, cropping, shearing)
Increased fibre binding/cohesion (latex, milling, resin etc.)
Increased fibre friction (as above, plasma, chlorination)

of those fibre, yarn, fabric and finishing parameters that have, in the main, a *beneficial* effect on fabric pilling (i.e. reduce pilling) for single jersey (plain) and 1×1 rib knitted wool fabrics. Beltran and co-workers,[29–31] using artificial neural networks, ranked the importance of the various parameters on pilling. Such a ranking would, however, depend upon fabric construction, fibre type and properties and probably upon the particular pilling test method employed. In recent years, various workers have applied different methods to objectively evaluate, model and predict fabric pilling, including ANN,[32] laser triangulation, wavelength fractal[33] and other methods (largely image analysis based) of analysing fabric surface texture.[33–37] Nevertheless, none of these methods have found much application in practice.

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4
Bagging of fabrics and garments

L. HUNTER

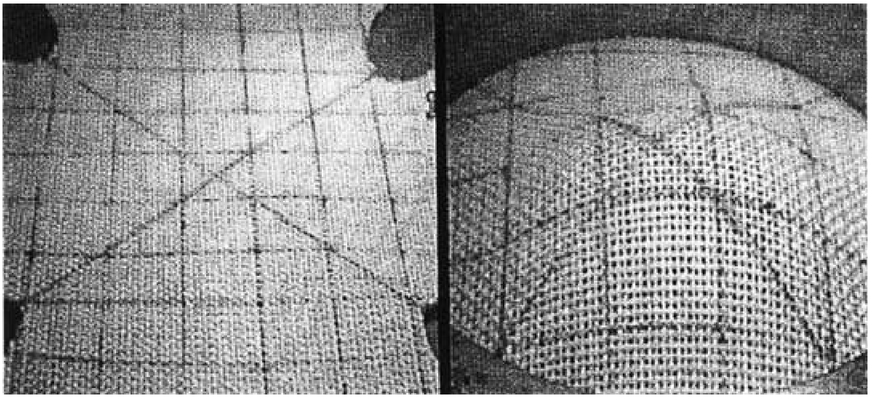
Abstract: Bagging, defined as the residual three-dimensional distortion occurring in fabrics and garments during wear, can be a particular problem in tight fitting (figure hugging) garments. The measurement of bagging, as well as the fibre, yarn and fabric properties that play a role in determining the degree of bagging, are discussed. The role and importance of garment construction and wear conditions in determining bagging are also addressed.

Key words: fabric bagging, garment bagging, bagging propensity, bagging evaluation, bagging testing.

4.1 Introduction

During wear, a garment conforms to the body movement by slippage over the skin, space allowance between body and clothing and fabric deformation.[1] It is the fabric deformation that can lead to the phenomenon termed bagging. Ideally, the fabric and garment should change shape (i.e. deform) easily to accommodate the body shape and movement, to provide 'dynamic comfort', but then recover their original shape once the deforming forces are removed, and this should be so for the entire wear life of the garment.

Bagging may be defined as the residual three-dimensional 'dome-shaped' deformation (distortion) in fabrics (notably knitted garments) caused during wear which often leads to an unsightly and unacceptable appearance of the garments. It is largely the consequence of the fabric's inability to fully recover its shape after multi-directional tension and deformation, usually of a repetitive and/or prolonged nature. It is therefore the fabric stretch (deformation) in use, in combination with its inability to fully recover from such stretch, which is the cause of bagging.[2] This three-dimensional deformation, and associated bagging, most often occur at the elbows of jerseys and jackets and at the knees and seats of pants and trousers, occurring as a result of forces exerted on the garment during movement and during sitting, bending etc., causing the fabric to deform into a 'dome' and bulge. Under a bagging load, the fabric suffers a complex deformation, with bi-axial tension and shearing[3,4] (Fig. 4.1[3]). Bagging is largely



4.1 Fabric bagging deformation characteristics. Source: Zhang *et al.*, 1999[3]

the consequence of a force or forces applied perpendicular to the fabric plane causing deformation. It is attributed to a loss in fabric elastic energy with time,[3] and can be regarded as a kind of garment fatigue behaviour.[3] Normally, repeated deformation is required to cause a 'permanent' residual deformation at such 'high pressure' points, this then being termed 'bagging'. Such a deformation is dependent upon many fibre, fabric, garment and wear parameters, including:

- Elastic and visco-elastic properties of the fibres and fabric
- Inter-fibre and inter-yarn friction
- Fabric and garment construction
- Type of garment and garment fit; notably the tightness or snugness of fit
- Wearer's size
- Level and nature of deforming forces
- Duration and number of deformation and recovery cycles.

In essence, the bagging behaviour of a fabric is determined by its ability to resist three-dimensional forces (bagging resistance), together with its ability to recover from any deformation resulting from such forces, notably from repetitive cycles of such deformation, with the latter being the more important.

The elastic and visco-elastic properties of the fibres, inter-fibre and inter-yarn friction, constructional features of the yarns and fabrics, as well as the garment construction and fit all play a role in determining the deformation, and recovery therefrom, suffered by the garment during wear. In addition, the wear conditions and nature of the wearer also play an important role in garment deformation, and ultimately in the residual deformation (i.e. bagging). Often there has to be a trade-off or compromise between snugness of fit (i.e. close fitting garments), ease of movement, and associated 'dynamic' comfort (i.e. lack of movement constraints) and fabric distortion (i.e. bagging).

Zhang *et al.*[3] classed bagging deformation into three main categories: elastic, visco-elastic and plastic, the latter including a form of frictional deformation due to slippage between fibres and yarns and yarn rotation at intersections. They stated that in practice it was difficult to distinguish between plastic and visco-elastic energies and that the energies involved during bagging could be considered to consist of two essential components: the recoverable elastic energy and the decaying visco-elastic–plastic energy. Experimental and theoretical studies indicate[4] that the fatigue in the fabric bagging process results from two basic causes: the stress relaxation of the fibres due to the fibres' visco-elastic behaviour, and the inter-fibre and inter-yarn friction due to frictional restraints inherent in fabric structures. It is perhaps worth mentioning that cleaning processes, e.g. laundering and dry-cleaning, can enable some recovery from bagging deformation.[5]

The response of most textile fabrics to deformation is time-dependent and visco-elastic in nature, with elements of creep relaxation. As such, the fabric does not recover totally from deformation, thereby leading to undesirable residual deformation, such as stretching and bagging. The ability of textile fabrics, notably knitted fabrics, to deform under external forces is in most cases a desirable characteristic, providing movement comfort and enabling the two-dimensional fabric to be deformed into the three-dimensional shape required for a particular end-use, e.g. knitted and felted hats, and jacket sleeves and shoulders.

Lloyd[6] and Amirbayat and Hearle[7] have given the following categories of fabric deformation:

- In-plane deformation
- Uni-axial bending
- Torque in the fabric plane
- Conforming to a spherical surface. This occurs when the fabric is subjected to three-dimensional deforming forces so as to conform to a spherical or near-spherical shape, such as at the elbow and knee. It is deformations such as these that lead to bagging.

Two types of major deformation, viz. multi-directional tensile deformation and shearing deformation, lead to fabric bagging.[5] Zhang *et al.*[8] stated that bagging results from a lack of dimensional stability or recovery caused by a number of factors, including plastic deformation, primary creep (recoverable with time) and inter-fibre as well as inter-yarn frictional restraint in the fabric structure. Zhang *et al.*[9,10] used a three parallel-component rheological model to describe the physical mechanism of bagging and to develop a mathematical model[10] to predict the bagging of woven fabrics. The model consists of:

- Fibre elasticity, represented by a spring (E_1)
- Fibre visco-elasticity, represented by Maxwell's unit of a spring (E_2) in series with Newton's viscous dashpot η
- Inter-fibre friction, represented by a frictional element (β).

The relative contributions of each component were characterised by three weighting coefficients, k_3, k_4 and k_5.

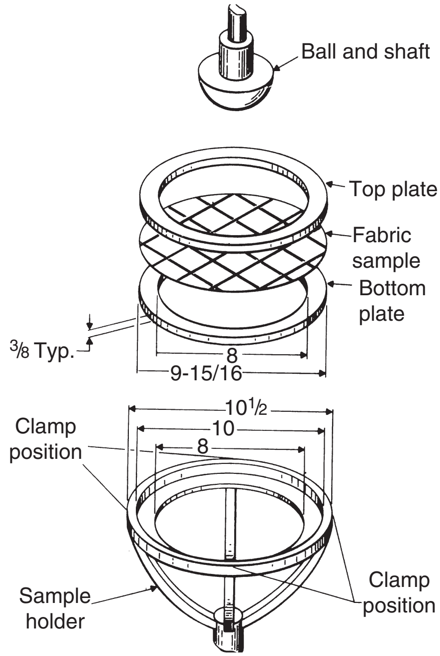
Considerable work has been done, and reviewed by Şengöz,[11] on the various types of deformation and the modelling of such deformations. One of the conclusions drawn was that in-plane shear deformation occurs when woven fabrics are forced to conform to a spherical surface and that this plays an important role in determining the response of fabrics to such deformation and subsequent shape recovery (i.e. bagging).

4.2 The measurement of bagging

Bagging involves the deformation and elastic recovery from such deformation. Testing therefore attempts to measure this, either by mono-axial or bi-axial deformation and recovery. Considerable work has been done on developing laboratory tests to measure bagging and to correlate test results with wearer trials. Broadly speaking, three approaches are used, namely:

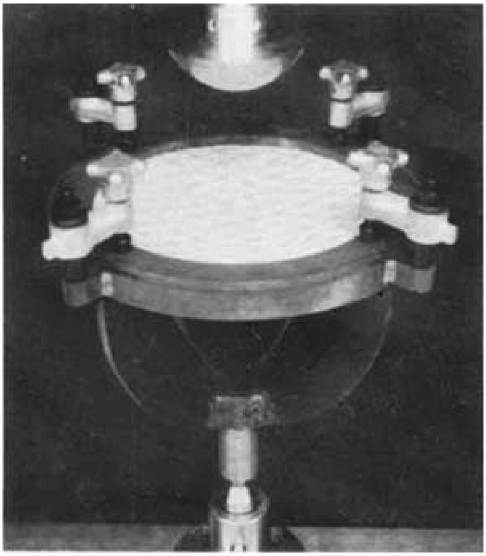
- Strip or uni-axial
- Bi-axial
- Simulated 'arm' (DIN53860).

All three tests can involve static (constant extension and/or force) and dynamic (cycling) elements. Schubert[12] concluded that all three approaches (strip, arm and bi-axial spherical deformation) appear suitable for testing knitted fabrics. Schubert[12] and Şengöz[11] have reviewed and discussed the different test methods and approaches developed to measure bagging. By and large, most of the techniques and test methods used to measure drape involve securely clamping the fabric sample, usually circular in shape, around its perimeter and then subjecting the 'central' unclamped section to deformation, generally cyclic, by means of a 'dome shaped three-dimensional' deforming sphere or force. The sphere causing the deformation can be a solid 'dome shape', a 'hemispherical' ball (sphere), or a circular diaphragm which is initially flat but then extends into a dome or hemispherical shape due to hydraulic or pneumatic forces. Undoubtedly, the most suitable test method is dependent upon the type of fabric (e.g. knitted or woven) and garment and the wear conditions.



4.2 Celanese bagging apparatus.
Source: Originally published in Thomas, W., 'Celanese Bagging Test for Knit Fabrics', *Textile Chemist & Colorist*, Vol.3, No.10, 1971, pp.57–59; reprinted with permission from AATCC, www.aatcc.org, copyright holder[13]

One early example, which illustrates the general principles of testing for bagging, is the 'Celanese' bagging test for kitted fabrics,[13] which is particularly suitable for double jersey and warp knitted fabrics of average tightness used in ladies' dresses, uniforms and slacks, and in men's outerwear. Details of the apparatus are shown in Fig. 4.2[13]; the apparatus can be mounted on tensile testers, such as an Instron (see Fig. 4.3[13]). Essentially, the ball descends onto the fabric and continues until the maximum predetermined load (e.g. 7.5 kgf) is reached; it then cycles at 25 cm/min between the minimum (e.g. 0.25 kgf) and maximum loads for 2 minutes. The test is interrupted at the maximum load and held for one minute, then returns to the lower load limit, and the upper gauge reading is recorded as the 'immediate growth' (*IG*). After this, the crosshead is lowered until the plunger is no longer in contact with the sample; it is held there for one minute, and then returned to the lower load limit (0.75 kgf); the upper load extension gauge reading is recorded as the 'immediate distortion' (*ID*). The 'immediate recovery' (*IR*) is then calculated as follows:[13]

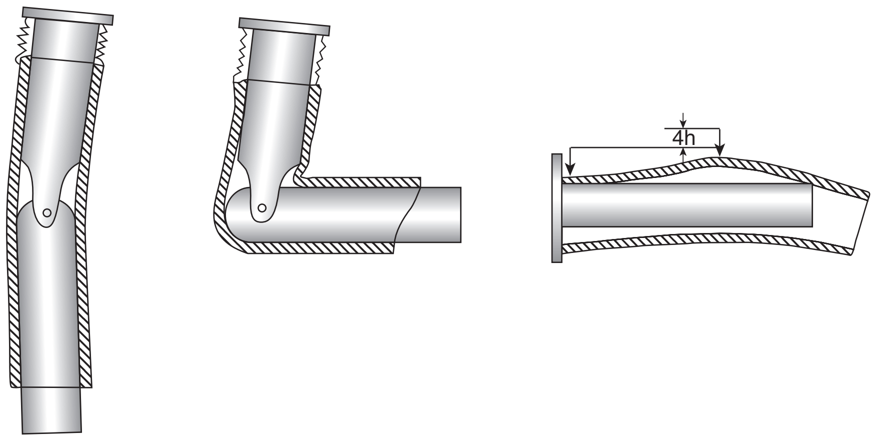


4.3 Close-up view of Celanese bagging apparatus.
Source: Originally published in Thomas, W., 'Celanese Bagging Test for Knit Fabrics', *Textile Chemist & Colorist*, Vol.3, No.10, 1971, pp.57–59; reprinted with permission from AATCC, www.aatcc.org, copyright holder[13]

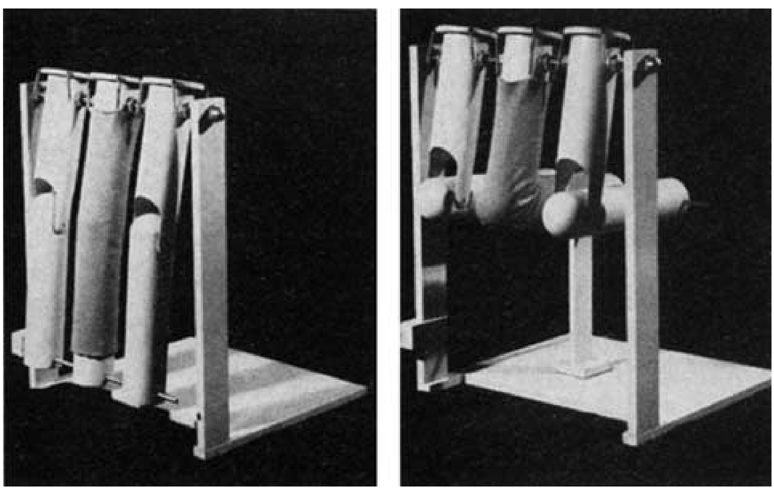
$$IR = \frac{IG - ID}{IG} \times 100 \qquad [4.1]$$

IR values greater than 59% were regarded as satisfactory and values lower than 53% as unsatisfactory.[13] Yaida[14] used a similar approach.

An example of a different approach to bagging testing is that taken by Grünewald and Zöll[15–17] (see Figs 4.4 and 4.5[16]), also referred to as the Zweigle-type bagging tester, in which a fabric tube is sewn and then drawn over an 'artificial arm' with an 'elbow joint' (and held in position under tension), which is flexed and held bent for a number of hours to simulate the action that occurs in practice at the elbow (or even knee). The 'arm' is then straightened for 10 minutes, after which the fabric tube is carefully fitted over a vertically suspended tube, which is tilted to a horizontal position and illuminated by parallel light to cast a shadow on a surface placed behind the tube. The height of the 'bagging' shadow (i.e. bulge) is measured directly with a millimetre graduated scale. (Initially, the height of the 'bulge' was measured directly on the sleeve, but this could give an erroneous result if great care was not exercised.) A bagging limit of 5 mm was considered to differentiate between wearable and non-wearable fabrics. The ITF in France proposed a different approach[18] for



4.4 Schematic diagram of 'artificial-arm' bagging tester and bagging height (Δh) measurement. Source: Grünewald, 1977[16]



4.5 Artificial arm bagging tester. Source: Grünewald, 1977[16]

measuring bagging. Şengöz[19] developed a bi-axial method using a computer-aided universal testing machine and concluded that a square, as opposed to circular, frame was preferable.

Abghari *et al.*[20] recently developed a test method to measure woven fabric bagging, involving a rectangularly clamped fabric specimen, strain gauges and real time data acquisition. They characterised fabric bagging behaviour in terms of bagging resistance, bagging fatigue, residual bagging height and residual bagging hysteresis, simulating it with finite element analysis. They concluded that anisotropic fabric properties are involved in fabric bagging deformation and that the bagging resistance and residual bagging height were highly, though non-linearly, correlated to each other. They concluded that the bagging behaviour of woven fabrics can be predicted from the bi-axial tensile properties under low-stress fabric mechanical conditions.

Zhang *et al.*[21] reported on the psychophysical mechanisms of consumers' perceptions of fabric bagging. They found a linear relationship between the subjective perceptions of bagging, based upon a series of photographs of bagged samples, and the measured residual bagging height using their own test method.[22] The subjective perception of fabric bagging followed the Stevens' power law. The residual bagging height accounted for some 94% of the total variance in the perception of bagging.

Although wearer trials represent the ultimate assessment of fabric and garment bagging propensity and laboratory bagging tests, they are notoriously time-consuming and difficult to organise in such a way so as to obtain meaningful and reproducible results. Matsuoka *et al.*[23] developed a test apparatus which simulated the bagging of slacks and then measured the 3-D shapes of the bagged fabrics using moiré topography, the volume of the bagged fabric being used as a measure of bagging propensity. The test was considered to simulate 500 hours of wear.

Yeung *et al.*[24] used image processing to evaluate and predict woven fabric bagging, using eight criteria to characterise the bagging, including bagging height, volume, and shape and fabric surface appearance. They showed that bagging appearance (Y) can be predicted from these eight parameters, with the following regression model providing the best fit:

$$\begin{aligned} Y = {} & 20.25\ln(X_1) - 7.85(X_2) - 2.67\exp(X_3) \\ & + 8.2\exp(X_4) + 5.43(X_5) + 2.465(X_6) \\ & - 2.29(X_7) + 0.26(X_8) - 4.0 \end{aligned} \qquad [4.2]$$

where:

X_1 is the maximum contrast of the warp and weft images
X_2 and X_3 are estimates of the bagging shape
X_4 is the effective bagging volume
X_5 and X_6 are measures of bagging anisotropy (correlation coefficient and bagging anisotropy, respectively)
X_7 and X_8 are measures of the fabric surface patterns (peak numbers and wave amplitude, respectively).

4.3 Effects of fibre properties

The elastic, visco-elastic and fibre-to-fibre frictional properties, particularly the first two, play the main role in fabric bagging. In essence, if the fabric constructional parameters and wear conditions are constant, the bagging propensity of the fabric will mainly depend upon the fibre visco-elastic (elastic and stress-relaxation) properties, and, to a much lesser extent, the fibre frictional properties.

All other factors being constant, the fibre initial modulus will determine the fabric resistance to bagging deformation, resistance increasing with increasing fibre initial modulus. The recovery from bagging deformation will depend mainly upon the elastic recovery and stress-relaxation properties of the fibres (i.e. elastic and visco-elastic properties) and to a much lesser extent on the fibre-to-fibre frictional properties. Any factor which affects the fibre visco-elastic properties, such as temperature and fibre moisture content, will therefore affect the fabric bagging.

Zhang *et al.*[9] studied the visco-elastic behaviour of fibres during woven fabric bagging by a series of experiments and a mathematical model to simulate bagging. They concluded that the fibre visco-elastic behaviour played a key role in determining fabric rheological behaviour during bagging. Important fibre parameters were the relaxation time (τ, the longer the better), the visco-elastic modulus (E_2, usually associated with the non-crystalline fibre components) and the elastic modulus (E_1, usually associated with the crystalline fibre components). Fabric bagging was dependent upon both the fibre visco-elastic parameters (E_2 and τ) and the time of deformation. The fibre visco-elastic behaviour is described by E_1, E_2 and τ. Six parameters were required to describe the fabric bagging behaviour, namely three fibre parameters E_1, E_2 and τ and three weighting factors: the elastic weighting coefficient k_3, the visco-elastic weighting coefficient k_4 and the frictional weighting coefficient k_5. They concluded that, based upon Feughelman's[25] two-phase model, there are four independent parameters, E_2, τ, k_3 and k_5. Zhang *et al.*[9] concluded that the relative contributions of elasticity, visco-elasticity and friction are different for different fibres during bagging. For wool and nylon, the elastic component contributed more than the visco-elastic component, the reverse being true for polyester, viscose, silk and cotton. Fabric structural features, such as the ratio of the yarn curvature or length to its projected length, yarn count, fabric density, fibre strain coefficient and fabric tensile force coefficient, determine the absolute magnitude of the fibre visco-elastic contribution.[10]

For wool woven fabrics, the relative contributions of the different components were as follows:[26]

Elasticity (k_3): 60%
Visco-elasticity (k_4): 30%
Inter-fibre friction (k_5): 10%

The values were relatively stable and insensitive to fabric structural differences. Nylon had the slowest stress-relaxation of the six fibres, followed by wool, with that of silk, viscose and cotton being the quickest; the longer (slower) the stress-relaxation time, the lower the bagging fatigue and bagging.[9] Nylon also had the lowest visco-elastic modulus (E_2), indicating excellent elastic recovery. Clearly, these parameters can be influenced by temperature and fibre moisture content, the latter being particularly important for wool.

By and large, the fibre properties required for good wrinkling performance (see Chapter 2) will also produce good bagging performance. Essentially, two elements are involved in achieving good bagging and wrinkling performance: the first is good bagging and wrinkling (deformation) resistance and the other is good recovery from bagging and wrinkling (or deformation). The first requires high fibre elastic and bending modulus, relatively coarse fibres and high inter-fibre friction. The second requires fibres with high elasticity (elastic recovery), low stress-relaxation, high glass-transition temperature and low inter-fibre friction. Inter-fibre friction and secondary creep are very important factors, with the fibre's visco-elastic properties affected by ageing, annealing (accelerated ageing), glass transition temperature, humidity relationship and chemical modification.[5] Fibre geometrical properties (e.g. diameter, cross-sectional shape and crimp) play only a minor role in this respect.

4.4 Effects of yarn properties

During bagging deformation, yarns are subjected to a combination of tension, shearing, bending and compressional forces.[10] In essence, the yarn properties which reduce inter-fibre slippage within the yarn, e.g. increased yarn twist, and enable the fibres to take the strain during bagging deformation, will improve bagging performance. Smooth and low-hairiness yarns would exhibit better bagging performance. Furthermore, if fabric weight is constant, finer yarns would be preferable for low bagging. Therefore, fine, high twist, smooth yarns with low inter-yarn friction are to be preferred with respect to good bagging performance. The use of stretch yarns (e.g. Spandex, elastane, etc.) with good recovery properties will also favourably affect bagging performance.

4.5 Effects of fabric properties

It is necessary to discuss woven and knitted fabrics separately since their responses are quite different. The following factors are common to both woven and knitted fabrics:

- Tightness; all other factors being constant, tighter fabrics will improve bagging resistance and probably also bagging recovery
- Thickness; the thicker the fabrics, the better
- Weight; heavier fabrics should generally be able to resist bagging better and also recover better

The bagging propensity of stretch fabrics depends more strongly on inter-fibre and inter-yarn friction,[5] whereas the bagging propensity of conventional (non-stretch) fabrics depends more closely on the fabric visco-elastic properties.[5] The hysteresis that occurs during fabric cyclic deformation is due to two main factors, fibre plasticity and creep effects, and frictional restraint.[5]

4.6 Effects of garment construction

A garment so constructed that it accommodates the body contours and allows the various body parts easy movement, without constriction or constraint, and allows the fabric to slide over, rather than stick to, the skin, should provide the best bagging performance and smooth appearance.[27] It is generally believed that body skin strain is a function of the garment's fit, garment slip and fabric stretch, the first two being mostly affected by the coefficient of friction, the number of body contact points with the garment and by fabric extensibility. Skin strain at the knee reportedly varies from 19 to 29% in the horizontal direction, and 41 to 52% in the vertical direction.[5]

4.7 Effect of finishing

Essentially, finishing can affect fabric bagging in the following ways:

- Change the fibre elastic properties, by cross-linking for example
- Change the fibre visco-elastic properties
- Change the inter-fibre and inter-yarn frictional properties by, for example, inter-fibre elastic bonding (e.g. resin treatment) and/or reducing inter-fibre friction (e.g. by silicone or softener applications)
- Change the fabric 'internal energy' by, for example, fabric relaxation and heat setting

4.8 Fabric bagging prediction and modelling

Fabric mechanical properties related to fabric deformation, ease of recovery and energy loss are important in determining bagging.[28] Uçar *et al.*[28] derived the following empirical equation to predict the bagging of knitted fabrics from the fabric mechanical properties measured on the Kawabata KES-FB system:

$$R_{\text{residual}} = 43.11 - 67.8(G) + 18.8(2HG5) + 203.8(B) - 91.5(2HB) \quad [4.3]$$

where:

R_{residual} = relative residual bagging height
$2HG5$ = hysteresis of shear force at 5 degrees
G = shear rigidity
B = bending rigidity
$2HB$ = hysteresis of bending moment

Subjective rating values (R) were found to depend upon B and $2HB$ only, as follows:

$$R = 2.05 + 110(B) - 33.8(2HB) \quad [4.4]$$

Zhang *et al.*[10] developed a mathematical model to quantitatively simulate fabric bagging rheological behaviour and predict fabric performance by specifying basic fibre and yarn–fabric structural parameters.

Yokura *et al.*,[29] using the volume (V) of bagged fabrics as a measure of bagging, developed equations to predict the bagging propensity of stretch and non-stretch (conventional) woven fabrics, respectively, from the fabric mechanical properties, as obtained by the Kawabata KES-FB system. They arrived at the following two equations:

Conventional fabrics:

$$V = 23.43 \log k_{\text{d}} + 96.26 \log \varepsilon(0.1) + 3.61 \log 2HB - 5.68 \quad (R = 0.91) \quad [4.5]$$

Stretch fabrics:

$$V = 1.21 \log k_{\text{d}} + 47.44 \varepsilon(0.1) + 19.55 \log 2HB + 0.41 \quad (R = 0.92) \quad [4.6]$$

where:

k_{d} = creep rate of the dynamic test
$2HB$ = bending hysteresis
$\varepsilon(0.1)$ = strain at t = 0.1 minutes, from the dynamic creep test

They concluded that the mechanical hysteresis properties measured after wetting conditioning, as the simulation of the sweating state, correlated better than those measured under standard atmospheric conditions. Zhang *et al.*[4] found that the three parameters (Q, U, δ) describing the fatigue process of fabric bagging are dependent on fibre–yarn mechanical properties and fabric structural parameters, such as fabric thickness, weight, cover factor and interlacing points:[4]

Q is the initial visco-elastic–plastic energy of the fabric
U is the elastic energy of the fabric
δ is the decay rate of loss energy

They found that the initial energy of the fabric ($U + Q$) is a function of fabric interlacing, fabric thickness, yarn work and fabric cover factor, all of which influence the frictional resistance to mechanical deformation.[3] It is also a function of fibre initial modulus, indicating that the fibre mechanical properties are a major factor determining the ability of a fabric to resist bagging deformation when fabric structural features are fixed. δ depends on the yarn unbalanced work, indicating the effect of fabric anisotropy on decay rates. Q is related to yarn and fabric cover factor, indicating that loss energy is largely determined by the mechanical properties of the yarns and fabric tightness. Q is also related to fibre modulus and fabric thickness, indicating that fabric visco-elastic–plastic energy is determined mainly by fibre modulus and fabric thickness. The elastic energy, U, is a function of fabric interlacing, fabric cover factor and yarn work, indicating that yarn mechanical properties and fabric structural features determine the elastic behaviour of the fabric. The elastic energy (U) depends only on fibre initial modulus. Oono[30] examined the stress equations of the bi-axial extension of knitted fabrics and predicted their inflation deformation by means of the membrane theory.

4.9 Sources of further information and advice

Şengöz[11] and Schubert[12] are recommended for further reading.

4.10 Concluding remarks

The behaviour of garments during bagging deformation is a complex function of fabric mechanical properties and garment constructional parameters (e.g. size and fit). It is also highly dependent upon the wearer and wear conditions. The fabric mechanical properties, in turn, are dependent upon the fabric type (e.g. knitted or woven) and structure (e.g. tightness, yarn cross-over point density, yarn unit segment and float length), yarn structure (e.g. linear density, twist, hairiness and internal structure) and fibre mechanical and other properties (e.g. elastic and visco-elastic properties, friction and creep behaviour).

In the main, similar fibre properties are required to produce good bagging performance (i.e. low bagging propensity) as those required to produce good wrinkling performance (i.e. good wrinkle recovery).

Because of the complex nature of fabric deformation and recovery during bagging, it is, as yet, not possible to accurately predict or model fabric bagging propensity from fibre, yarn and fabric mechanical properties, for either woven or knitted fabric.

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5 Fabric and garment drape

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Abstract: The important role of fabric drape in determining garment handle, comfort and aesthetics is discussed in this chapter. Special attention is given to developments in the objective measurement and categorisation of drape, and to the prediction of fabric drape from fibre, yarn and fabric parameters and properties, using multiple regression analysis, modelling and various other approaches.

Key words: fabric drape, static drape, dynamic drape, drape prediction, drape modelling, drape measurement, drape simulation.

5.1 Introduction

An essential and distinguishing characteristic of a textile fabric is its ability to undergo large, recoverable 3-D draping (bending and shear) deformation by buckling gracefully into rounded folds of single and double curvature.[1] This characteristic plays a critical role in the fit, body conformation, comfort and aesthetic appearance (visual beauty) of garments and when translating 3-D body shapes into 2-D patterns and *vice versa*. According to the *Textile Terms and Definitions* of The Textile Institute[2], 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'. Cusick[3] defined the drape of a fabric as 'a deformation of the fabric produced by gravity when only part of the fabric is directly supported'. This, together with the effect of seams, interlinings and linings (e.g. bonded), determines the way in which a garment fits and moulds itself to the shape of the body. Drape is also a critically important parameter in the application of body scanning, mass customisation, CAD-CAM and automatic pattern making in clothing design and manufacturing. The most significant development in recent years has been the move towards 3-D design, simulation and virtual modelling (3-D virtual prototyping) which enables the designer to 'drape and validate' their design onto a computer-generated mannequin or one built off a body scan of a fit model, taking into account technical information, fabric type, colour, drape and stretch as well as the effect of seams.[4] Transforming 2-D patterns into 3-D configurations that follow a body surface involves modelling the fabric physical properties,[5] including drape.

During draping, a fabric undergoes large deflections but very small strains due to its high flexibility, with by far the largest deflections coming from bending, with only a small component being due to in-plane extension and shear deformation.

A great deal of research has been directed at the objective measurement and characterisation of fabric drape and relating it to the fabric physical and mechanical properties. It has been shown that fabric bending and shear properties play the major role in determining fabric drape. Nevertheless, 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.[6] 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.[7] In practice, drape is usually assessed visually, or subjectively, and the actual assessment greatly depends upon often changing factors, such as fashion, personal preference, human perception, etc. Bhatia and Phadke[8] have discussed the influence of drape on clothing styles.

There is also 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. Furthermore, the drapeability of a seamed or lined fabric or garment is affected by the draping characteristics of the materials as well as by the construction of the seam, and the method of lining or interlining (e.g. bonding).

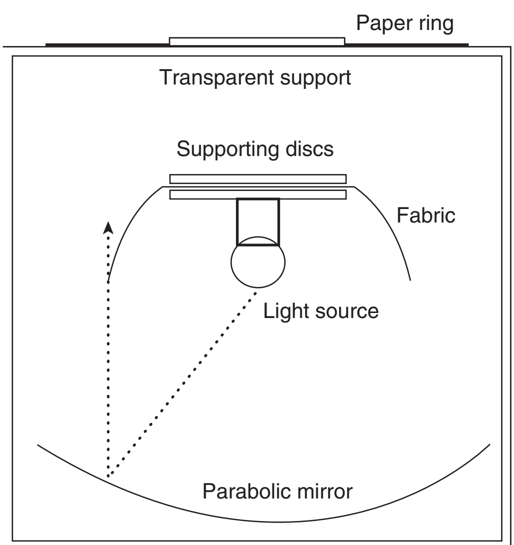
All the above factors need to be taken into consideration when engineering drape, since a number of subjective factors, including fashion, are involved in determining what the drape should be. Drape is therefore a complex combination of fabric mechanical and optical properties and of the seam and interlining properties, as well as of subjectively assessed properties.

5.2 Drape measurement

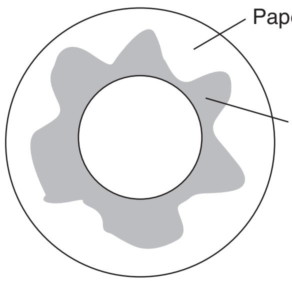
Although fabric draping characteristics are often assessed subjectively, considerable research and development has been directed to the objective measurement and characterisation of drape. Early work concentrated on the instrumental measurement of bending stiffness, because of its predominant effect on drape. Instruments were designed to measure fabric stiffness, mainly in terms of its fabric bending length (the length of fabric that bends to a definite extent under its own weight), which provided a fairly good measure of the fabric draping properties, more particularly of the two-dimensional (2-D) drape, as opposed to the three-dimensional (3-D) drape.

It was soon realised, however, that, in addition to the major role of fabric stiffness, the fabric shearing properties also play an essential role in determining fabric draping characteristics. Therefore, the traditional stiffness tests (cantilever method) are unable to accurately reflect fabric drape. Therefore, to better quantify the latter, various objective measurement techniques have been designed to include fabric shear and to simulate what occurs in practice by, for example, laying the fabric over a pedestal or mannequin, allowing the fabric to fall naturally into folds and assessing the size and frequency of the folds. At present, the most widely used method is still the traditional one in which a circular disc of fabric is allowed to drape into folds around the edges of a smaller circular platform or template, using instruments commonly referred to as 'drapemeters', and measuring the relevant parameters, such as a drape coefficient, drape profile and nodes. New techniques, such as image analysis, have been developed for measuring the size and shape of the draped fabric sample.

Pioneering work was carried out by Chu *et al.*,[9] who developed a method of measuring drape by means of the F.R.L. Drapemeter, quantifying drape as a dimensionless drape coefficient. Cusick[3,10] subsequently developed what has become known as Cusick's Drapemeter (Fig. 5.1), which is still the standard method of measuring drape and is widely used even today. 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 annular ring covered by the vertical projection



5.1 Cusick's Drapemeter. Source: Chung, 1999[12]



5.2 Drape image. Source: Chung, 1999[12]

Table 5.1 Drape coefficients (%). Source: Sudnik, 1972[15]

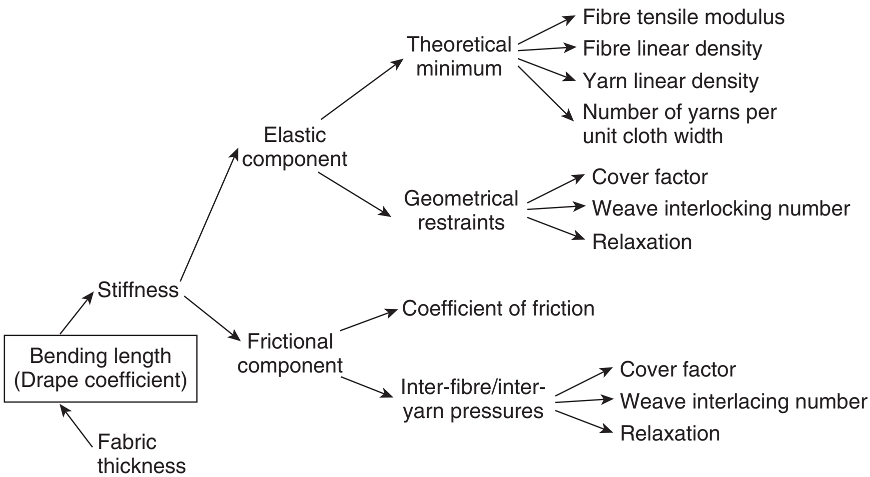
End-use	Template A (24)	Template B (30)	Template C (36)
Lingerie	<80	<40	<20
Underwear	65–90	30–60	15–30
Dresswear	80–95	40–75	20–50
Suitings	90–95	65–80	35–60
Workwear, rainwear	>95	75–95	50–85
Industrial	>95	>95	>85

of the draped fabric expressed as a percentage of the area of the flat annular ring of fabric, this being termed the drape coefficient.[3] In practice, the contour of the shadow is often traced onto the paper and cut out for weighing.[11] Cusick[11] 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. 5.2).

$$DC\% = W_2/W_1 \times 100 \qquad [5.1]$$

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 range from about 30% for a loose, open weave rayon fabric, to about 90% for a starched cotton gingham, and about 95% for stiff nonwovens.[13] Nevertheless, since different template sizes can be used, which influences 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%.

Sudnik,[15] using an improved version of Cusick's Drapemeter, gave a table of drape coefficients (Table 5.1), and concluded that the optimum drape coefficient depends upon fashion and end-use.



5.3 Some factors contributing to fabric drape behaviour. Direction of arrows indicates whether an increase or decrease in a given parameter will produce an increase or a decrease in the drape coefficient of the fabric. Source Anon., 1981[14]

Some of the factors contributing to fabric drape are shown in Fig. 5.3.

It is important to note that the drape coefficient (*DC*) is not sufficient to describe the physical drape and appearance of a draped fabric and garment; the number and location (position of peak) of nodes and overall drape profile are important additional factors.

Bhatia and Phadke[8] have stated that, since the draped sample will form pleats, it will not remain in one plane, and that the traced image is not necessarily the true projected one. They stated that understanding the drape mechanism requires a study of the following:[8]

- The drape geometry, i.e. the configuration of the draped sample.
- The drape diagrams, i.e. the projected 2-D simplification of the 3-D draped sample, which contains three significant items:
  - (i) The area, which is the basis of the drape coefficient
  - (ii) The number of nodes formed as a result of material buckling, the phenomenon of buckling, the type of load applications and the boundary conditions. The number of nodes decrease as the fabric stiffness and drape coefficient increase (inverse relationship),[8] Behera and Mishra[16] finding a negative correlation between the number of nodes and fabric bending rigidity. Hu[17] found that for $DC > 85\%$, there were 2 to 5 nodes; for *DC* between 50 and 85%, there were 6 to 8 nodes; and for *DC* between 30 and 50% there were 9 or 10 nodes.

(iii) The shape of the nodes; when the nodes are uniform, the drape diagram is a cyclic function in polar co-ordinates. Converting these polar co-ordinates into rectangular co-ordinates simplifies the analysis between the shape factor and the drape coefficient. Hu[17] concluded that the node shapes within the drape profile are similar for different fabrics.

Typical examples of 'drapemeters' include that of Cusick, F.R.L., I.T.F. and the M.I.T. Drape-O-Meter. Other principles of measuring drape include the force to pull a circular fabric sample at a constant speed through a ring, the force being termed the 'drape resistance' of the fabric. Collier[18] developed a digital drapemeter. Matsudaira *et al.*[19] used an image analysis system to measure static and dynamic drape. Vangheluwe and Kiekens[20] also used image analysis (a video digital camera and computer-based image processing system) to measure the drape coefficient, while Stylios *et al.*[21] developed a new drapemeter (the Martin Monroe Meter – M^3), enabling 3-D static and dynamic drape to be measured by means of a CCD camera as a vision sensor. Image analysis enables many measurements to be made in a relatively short time. Using photographs of draped fabrics varying greatly in drape coefficient, Suda and Ohira[22] concluded that the drapeability of fabrics of equal drape coefficient can be determined visually, and that it was easiest to do so with fabrics having a drape coefficient of around 30%. The recently developed Sylvie® 3-D Drape Tester[23] measures static fabric drape and stores 3-D geometrical properties of the draped sample form, using photographs. Kenkare and May-Plumlee[24] demonstrated a digital image processing method to measure drape using the Cusick Drapemeter. Behera and Mishra[25] proposed a computer vision (image acquisition) system to measure and integrate the most important aesthetic attributes of apparel fabrics, including drape, so as to develop a fabric appearance index (FAI). Sul *et al.*[26] explored the simulation of the Cusick Drapemeter by using particle-based modelling involving a triangular mesh, with a new bending model to control bending stiffness. The Drape Analyser DMO2 is a computerised version of Cusick's Drapemeter.[27] 3-D drape can also be measured on a real garment by using a Moiré Camera System.[28]

5.3 Engineering fabric drape

5.3.1 Introduction

When considering the question of engineering fabric drape, it is important to bear in mind that the type and style of garment, fashion, personal preference, etc. all play an important role in what is regarded as a good or desirable drape. Nevertheless, if drape can be pre-determined or predicted, then the drape can be engineered to meet the specific end-use requirements.

According to the research done to date, fabric drape is determined largely by the fabric bending and shear stiffness properties, with fabric thickness, tensile and weight also of some importance. Therefore, to be able to predetermine (i.e. engineer) the fabric drape, requires that the precise relationship between fabric drape and fabric bending and shear stiffness is known, and that the effects of fibre, yarn and fabric physical and structural variables on bending and shear stiffness are also known, as illustrated in Fig. 5.3. For the sake of simplicity, engineering fabric and garment drape will be considered from the point of view of drape coefficient (*DC*) only.

5.3.2 Effects of fibre properties

There can be little doubt that fibre bending stiffness plays a major role in determining fabric bending stiffness and therefore fabric drape; the higher the fabric bending stiffness, the higher will be the fabric drape coefficient. Within this context, the freedom of fibre and yarn movement within the fabric also plays a role, though a secondary one, the yarn and fabric stiffness, and therefore the drape coefficient, increasing as the fibre (and yarn) freedom of movement is restricted, i.e. as yarn and fabric compactness (tightness) and inter-fibre friction and adhesion increase.

In terms of fibre bending stiffness, the fibre bending modulus, fibre diameter (cross-sectional area), fibre cross-sectional shape and area variability all play a role: The following equation quantifies some of these effects:[29]

$$F = \frac{1\eta E T^2}{4\pi\rho} \qquad [5.2]$$

where:

F = fibre flexural rigidity (or stiffness) in $N.m^2$
T = fibre linear density ($kg.m^{-1}$)
E = specific bending modulus ($N.kg^{-1}.m$)
ρ = fibre density ($kg.m^{-3}$)
η = shape factor (= 1 for a circular fibre)

In practical units, the above equation becomes:[29]

$$F = \frac{1\eta E T^2}{4\pi\rho} \times 10^{-3} \text{Nmm}^2 \qquad [5.3]$$

where:

E is in N/tex
T is in tex
ρ is in g/cm^3

The shape factor η, and consequently rigidity, increases as the distance of the material from the fibre centre increases, it being greatest for a hollow cylinder. For the same type of fibre, T is a function of diameter squared, and therefore flexural rigidity is a function of diameter to the fourth power. Clearly, therefore, fibre diameter has by far the major effect on fibre stiffness and therefore also on fabric stiffness. Since fibre, yarn and fabric properties are often compared on the basis of constant mass (i.e. constant fibre and yarn linear density and fabric mass per unit area) it is convenient to express 'intrinsic' stiffness (or specific flexural rigidity), which is independent of fineness (i.e. per unit tex), as follows:[29]

$$R = \frac{1\eta E}{4\pi\rho} \times 10^{-3}\ \mathrm{Nmm^2/tex^2} \qquad [5.4]$$

where E is in N/tex and ρ is in g/cm^3. Morton and Hearle[29] give some typical shape factors and specific flexural rigidity values for different fibres.

Hunter *et al.*[30,31] found that for woven and knitted wool worsted fabrics of different structures, fibre diameter had by far the main effect on fabric drape. They found empirically that drape coefficient was proportional to (mean fibre diameter)^n, where n varied somewhat according to the fabric type and structure but was of the order of 0.9.

Hunter *et al.*[32] found that fabric shear stiffness (Kawabata G) and shear hysteresis (Kawabata $2HG$ and $2HG5$) increased with fibre crimp for both plain and twill weave wool worsted fabrics, both also increasing somewhat with a decrease in fibre diameter. In certain cases, the effect of changes in fibre crimp could be explained in terms of concomitant changes in fabric thickness. Fabric bending rigidity (Kawabata B value) was, as expected, essentially a function of mean fibre diameter, increasing as fibre diameter increased, as was found by Carnaby.[33] It also showed a slight increase with fibre crimp.

Therefore, in summary, it can be stated that, through their effects on fabric bending stiffness and shear stiffness, an increase in both fibre diameter and fibre crimp will increase fabric drape coefficient, the effect of diameter being the greatest.

5.3.3 Effect of yarn properties

The main yarn parameters that can affect fabric drape are linear density, twist factor (including plying to singles twist ratio), bulk/diameter/compactness (volumetric density), hairiness and structure, the latter including factors such as fibre orientation and migration, and wrapper fibres (e.g. OE spinning). At constant fibre properties and yarn linear density, which is generally the basis upon which different yarns are compared, the drape coefficient will increase with a decrease in fibre freedom of movement, which could be brought about by an increase in inter-fibre friction and adhesion and/or by a decrease in yarn diameter (an increase in yarn compactness) and the presence of surface 'wrapper' fibres. Nevertheless, the effects of changes in these yarn properties, within the normal practical and commercial limits, will generally be small compared to the effect of changes in fibre diameter and to a lesser extent fibre shape and bending modulus.

5.3.4 Effect of fabric properties

Of the various relevant fabric parameters, fabric thickness, tightness and weight play the main role in determining fabric drape, with fabric tightness (cover factor) or compactness, probably having the greatest effect due to its effect on the fibre and yarn freedom of movement. Therefore, any factor, such as weave structure and fabric relaxation, which increases the fibre and yarn freedom of movement within the fabric will decrease the fabric bending stiffness, and therefore the fabric drape coefficient. At a constant weight, the fabric drape coefficient will decrease as the float length increases. Thus, for example, a twill-weave fabric will have a lower drape coefficient than a plain-weave fabric of the same mass per unit area. Matsudaira and Kawabata[34] attributed the very low shear stiffness and hysteresis (and therefore drape) of silk fabrics to the space between the yarns in the fabric which occurred as a result of the removal of sericin. Yan *et al.*[35] showed that total fabric hand (in terms of the Weighting Euclidian Distance–WD) was highly correlated with fabric drape coefficient.

5.3.5 Fabric finishing

Fabric dyeing and finishing (including setting and pressing) can affect fabric bending and shear stiffness, and therefore fabric drape, significantly. This is mainly due to their effect on the internal stresses (forces) in the fabric, the associated changes in the fabric state of relaxation and energy, and the concomitant changes in the ease of fibre and yarn movement within the fabric, together with their effects on inter-fibre and inter-yarn friction and cohesion. Good examples are the scouring and crabbing of wool fabrics and the scouring and bleaching of cotton fabrics, as well as the heat setting of fabrics containing thermoplastic fibres, for example polyester and nylon. Fabric dyeing can produce similar effects of stress reduction and relaxation. Any treatment which increases inter-fibre and inter-yarn friction and cohesion (e.g. fibre bonding) will increase both fabric bending and shear stiffness, and therefore fabric drape.

5.3.6 Garment construction

The garment construction and type, notably the number and type of seams, linings and interlinings as well as cut and style, clearly play a significant role in the draped appearance of the garment, the presence, nature and bonding of interlinings, etc. having a major effect. So too will the fabric colour, depth of shade and pattern have a significant effect, although these effects are essentially optical in nature and not due to actual changes in the fabric drape *per se*. With respect to the effects of seams, including seam and stitch type, these have been studied and reviewed in detail by Chung,[12] Hu[17] and Sharrouf,[36] their main effects being on the stiffness (both bending and shear) of the fabric in their immediate vicinity and on their positioning within the garment. Chung[12] presented a detailed review of studies on drape, both static and dynamic, and investigated the effect of seam allowance, type and position on woven fabric drape. She found that bending length increased with the insertion of a vertical seam, while drape coefficient increased with the addition of radial seams, increasing the seam allowance having little effect. The highest drape coefficient occurred with the circular seam located just out of the pedestal.

According to Hu,[17] the drape coefficient increases with the addition of a radial seam, increasing with the number of seams, being highest with four seams. The drape profile of unseamed fabrics is unstable while that of fabrics with four radial seams is more stable and regular. For fabrics with a circular seam, the highest drape coefficient was obtained when the seam was located just out of the pedestal, and lowest when located at the edge of the fabric. The seam characteristics and seam allowance affect the drape properties of the seamed fabric.[17] Schenk *et al.*[4,37] developed a new method to measure the effect of seam stiffness on that of adjacent fabrics.

Wang *et al.*[38,39] reviewed work done on deriving ease allowance, and developed an Ease Distribution Model focusing on an X-line style jacket (hourglass silhouette) to be used in garment drape modelling.

5.4 Empirical prediction of drape

The development of empirical prediction equations and models represents an important step in the engineering of fabric and garment drape, and some of the most important ones will be discussed below. It is worth noting that Ng *et al.*[40] found a difference between fabric and garment (circular flared skirt) drape, the difference being influenced by the KES-FB LC and WC parameters.

5.4.1 Static drape

A number of experimental studies have been undertaken to identify those fabric properties that affect drape and which therefore need to be taken into consideration when predicting and engineering drape. Such effects have been quantified empirically, by means of regression equations, artificial neural networks and other analytical techniques.

The earliest research studies on fabric drape[9,41] demonstrated the dominant role of fabric stiffness on drape; fabric weight plays a lesser role, Chu *et al.*[9] showing that drape depended upon three basic fabric properties, namely Young's Modulus (Y), cross-sectional moment of inertia (I) and fabric weight (W), with drape coefficient = f(B/W), where $B = (YI)$.

Later studies[3,11,42–44] demonstrated the effect of fabric shear and also shear hysteresis[18,45] on drape for both woven and knitted fabrics, 'shearing' being the deformation which results in a flat fabric when opposing forces act parallel to each other (shear stiffness is the shear angle at which a fabric begins to buckle). Xu and Wang[46] derived the following prediction equations for the shearing rigidities of worsted fabrics with short floats (e.g. plain, 2/1 twill, 1/2 twill and 2/2 twill):

$$G_1 = kn_2(0.4750S + 0.0151) \quad [5.5]$$

$$G_2 = kn_1(0.4676S + 0.0102) \quad [5.6]$$

where:

G_1 and G_2 are the warp and weft shear rigidities, respectively
n_1 and n_2 are the ends/cm and picks/cm, respectively
k is a constant depending upon the weave structure (= 1 for plain weave, 0.67 for 1/2 and 2/1 twill, and 0.5 for 2/2 twill)
S is the product of the warp and weft yarn diameters (in mm)

The yarn diameter (in mm) = $0.0465\sqrt{tex/\rho}$, where ρ = fibre density.

Therefore, on the basis that the drape coefficient (DC) increases with increasing shear stiffness (G), the above relationships show that, all other factors being constant, DC is highest for plain weave fabrics, followed by the 1/2 and 2/1 twills, and is lowest for the 2/2 twill, DC increasing with increasing sett and yarn diameter.

Using multiple regression analysis on the results obtained on 130 fabrics, Cusick[3,10,11] derived the following empirical equation, relating drape coefficient to bending length and shear angle:

$$DC = 35.6C - 3.61C^2 - 2.59A + 0.0461A^2 + 17.0 \quad [5.7]$$

where:

DC = the drape coefficient
C = the bending length measured with the Shirley Stiffness Tester and obtained as follows:
$C = ¼(C_1 + C_2 + 2C_b)$

where:

C_1 = bending length in the weft direction
C_2 = bending length in the warp direction
C_b = bending length in the bias (45%) direction and
A = the shearing angle at a shearing stiffness value of 2 gwt. cm/cm^2.

Ayada and Niwa[47] showed that bending, shear and weight were the main fabric properties influencing drape and garment appearance. Tanabe *et al.*[48] used multiple-variance regression analysis to show that drape coefficient is affected by fabric bending modulus (B), bending hysteresis (HB) and weight (W), the correlation being increased by introducing the anisotropy of the bending properties into the regression equation.

Using the F.R.L. Drapemeter, Morooka and Niwa[49] derived the following empirical equation relating fabric drape to KES parameters, finding that fabric weight and bending modulus were the most important parameters:

$$DC = 5.1 + 115.0\sqrt[3]{\frac{B_{90}}{W}} + 131.1\sqrt[3]{\frac{B_0}{W}} + 1.2\sqrt[3]{\frac{B_{45}}{W}} \quad [5.8]$$

where:

W = fabric weight per unit area (mg/cm^2)
B_{90} = bending rigidity (g.cm^2/cm) in the warp direction
B_o = bending rigidity (g.cm^2/cm) in the weft direction
B_{45} = bending rigidity (g.cm^2/cm) in the bias direction
DC = drape coefficient.

Therefore all other factors being constant, the drape coefficient increases with decreasing fabric weight.

Collier[50] found that, for the KES properties (parameters) measured, shear hysteresis and bending stiffness were the most important for predicting drape coefficient.

Using a theoretical approach, Hearle and Amirbayat[51] showed that a more complicated relationship existed between fabric drape coefficient and mechanical properties – possibly involving anisotropic in-plane and out-of-plane bending, cross-term elastic constants and nonlinearity of response. They related the fabric geometric form to two dimensionless energy groups J_1 and J_2, where, in terms of material properties:

$$J_2 = Y\ell^2/B \quad \text{and} \quad J_2 = W\ell^3/B \qquad [5.9]$$

where:

B = bending stiffness
W = fabric weight
Y = fabric membrane modulus
ℓ = the characteristic length defining the size of the material.

The more generalised expression is:

$$DC = f(J_1, J_2, \pi_3\pi_4\pi_5) \qquad [5.10]$$

where:

DC = drape coefficient
$\pi_3 = G/Y$
$\pi_4 = T/B$
$\pi_5 = \mu$,

where G, T and μ, respectively, are the overall shear modulus, overall torsional rigidity and overall Poisson's ratio for all directions.

Niwa and Seto[52] introduced bending and shear hysteresis into the relationship, relating drape coefficient to mechanical properties as follows:

$$DC = b_0 + b_1\sqrt[3]{\frac{B}{W}} + b_2\sqrt[3]{\frac{2HB}{W}} + b_3\sqrt[3]{\frac{G}{W}} + b_4\sqrt[3]{\frac{2HG}{W}} \qquad [5.11]$$

where:

DC = drape coefficient
b_0 to b_4 are constants (e.g. b_0 = –22.66; b_1 = 291.8; b_2 = 387.71; b_3 = –3.71 and b_4 = 30.53)
B = bending rigidity
$2HB$ = bending hysteresis
W = fabric weight per unit area
G = shear stiffness
$2HG$ = shear hysteresis

Hu[17] and Chan[13] related the Cusick Drapemeter drape coefficient to the KES-FB mechanical properties, finding logarithmic regression equations of the form:

$$DC = b_0 + \sum_{i=1}^{n} b_i \ln x_i \qquad [5.12]$$

or

$$\ln DC = b_0 + \sum_{i=1}^{n} b_i \ln x_i \qquad [5.13]$$

Better than simple linear regression equations, their results for bending and shearing were similar to other results, but two additional parameters, LT (tensile) and MMD (surface roughness) were also significant. They compared the various models, and found that all bending and shear properties could be related to drape, but that three or four parameters were probably enough for an accurate prediction.

Matsudaira and Yang[53] found that there existed an inherent node number for any fabric, and the conventional static drape coefficient (D_s) could be measured accurately by an imaging system. Yang and Matsudaira[54] also derived regression equations from the static drape shape of isotropic and anisotropic fabrics, using cosine functions, and showed that static drape coefficient (D_s) and the number of nodes (n) can be calculated from the following equations:

$$D_s = \frac{4a^2 + 2b^2 + 2a_m^2 + b_m^2 - 4R_0^2}{12R_0^2} \qquad [5.14]$$

$$n = 12.797 - 269.9\sqrt[3]{\frac{B}{W}} + 38\,060\frac{B}{W} - 2.67\frac{G}{W} + 13.03\sqrt{\frac{2HG}{W}} \qquad [5.15]$$

where:

R_o = the radius of the circular supporting stand of the drapemeter (e.g. 63.5 mm)

a = a constant showing the total size of a two-dimensionally projected area (mm)

b = a constant showing the height of a sine wave of the two-dimensionally projected shape (mm)

a_m and b_m = constants showing fabric anisotropy, derived as follows:

$$a = 35.981 + 1519\sqrt[3]{\frac{B}{W}} - 204\,300\frac{B}{W} + 23.27\sqrt[3]{\frac{G}{W}} + 0.0178G \qquad [5.16]$$

$$b = 29.834 - 1.945n - 0.0188G - 91.84\frac{2HG}{W} \qquad [5.17]$$

$$a_m = 9063\left(\frac{B_1 - B_2}{W}\right)^{2/3} \quad \text{and} \quad b_m = 6224\left(\frac{B_1 - B_2}{W}\right)^{2/3} \qquad [5.18]$$

where:

B = bending rigidity (mN.m^2/m)

G = shear rigidity (N/m/rad)

$2HG$ = shear hysteresis at 0.0087 radian (N/m)
W = fabric weight (g/m^2)
B_1 = bending rigidity in warp direction
B_2 = bending rigidity in weft direction.

Yang and Matsudaira[55] also quantitatively related the basic fabric mechanical parameters to static drape shape, using computer simulation.

Okur and Cihan[56] related drape to FAST properties, finding the shear coefficient to have the greatest effect on drape, followed by the bending properties and the extension at 45° bias angle (used to calculate shear stiffness); 86% of the variation in drape coefficient could be explained by C2, Cl, EB5 and E20-2, only the first three being useful for the prediction of the drape coefficient. Behera and Mishra[16] found a negative correlation between fabric formability and drape coefficient.

Sang-Song[57] used discriminant analysis to discriminate between four groups of fabrics (wool, silk, cotton and linen) with different characterised drape forms based on the Cusick Drapemeter. Vaitkevičiene and Masteikaite[58] developed a method of evaluating flared garment drapeability and investigated the influence of anisotropic fabric properties on drape. They presented a mathematical model for predicting the shape of horizontal projections of draped specimens, including those with seams.

5.4.2 Dynamic drape

Elements of movement are frequently involved in garment drape, various workers having investigated dynamic, as opposed to static, drape. Yang and Matsudaira[59,60] defined drape coefficients in the revolving state and also with a swinging motion, and proposed a relationship between these coefficients and the basic Kawabata KES-FB mechanical parameters. They[59] derived the following dynamic drape coefficient (D_d) with swinging motion, which is more closely related to human motion in walking:

$$D_d = 90.217 + 0.1183W - 720.7\sqrt[3]{\frac{B}{W}} - 41.1\sqrt[3]{\frac{G}{W}} \qquad [5.19]$$

Izumi and Niwa[61] found that the 'beauty of dynamic drape' for skirts having gathering waves is highly correlated with L_3c,

where:

$L_3c = 0.409\ (2HBc)^{0.956}\ (Bc/W)^{0.652}$
Bc = bending rigidity (g.cm^2/cm)
$2HBc$ = bending hysteresis (g.cm/cm)
W = fabric weight (mg/cm^2)

Matsudaira *et al.*[19,62] showed that both the static and revolving dynamic degree of spreading of the (revolving fabric) drape coefficients decreased through the various finishing stages, especially with relaxation.

Sang-Song[57] applied the regression method and an artificial neural network to predict the dynamic visual appearance of a swirling skirt from the fabric mechanical properties with a view to replacing the subjective assessment with a more objective assessment. It was found that the neural network method provided a more accurate prediction than the regression method. Two fabric mechanical properties were key in the prediction of skirt swirl, namely:

B = bending rigidity: gf.cm^2/cm
$2HG$ = hysteresis at 0.5°: gf.cm

5.5 Modelling fabric and garment drape

Hu[17] has thoroughly reviewed and discussed the modelling of fabric and garment drape (2-D and 3-D) and related fabric structural and mechanical properties.

There is an increasing trend towards incorporating fabric mechanical properties, more particularly drape (or alternatively fabric bending and shear properties), into 3-D garment systems. Hardaker and Fozzard[63] stated that one of the main obstacles in developing 3-D garment CAD systems is the difficulty in modelling garment drape. Various researchers have attempted to model the draping behaviour of fabrics and garments, testing their models against experimental results. Generally two approaches are followed in modelling garment drape, namely geometric and physical.[64]

Hu[17] mentions that, at the time, there existed two main approaches to modelling fabric drape deformations, namely the finite element approach, employing a shell element, and a more empirical approach such as the particle-based model of Breen *et al.*, both approaches having certain shortcomings. Hu[17] considered the finite volume approach appropriate for simulating and modelling fabric draping deformation, developing the theoretical analyses and computational evaluation of the model. Hu[17] found excellent agreement between DC, based upon a theoretical model of drape profile using constants (p, q and k) from polar co-ordinate fitting, and experimental results for DC. She selected the following trigonometric function for modeling:[17]

$$r = p + q\sin(k\theta + \alpha) \qquad [5.20]$$

where:

p is the average radial length, taken between peaks and troughs of the draped profile

q is the half depth of the draped node
r is the the radius of the projected drape profile
k is the number of nodes (peaks) in the drape profile
α is a constant which represents an angle between the fabric warp direction and its neighbour peak.

She empirically derived[17] the following regression equations, relating the constants used in the model, to the KES parameters:

$$p = 10.795 + 7.458(2HB_T) + 0.1087(2HG5_T) \quad [5.21]$$

$$q = 0.5116 + 1.861(2HB_T) - 0.122(2HG_T) \quad [5.22]$$

$$k = 2.753 + 0.8153(2HB_T) - 0.469(2HG5_T) \quad [5.23]$$

where $2HB$, $2HG$ and $2HG5$ are the bending hysteresis, shear hysteresis at 0.5° and shear hysteresis at 5°, respectively, with the suffix T indicating the mean values of warp, weft and 45° bias directions. This indicated that draped nodes and locations are affected by bending hysteresis and shear hysteresis in the various directions. Both drape profile and drape coefficient could be predicted from the drape profile model.

The geometrical approach treats the fabric as a deformable object, represented by a grid or two-dimensional array in three-dimensional coordinates, and drape is simulated by approximating the shape of the fabric surface to constraint points.[65–67] Fabric properties need to be incorporated into geometrical models for them to be applicable to 3-D CAD.

The physical approach employs a conventional theory of mechanics, elasticity and/or deformation energy to model complex fabric deformation during draping. Conventional continuum mechanics and the finite element method[68–70] have been used to simulate complex fabric draping with only limited success compared to the simple geometric approach because the fabric undergoes complex and large deformation. For example, Collier *et a1.*[71] used a geometric nonlinear finite element method to predict drape. They assumed the fabric to be a shell membrane with orthotropic rather than isotropic properties, finding that three independent parameters, tensile moduli in the two principal planar directions and Poisson's ratio, were required to predict drape. Gan *et al.*[72] applied geometric nonlinear finite elements, associated with a shell element, to model large fabric deformations such as drape, the fabrics being considered as orthotropic and linearly elastic. Chen and Govindaraj[73] used a shear flexible shell theory to predict fabric drape, taking the fabric to be a continuous, orthotropic medium and using finite element formulations to numerically solve the governing equations under specific boundary conditions. The fabric characteristics used in the model were Young's modulus in the warp and weft directions, shear modulus and Poisson's ratio. Their physically-based modelling tied in closely with the processes of mathematical modelling, and moved towards using drape modelling in apparel CAD and made-to-measure garment-making applications, also being applicable to the study of fabric deformation during the apparel assembly process.

Postle and Postle[74] developed a commercially applicable mathematical model for fabric buckling, folding and drape; with fabric bending and inter-fibre friction within the fabric being considered in their mathematical model, which involved solving nonlinear differential equations that had analytical – as opposed to numerical – solutions (called solitary wave or soliton solutions).

Kang and Yu[75] developed a nonlinear finite element code to simulate the three-dimensional drape shapes of woven fabrics, assuming the fabric was an elastic material with orthotropic anisotropy, and considering fabric drape to be a geometric nonlinear phenomenon.

Stump and Fraser[1] applied a simplified model of fabric drape (based upon a two-dimensional elastic ring theory) to the circular geometry of the drapemeter, using a parameter incorporating fabric properties and drape geometry to characterise the drape response of the energy contained in a series of deformed rings. They could also explain the fact that a particular fabric does not always drape with the same number of nodes. They focused attention on the large deflection and nonlinear kinematics associated with deep drape.

Bao *et al.*[76] conducted experimental and simulation studies on the MIT drape behaviour of fabrics, finding that the nonlinear finite element method, combined with the incremental method in which an elastic shell models the fabrics, simulated the large deformation of a fabric, such as in drape. They found that the fabric drape depended upon bending and torsional rigidity, but not on extensional or shearing rigidity.

Lo *et al.*[77] found that their model, using polar co-ordinates, for predicting fabric drape profile (characterised in terms of drape coefficient and node locations and numbers) could accurately predict the drape coefficient, node locations, node numbers and node shape in the fabric drape profile. Constants in the drape profile model could be obtained by regression analysis involving bending and shear hysteresis. They concluded that drape profile may be better predicted directly from bending and shear hysteresis.

Termonia[78] used a discrete model of fibres on a lattice to determine the importance of bonding pattern, lay-down non-uniformities, fibre length and orientation distribution on the bending stiffness and drape of nonwovens.

Another physical approach involves the use of deformation energies with certain dynamic constants,[18,19,79,80] which is particularly suitable for modelling dynamic garment drape in a virtual manner, provided effective collision direction and response algorithms are developed.

Particle-based physical models[81–83] have been proposed and show some potential. Based on the microstructure of woven fabric, Breen *et al.*[81] assumed that the fabric consists of a set of particles interacting according to certain physical laws. Eberhardt *et al.*[84] extended Breen's model by using a different, faster technique to compute the exact particle trajectories.[17] Stylios *et al.*[21] assumed that the fabric is formed of rigid bar-deformable nodes, and the governing differential equations of motion and deformation incorporating fabric mechanical properties were used to produce draping simulation.

Fan *et al.*[64] stated that such conventional methods, based upon fabric mechanics, have the advantage of understanding the fundamentals but have difficulty in accounting for the effects of accessories, seams and styles, their application to more complex garments being questionable.

Using a database of stored drape images of garments made of typical fabrics, Fan *et al.*[64] demonstrated the feasibility of using a fuzzy-neural network system to predict and display drape images of garments comprising different fabrics and styles. A prototype drape prediction system was developed to predict the drape of a ladies' dress style made from different fabrics. The advantage of the fuzzy-neural network approach is that it allows very fast computation, provided that the database contains an adequate number of drape images, and is used to train the fuzzy-neural model; the predicted drape image will be very close to the actual one. The disadvantage is that only a limited number of styles and changeable feature dimensions can be accommodated. Cho *et al.*[85] developed a method of individual pattern making by modifying traditional systems, so that it can be used in conjunction with modern 3-D modelling techniques. It enables customised pattern making for individuals. They used a five-step drafting process, viz. (i) defining the surface shape, (ii) setting grainlines, (iii) fitting the fabric to the surface shape, (iv) cutting of the 3-D surface and (v) developing the 3-D fitted fabric into a 2-D pattern. They used 3-D body data obtained by body scanning, and their entire process involved the use of geometrical computer models.

Doraiswamy *et al.*[86] developed an ANN based model to predict fabric sensory properties, including drape, from air-jet yarn properties. Fan *et a1.*[64] concluded that drape simulation was a complex and challenging task, and that their approach tested satisfactorily against ladies' dresses and a wide range of fabrics. Ji *et al.*[87] developed a practical mass–spring system to simulate the draping of woven and knitted fabrics, incorporating the fabric properties measured on the Kawabata system into the model to simulate dynamic draping behaviour. They[88,89] developed a method of 3-D garment drape modelling, simulating the garment using a 3-D quadrangular mesh based on the mass–spring system. The dynamic garment simulations can be implemented on a moving body. Zhong and Xu[5] used a separate wrapping procedure for 3-D dressing simulation by introducing a force adaptation field to move all the particles on a pattern to form a 3-D configuration that follows the mannequin surface. The 3-D wrapped configuration provides a virtual garment for checking the fit of the designed patterns on a given mannequin and an initial state for the draping simulation. Liu and Geng[90] reported on an expert system and 3-D modelling technique for the intelligent design of 3-D garments. They constructed a 3-D garment prototype using the techniques of parametric cubic spline and bi-cubic surface patch. A series of production rules for the design of a 3-D garment style was developed, and using object-oriented technology the knowledge base for 3-D intelligent garment design was built.[90]

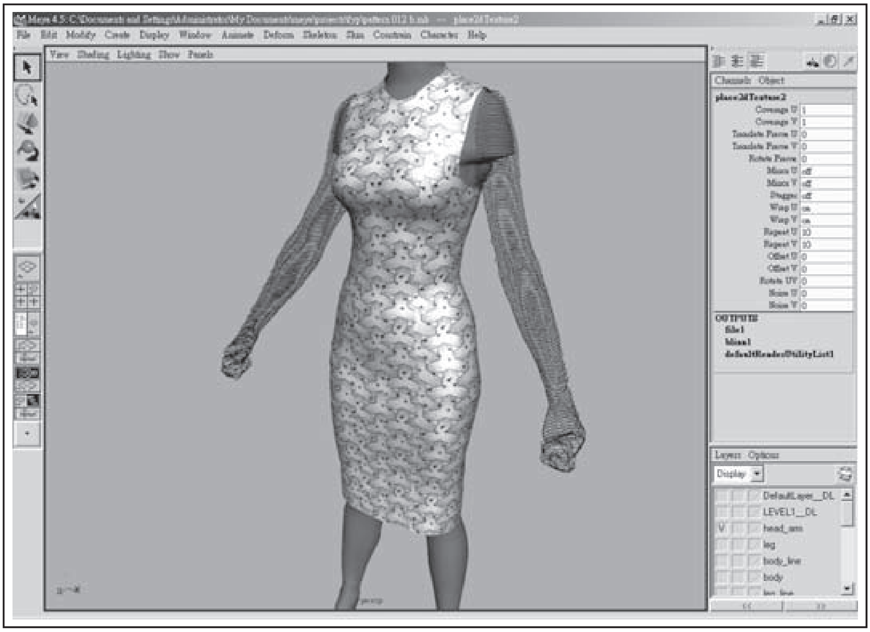
Niwa *et al.*[91] developed a method of objectively designing the optimum silhouette of ladies' garments based on fabric mechanical properties, such as tensile, shearing and bending properties. The optimum silhouette is objectively discriminated into three silhouette groups (tailored, anti-drape and drape), using a discriminant equation. Wang *et al.*[92] developed a digital engineering design system on the basis of particle-based models to simulate clothing dynamical behaviour.

Charfi *et al.*[93] presented a new experimental way to determine viscosity energy damping parameters in cloth simulation models. Wang *et al.*[94] modelled the cross-section shape of women's jacket designs incorporating girth measurement and fabric bending rigidity, the outline of the cross-section being fitted by a second-order polynomial model.

5.6 Drape models in CAD and Internet systems

Drape modelling, in particular 3-D visualisation of designed garments in draped form, is one of the key technologies in computer-aided garment design (CAD) and Internet apparel systems, since it enables designers to assess the design, fabric suitability and the accuracy of garment patterns in a computer environment, and it is also essential for the popular Internet systems to work effectively for trading and retailing as, without it, buyers and consumers will not be able to assess garment style, appearance, fit and suitability through the Internet.

Commercial apparel CAD, such as the Lectra system,[95] Gerber system,[96,97] and the PAD system, offers the following software systems[98–100] that can allow pattern makers to select patterns from a file library and instantly view them assembled on a 3-D dress form. The virtual stand can be rotated to allow the garment to be viewed from any angle. The garment can also be adjusted to any specific body measurements, whether standard sizes or individual customer measurements, to allow the operator to visualise any size. Any changes made to the patterns on the stand are automatically translated into a two-dimensional pattern and *vice versa*.



5.4 Computer screen of Maya Cloth.™

The scanned or digitally photographed images of the fabric can be rendered on the garment surface to give a realistic look in terms of colour, texture and surface design. Since fabric mechanical properties are important to drape (for example, a garment in the same pattern made of soft-flowing silk will give a completely different look from that made of a stiffer cotton material), a number of fabric coefficients in the KES-FB measurements or fuzzy values can be entered, to simulate the drape properties of different fabric types, giving a relatively accurate visualisation of the finished sample. Full-colour 3-D styles can be printed on any Windows-compatible colour printer, essentially creating a virtual sample.[96]

The 3-D drape of garments can also be modified by altering the pattern and the properties of material in terms of thickness, weight, extensibility and stiffness, in a relative scale (not in terms of strict mechanical properties).[101] Figure 5.4 shows a clothed person created using the Maya Cloth™ software. Draping models are also built into software designed for the animation industry, such as Maya Cloth (Fig. 5.4) and the Syflex LLC system.[102] Compared with apparel CAD systems, the pattern design and grading function may not be as advanced, but they can simulate garment drape on a virtual person (instead of just on a dress stand or dummy); the dynamic draping effects created by wind or body motion can also be simulated.

5.5 Virtual draping of cloth in My Virtual Model.™ Source: URL[105]

Another category of commercial CAD system, such as Poser 7[103] and Virtual Fashion Professional,[104] is targeted at creating virtual fashion collections. Designers can create different items of coordination, such as ear wings, head bands, shoes, hats, etc. For such software, high-resolution images, rendering of specific scenes and realism in animation are crucial. Poser, for example, has the ability to add dynamic hair and clothing to the virtual figure. By controlling these two dynamic parts of a virtual figure, enhanced realism can be achieved with the animations. Clothing can drape naturally and deform as if in real life over a human figure, while hair can be grown, styled and controlled dynamically, as if blown by the wind.

Drape models have been incorporated in Internet websites for virtual shopping. For example, in landsend.com,[105] customers can log on to the Web using My Virtual Model™ (Fig. 5.5) to create their own model (3-D mannequin) by submitting their body measurements and appearance details, such as height, weight, shoulder width and hair colour. After creating their own model, customers can select the outfit from the web store to drape onto the model. Users can also rotate the model to view the outfit from different sides.

Commercial fabric design software, such as SoftWeave Jacquard and Dobby Designer, may also display the draping effect of newly designed fabrics. However, the display is just one of several fixed drape settings[106] with changes only in texture and pattern details, i.e. the draping effect is not modelled from the fabric mechanical properties.

5.7 Sources of further information and advice

A recent book[107] deals comprehensively with draping technology and related technologies and issues.

Jacob and Subramaniam,[108] Hu[17] and Chan[13] have briefly reviewed published work on drape. Subramaniam[109,110] undertook thorough reviews of the published work on fabric bending and drape and in 1983 Subramaniam *et al.*[111] also reviewed published work on fabric shearing properties, which play an important role in fabric drape. Bhatia and Phadke[8] reviewed the influence of drape properties on clothing styles. Chung,[12] Hunter and Fan[112] and Bhalerao[27] also reviewed the subject.

5.8 Concluding remarks

Earlier work on drape concentrated mostly on its accurate measurement and on the empirical prediction of drape from the fabric mechanical properties, notably bending and shear rigidity, and hysteresis. Various prediction equations and models (e.g. regression and neural networks) were developed in the process. More recently, however, attention has increasingly focused on the 'modelling garment drape' – this being important for developing 3-D garment CAD systems. After reviewing most of the related software and tools, it could be summarised that the ideal drape models should not only display the static drape of the garment realistically with 3-D renderings of design features, colours and surface textures, but should also be able to simulate animated dynamic drape. It should have the capability to convert 3-D shapes into 2-D patterns or vice versa. Although most apparel CAD systems or drape models available on the Internet claim to present realistic draping effects, their real performance needs to be evaluated by the end user.

Although significant improvements in the drape models have occurred over the past two decades, further development in this area is still needed. As Wentzel[113] pointed out, 'the imagery of the virtual 3-D sample tends to be flat, with the stand and garment looking somewhat sterile. Although fabric coefficients can be entered, the representation of the fabric drape still leaves some room for improvement.' When 3-D animation is to be achieved, the challenge is greater. The resolution of the 3-D virtual garment is often still low in real-time presentation. Owing to the complexity and high polygon calculation, it takes a long time to achieve accurate performance of 3-D animation. When the virtual garment is presented in a dynamic way or 360° rotation, the figure frequently tends to show a lot of shading and poor texture effects.

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6
Appearance issues in garment processing

J. FAN, L. LAU and L. HUNTER

Abstract: The appearance of a garment is affected by the quality of the fabrics used in its manufacture, as well as the factors determined by the technology and parameters of the garment manufacturing process. In this chapter, appearance issues relating to garment processing, including seam appearance, appearance of fused parts, appearance issues in garment dyeing, appearance issues in pressing, storage and packaging are discussed.

Key words: garment appearance, sewing, fusing, garment dyeing, pressing.

6.1 Introduction

The conversion of a two-dimensional fabric into a three-dimensional garment or article involves many processes, such as handling, cutting, sewing, and pressing the fabric, as well as parameters such as sewing needle and thread, and sewing machine.[1] The appearance of a garment is affected by the quality of the fabrics used in its manufacture, as well as the factors determined by the technology and parameters of the garment manufacturing process. The selection and use of the processes and parameters can ultimately affect the garment appearance. In this chapter, appearance issues relating to garment processing, including seam appearance, appearance of fused parts, and appearance issues in garment dyeing, pressing, storage and packaging are discussed.

6.2 Seam appearance

In the formation of a seam, at least four components are involved: an upper fabric, a lower fabric, a needle thread and a bobbin thread. When forming the seam, the four components are acted upon by the feed and needle mechanisms of the sewing machine, which exert on each seam component a fairly complex system of forces. The forces acting on the different components may differ, since the deformation may be different in each component. As a result, when the components start to recover after the release of the seam, distortion, termed 'seam pucker', may occur.[2,3]

Seam pucker is defined as 'a distortion of the fabric along the seam line, causing a wrinkled appearance. It may occur immediately after sewing, dry relaxation, steaming or laundering.'[3] Reducing the pucker by ironing or pressing may be a temporary solution, as after laundering, pucker may re-occur.[4] Seam pucker can be caused by fabric structure and properties, sewing thread properties, and garment processing parameters.

6.2.1 Effect of fabric structure and properties

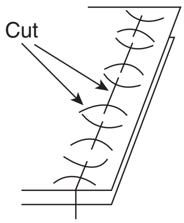
Fabric structure and properties related to seam pucker include fabric weight, fabric construction and density, fabric extensibility, and fabric dimensional properties (i.e. relaxation shrinkage and hygral expansion).

Fabric weight

In general, lightweight and dense fabrics pucker more easily than heavy-weight fabrics. However, if a lightweight fabric has sufficient space between the yarns for the needle to be inserted, pucker is unlikely to occur. Furthermore, excessively heavy fabrics can also cause seam pucker. According to research by Behera *et al.*,[1] the weight of a denim fabric is one of the factors affecting the seam appearance; results showed that puckering consistently increased with an increase in the weight of denim fabric. When the sewing thread penetrates a heavy fabric, it introduces a very high contractive force. Consequently, severe puckering can take place in heavy fabrics.

Fabric density

Seam pucker is common in woven fabrics but not in knitted fabrics. The situation becomes worse in tighter fabrics, particularly in the warp direction. Seam pucker caused by the dense structure of the fabric is called inherent pucker (Fig. 6.1). Inherent pucker occurs because of fabric structural jamming (or yarn displacement). This means that the fabric has been so densely (tightly) constructed as to be very close to the practical weaving limit, i.e. there is insufficient space left between the yarns for the sewing thread to be inserted. Dorkin and Chamberlain[2] conducted a test on plain weave fabrics woven from hard-twisted and relatively fine yarns using a set close to the weaving limits. Their results showed that structural jamming was a major cause of seam pucker. This type of seam pucker is entirely independent of the mechanics of the sewing machine.[2] The problem can be avoided or reduced by using a thinner thread and a smaller needle point; a needle plate and a presser foot with a smaller needle hole; fewer stitches



6.1 Inherent pucker. Source: URL[7]

per cm; and stitching in a direction which allows the different yarns in the construction of the fabric to be displaced.[2,3,5,6]

Fabric extensibility

Seam pucker is much more of a problem on stretchy woven fabrics than on standard woven fabrics, particularly for seams that run on the bias. Also, if the fabric stretch of the two plies of fabrics is different, feed pucker may occur. To minimise seam pucker, one can use sewing machines with differential feed.[7] Too low fabric extensibility can also cause seam pucker. Too low fabric extensibility corresponds to low in-plane compression, which means the fabric is easy to buckle and therefore pucker when compressed in its own plane resulting from the insertion of sewing thread and thread contractive forces.

Fabric dimensional properties

As mentioned in Section 6.2, pucker can be caused by dry relaxation (e.g. wearing), steaming or laundering. When two components sewn together have different shrinkage rates, shrinkage pucker can quite easily occur. The component that has the lower shrinkage rate will buckle, resulting in a shrinkage pucker. To prevent or reduce this type of pucker, it is necessary to use compatible components that have similar dimensional stability.[3,8]

6.2.2 Effect of sewing thread properties

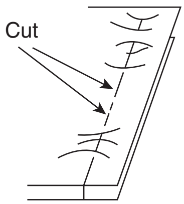
The use of a better sewing thread to minimise the problem of seam pucker is the easiest, least expensive option. Mori and Niwa[9] studied the effect of various mechanical properties of sewing threads on seam pucker. The study defined a range of thread mechanical properties and placed the threads into two broad categories, soft threads and hard threads. Soft threads had low and elastic modulus and high residual strain, and low bending rigidity and low frictional force. Hard threads had high elastic modulus and low residual strain, and high bending rigidity and high frictional force. There may be an optimum thread for each type of machine. Serious seam pucker can occur with a sewing machine on which high needle thread tension is required to obtain balanced seams. For such sewing machines, a hard thread is more suitable than a soft thread for reducing pucker. In the case of sewing machines for which a lower thread tension is best, a soft thread is more suitable than a hard thread.

Composition

The composition of the sewing thread can influence the seam appearance of a garment. Dobilaite and Juciene[10] compared the appearance of seams sewn using polyester and cotton threads, respectively. Better seams were sewn when using polyester threads owing to their lower reversible strain. Because of yarn swelling, seams sewn with cotton sewing threads tend to produce more pucker after washing and drying than those sewn with polyester sewing threads.

Extensibility and contraction

Two sewing threads are generally used in making a seam, and both are subjected to tensile forces during the process of seaming, which tend to stretch them. The upper, or needle thread operates at a much higher tension than the lower, or bobbin, thread because during the making of the stitch, the upper thread has to snatch or tug the lower thread up from below the fabric to form a loop midway between face and back of the seam, and this requires considerable force. Typical sewing tensions might be 200 grams in the upper thread and 30 grams in the lower.[2] When the thread tension is relieved after sewing, the threads start to contract, and the stitch length will decrease. If the decrease in stitch length is greater than the contraction of fabric within the stitch, thread tension pucker will appear[3] (Fig. 6.2). In 1961, Dorkin and Chamberlain[2] identified five causes of seam pucker, two of which were associated with the sewing threads – namely seam pucker due to the extension and contraction of the sewing threads, and that due to structural jamming, which is associated with sewing thread diameter. The effect of the extensibility of the sewing threads was included in Amirbayat and Morton's[11,12] theoretical models. The higher the thread tension, the greater the tendency for seam pucker. Although sizing or resin on the fabric can prevent or reduce this problem, the seam will still become puckered after laundering. Thread tension pucker can be minimised by reducing the thread tensions on the sewing machine, or using a thread with a low elongation or high initial modulus to minimise stretching during



6.2 Thread tension pucker. Source: URL[7]

sewing. If structural jamming does not occur, it is beneficial to increase the needle size or use a needle with a ball eye (ball point) to open up a larger hole in the fabric so the stitch can be set. The take-up spring, thread control guides and eyelets should also be properly set to avoid undue tension of the sewing thread during sewing.[4]

Diameter

Thread diameter is the factor which most influences fabric structural jamming.[10] If the thread diameter is high, and the fabric is very dense (i.e. tight), there is insufficient space to accommodate the sewing thread. Geometrical relationships between fabric and sewing thread were developed for lock-stitch seams in plain woven fabrics by Ferd. Schmetz GmbH.[13] The tendency to pucker caused by structural jamming increases with sewing stitch count and decreases with thread size (i.e. with decreasing yarn diameter). Fan and Leeuwner[14] found that the thinner the sewing thread, the better the thread in terms of seam appearance, i.e. lower pucker.

Twist

Thread twisting can influence the thread properties. Rudolf and Gersak[15] investigated the effect of twists on the mechanical properties of 100% polyester core-spun threads with a nominal linear density of 13.5 tex × 3 and final twist in Z-direction and with the number of turns changed from 800 to 1200 turns/metre. The study showed that the increase in the number of turns of the thread resulted in a decrease in breaking tenacity values, elasticity modulus and tension at the yield point, and an increase in breaking extension. Therefore, thread twist can indirectly affect the appearance of the seam.

Bending stiffness

Stylios and Lloyd[16] believed that the difference between the stiffness of the fabric and the stiffness of the sewing thread affected the occurrence of seam pucker in structurally jammed woven fabrics. This was based on the observation that the bending stiffness of the thread tended to be higher than that of the fabric for those fabrics that exhibit severe seam pucker.

Friction

The higher the friction between the fabric and the thread during the formation of a seam, the higher the thread tension, and the greater the tendency for seam pucker. A higher thread tension develops when sewing with threads of a higher surface friction, and therefore the contraction of the threads after sewing is greater, as is the probability of seam pucker.[14]

Irregularity

Irregularity can have an effect on seam pucker because, understandably, the thick places in a sewing thread can cause structural jammed seam pucker, in the same way as a coarse thread. Irregular threads also exhibit differences in extension during sewing and, therefore, potential differences in subsequent contraction.[14]

Sewing Thread Pucker Index

Fan and Leeuwner[14] proposed a parameter called 'Sewing Thread Pucker Index' (STPI) to combine the effects of various sewing thread properties on the occurrence of seam pucker. STPI can be calculated as follows:

$$\text{STPI} = 1.46LD + 1.51CVI + 27.1EXT + 1.01FR - 57.0 \qquad [6.1]$$

Where LD is thread linear density in tex, CVI is thread evenness measured on an Uster Tester III, EXT is extension at 1 newton measured using an Uster Tensorapid and FR is thread surface friction, measured using a SAWTRI yarn friction tester. The lower the STPI is, the better the thread in terms of seam appearance.

Measurement of relevant sewing thread properties

Table 6.1 lists the test methods and instruments for measuring some important sewing thread properties.

6.2.3 Effect of garment processing parameters

Garment processing parameters, such as type and size of needle, type of feed dog, and sewing machine setting, can all influence the seam appearance.

Table 6.1 Methods and systems for testing some important sewing thread properties

No.	Sewing thread properties	Test methods and instruments
1	Thread linear density/ticket number	Linear density can be determined by measuring the mass and length of the threads under standard atmospheric conditions (20°C, 65%RH). Ticket number can be designated according to BS4134 (1990) or ASTM D3823-88
2	Tensile properties: tensile strength, loop strength, knot strength, tenacity, elongation at break, and modulus	(a) Uster Tensorapid (expect for loop and knot strength) (b) Instron in accordance with BS1932: Parts I (1965) and II (1966)
3	Elasticity	Extend the thread on an Instron to a pre-defined load or extension and then measure its recovery
4	Evenness	Uster Yarn Evenness Tester
5	Hairiness	Shirley Yarn Hairiness Tester
6	Surface friction	SAWTRI Yarn Friction Tester
7	Shrink resistance to heat and boiling water	ASTM D204-82
8	Abrasion resistance	Specially prepare the sample for testing on the Martindale Abrasion Tester
9	Colour fastness to weathering, light, sunlight, crocking, perspiration, washing, dry-cleaning, ironing, dry heat, laundering and gas fumes, etc.	Appropriate AATCC methods

Needle diameter

If the needle diameter is too high so that the fabric has insufficient space to accommodate the needle, seam pucker will occur. To reduce or avoid this phenomenon, the use of a finer needle is recommended.

Feed dog

Inappropriate feed dog height and back-feeding can cause seam pucker. The feed dog should have the optimum number of teeth and rows of teeth for the operation and fabric being sewn. Sometimes, pucker occurs when the material is not held down flat as it is being fed through the machine, creating a rippled appearance as the plies conform to the feed dog teeth. Generally, lightweight, wrinkle-resistant fabrics should be sewn with feed dogs having 20–24 teeth per inch. Medium-weight fabrics such as for men's trousers should be sewn with feed dogs having 14–18 teeth per inch. Heavyweight fabrics are usually sewn with feed dogs with 8–12 teeth per inch.[6]

Presser foot pressure

The seam pucker caused by the pressure of the presser foot is also called 'waviness'. The pressure exerted by the presser foot against the needle plate causes the fabric to spread. Therefore, the seam is produced on a fabric the dimensions of which have been momentarily altered. When the fabric returns to its normal dimensions, waviness occurs. Reducing the pressure of the presser foot can prevent or at least reduce waviness.[3] Furthermore, high presser foot pressure tends to cause differential feed between the top and bottom layer of the fabric. When the pressure is too high, the top fabric layer tends to be fed slower than the bottom layer due to the higher friction between the presser foot and top fabric. Differential feed is also a major cause of seam pucker.[2]

Sewing speed

When the sewing speed increases, it requires an increase in the pressure of the presser foot in order to control the feed and prevent the presser foot from bouncing under the impact of the feed dog movement. The bouncing of the presser foot disturbs the fabric feed, leading to a puckered seam and uncontrolled sewing conditions. To obtain controlled conditions, some additional pressure has to be applied to the presser foot. This results in a greater retarding force between the presser foot and the top fabric producing further displacement between the fabrics, thereby leading to greater seam pucker.[3]

Human factor

Seam pucker can be caused by a lack of skill and/or carelessness in operations (e.g. mismatched garment pieces). For example, an operator holds back the bottom ply of fabric and pushes the top ply into the sewing machine, resulting in the two plies being fed into the seam at different rates, thereby causing pucker.

6.2.4 Causes of seam pucker and their solutions

As discussed above, seam pucker can be caused by fabric construction and properties, sewing thread properties and garment processing parameters. The causes and solutions of seam pucker are summarised in Table 6.2.[8,13,17–22]

Table 6.2 Causes of, and solutions for, seam pucker

Causes	Solutions
Fabric dimensional instability (excessive shrinkage or hygral expansion)	• Control the dimensional stability (shrinkage or hygral expansion) of the shell fabric within the acceptable limit. • Select linings, interlinings and threads which have similar dimensional stability as the shell fabrics. • For cotton threads, the wet moisture shrinkage should be checked. • For synthetic threads, the heat shrinkage should be checked.
Differential fabric dimensional stability	• Ensure the fabrics joined together have similar dimensional stability. • Use lining and interlining which match the shell fabric in terms of dimensional stability.
Poor fabric sewability (e.g. too thin, very inextensible, very dense fabric structure, slippery fabrics)	• Use objective evaluation systems, e.g. KES or FAST, to evaluate the sewability of the fabrics. • For such fabrics, extra care must be taken during sewing to avoid pucker. • Apply minimum thread tension and presser foot pressure during sewing.
Excessive shrinkage of sewing thread	• Use pure synthetic or synthetic blend sewing threads which have low wet shrinkage, such as polyester, polyester/cotton. • Use synthetic threads for synthetic fabrics.
Structural jamming	• Try to minimize seams parallel to the warp or weft; instead, have seams at an angle (e.g. 15°) to one of the weave directions. • Use matching needle hole in the throat plate in order to avoid fabric flagging. • Avoid multiple rows of stitching/decorative stitching. • Avoid seams, such as lap fell seams, which need double needles. • Use chain stitches or over-edge stitches instead of lockstitches, if possible. • Use finest possible thread with finest possible needle compatible with the fabric thickness. • Reduce stitch density. • Use fine and lubricated threads compatible with the fabric.
Poor thread quality (e.g. thread shrinkage)	• Use a synthetic thread which has lower wet and relaxation shrinkage. • Within the strength requirements, thinner threads, having a higher tensile modulus, lower hairiness, lower friction and lower irregularity, are better. • Ensure the threads have good dimensional stability to heat, steam and water.

Table 6.2 Continued

Causes	Solutions
Too high sewing thread tension	• Regulate the tension spring and thread control guide to reduce the tension. • Release bobbin thread tension so that the bobbin case will slowly slide down when one holds the end of the bobbin thread. • Ensure bobbin thread and needle thread tensions are matched to form a balanced stitch. • Check threading is correct before sewing. • Use tension meter to control the thread/bobbin thread tensions. • Use 'puckermeter' attachment for sewing machine. • Use a thinner thread which requires less tension. • Use low friction threads.
Unequal feeding of sewing machines (unmatched feeding plates' movement and fabric movement)	• Check the feed dog – height, teeth/inch, number of rows, make sure it is appropriate for the fabric and operation. • Raise the back of the feed dog to enhance the feeding of the fabrics during sewing. • Use cloth pullers.
Differential fabric stretch	• Check whether fabrics are fed with the feed dog movement. Make sure the feed dog matches the fabric in terms of height, teeth/inch and number of rows. • Make sure the timing of feed dog and needle are matched. • Reduce the sewing speed. • Use low-friction presser foot, such as a Teflon foot or roller foot. • Minimize the presser foot pressure.
Too much ease/fullness on the pattern: • Mismatched patterns • Misaligned notches	• Check and revise the pattern. • Implement in-process quality control in pattern making, cutting and sewing. • Provide proper training to cutting technicians and sewing operators.
Improper handling by operators: • Unmatched fabric length during sewing • Unequal tensions of fabric layers during seaming	• Train operators to reduce the seam puckering from handling, cutting and pattern errors. • Avoid holding back of either top or bottom plies. • Check balance of forces applied to the top and bottom fabrics. • Make sure sewing machines are properly set before sewing.
Uneven fabric thickness (e.g. change of fabric thickness in front pocket)	• Reduce the fabric thickness by cutting the excess fabrics between panels. • Use skilled operators to sew the operations with uneven fabric thickness. • Steam press the seam line before sewing.

6.2.5 Objective evaluation of seam appearance

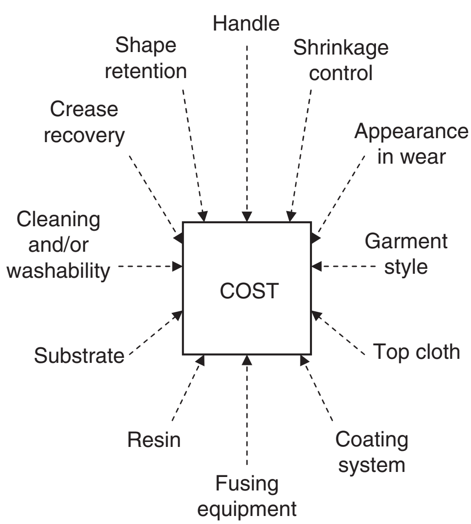
The AATCC grading method[23] is well established for evaluating seam pucker but it is a subjective method, and therefore subject to error and variability between occasions and locations, particularly for patterned materials and darker shades. It is also time-consuming and involves several people. From the 1950s to the 1970s, several instruments[24,25] using photo or displacement sensors were developed to measure the surface contours of seams. These instruments, however, had problems of accuracy and reproducibility. With the development and wide application of computer and sensor technology, renewed attempts have been made in recent years. In the 1990s, Stylios and co-workers[26,27] used a CCD camera to capture the image of a seam, and this information was then fed to a computer that could predict the grade or severity of seam pucker using an artificial intelligence algorithm. The CCD camera had difficulties in pattered fabrics, so was later replaced by a laser scanner.[28] In the last few years, a number of other researchers[29–31] have done similar work in this field using laser scanners. In 1999 and 2000, Fan *et al.*[32–35] developed a method for extracting the pucker signal from seam profiles measured with a laser scanner, when the seamed samples were laid on both curved and tilted surfaces to simulate seams in three-dimensional garment surfaces. Kang and his co-workers[36,37] proposed to use the fractal dimension to evaluate the surface ruggedness of wrinkles and puckers.

6.3 Appearance issues in fusing

Using fusible interlinings can prevent or reduce the problems of seam pucker. A fusible interlining is defined as a base fabric having a deposit of thermoplastic adhesive resin (usually on one surface only), which can be bonded to another fabric by the application of heat and pressure.[38] Fusible interlinings have enabled the apparel industry to make great strides in efficiency and quality in the past several decades, but the matter of finding the right interlining for a specific shell fabric continues to present challenges. If fusing is not handled properly, the shell fabric can change in colour or surface appearance, shrink, stretch or stiffen.[39]

6.3.1 Compatibility between shell fabric and interlining fabric

To ensure good appearance and drape of the finished garment, the interlining should be compatible with the shell fabric. However, fusible interlinings vary in terms of base fabric composition, base fabric structure and type of adhesive and finish. Fusible interlining suppliers are numerous.[40] It is not an easy task to select the most suitable fusible interlining for a specific shell fabric or a specific range of shell fabrics. In general, most companies have guidelines on how to select fusible interlinings. The traditional method of choosing a suitable interlining fabric is trial and error and/or by past experience. In general, many problems in fusible interlining selection and use can be avoided if manufacturers collaborate with their interlining suppliers in choosing the right fusible, and conduct pre-production testing to ensure consistent performance.[39] Moreover, some objective evaluation methods were developed to help with the selection of the most appropriate fusible interlining. Nitta[41] suggested the optimum combination of interlining and suiting materials based on the objective measurement of fabric mechanical properties and personal experience. Optimum zones for bending rigidity and shear stiffness of interlining fabrics were found in relation to the fabric properties. Results showed that the flexibility in bending of interlining has no significant effect on its performance, but ease of shearing causes difficulty in the tailoring operation as it becomes difficult to keep the shape of the interlining during the lining operation when the interlining has low shear stiffness. Cooklin[38] stated that the selection of fusible interlinings is governed by the cost and performance relationship. He outlined the factors influencing the choice of fusible interlinings (Fig. 6.3). Fan *et al.*[42–44] proposed a control chart to objectively evaluate the quality of the fused front parts of tailored jackets and to select compatible interlinings for specific



6.3 Factors influencing the selection of fusible interlinings. Source: Cooklin, 1990[39] outer fabrics in terms of low-stress mechanical properties. The desirable range of mechanical properties of fusible interlinings can be estimated from the mechanical properties of the outer fabrics, using the following equations:

Mass

$$Mi \leq 0.5Mf \qquad [6.2]$$

Where *Mi* is the mass of fusible interlining, *Mf* is the mass of outer fabric.

Warp extensibility

$$\begin{array}{ll} Eiwp = \text{as high as possible} & (\text{when } Efwp \leq 0.33) \\ Eiwp \geq Efwp/(3.0Efwp - 1.0) & (\text{when } 0.33 < Efwp \leq 2.2) \\ Efwp/(3.0Efwp - 1.0) \leq Eiwp & \\ \quad \leq 2.2Efwp/(Efwp - 2.2) & (\text{when } Efwp > 2.2) \end{array} \qquad [6.3]$$

where *Efwp* and *Eiwp* are the warp extensibilities of the outer fabric and fusible interlining in percent, respectively.

Weft extensibility

$$\begin{array}{ll} Eiwt = \text{as high as possible} & (\text{when } Efwt \leq 1.1), \\ Eiwt \geq 1.1Efwt/(Efwt - 1.1) & (\text{when } 1.1 < Efwt \leq 5.8) \\ 1.1Efwt/(Efwt - 1.1) \leq Eiwt & \\ \quad \leq 5.8Efwt/(Efwt - 5.8) & (\text{when } Efwt > 5.8) \end{array} \qquad [6.4]$$

where *Efwt* and *Eiwt* are the weft extensibilities of the outer fabric and fusible interlining in percent, respectively.

Warp bending rigidity

$$22.0/(Bfwp^2) \leq Biwp \leq 658.5/(Bfwp^2) \qquad [6.5]$$

where *Bfwp* and *Biwp* are the warp bending rigidities of the outer fabric and fusible interlining in μN.m, respectively.

Weft bending rigidity

$$\begin{array}{ll} 5.3 - 0.57Bfwt \leq Biwt & \\ \quad \leq 11.5 - 0.57Bfwt & (\text{when } Bfwt \leq 9.3) \\ Biwt \leq 11.5 - 0.57Bfwt & (\text{when } 9.3 < Bfwt < 20.2) \\ Biwt = \text{as low as possible} & (\text{when } Bfwt > 20.2) \end{array} \qquad [6.6]$$

where *Bfwp* and *Biwt* are the weft bending rigidities of the outer fabric and fusing interlining in μN.m, respectively.

Shear rigidity

$$\begin{aligned}
&22.1 - Sf \le Sf \le Si \\
&\quad \le \min\{(81.2 - Sf), \\
&\qquad (\exp(0.051 * Sf + 2.79) \\
&\qquad - Sf)\} && (\text{when } Sf \le 22.1), \\
&Si < \min\{(81.2 - Sf), \\
&\qquad (\exp(0.051 * Sf + 2.79) \\
&\qquad - Sf)\} && (\text{when } 22.1 < Sf < 81.2), \\
&Si = \text{as low as possible} && (\text{when } Sf \ge 81.2)
\end{aligned} \qquad [6.7]$$

Where *Sf* is the shear rigidity of the outer fabric in N/m, and *Si* is the shear rigidity of the fusible interlining in N/m.

6.3.2 Strike-through and strike-back

During fusing, three parameters must be considered: the fusing method; the fusing machine; and the condition of the fusing (viz. temperature, time, pressure and cooling). If the parameters are not properly selected and/or adjusted, fusing problems (e.g. strike through and strike back, colour changes and fusing distortion) can occur.

Strike-through (Fig. 6.4) means that the adhesive resin appears on the outer face of the fabric being fused. Table 6.3 summarises the causes and solutions for strike-through.[22,38,45–48]

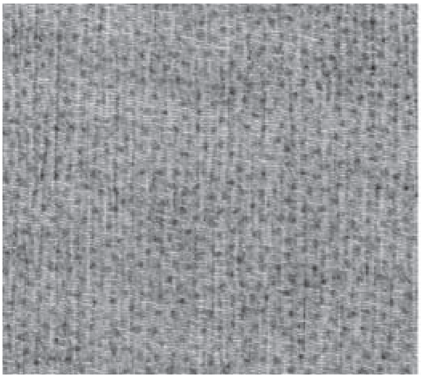
Strike-back (Fig. 6.5) means that adhesive resin appears on the non-adhesive side of the fusible interlining after fusing. Table 6.4 lists the causes and solutions of strike-back.[22,38,45–48]

6.3.3 Colour changes during fusing

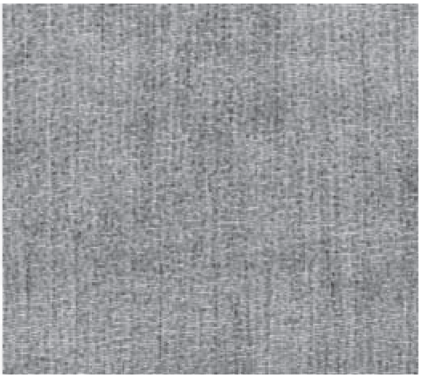
Inappropriate fusing can cause temporary or permanent colour changes (shine/glazing and/or discoloration) in fabrics (Fig. 6.6). Colour changes during fusing are caused by the action of heat on certain dyes. The causes and solutions for this phenomenon are listed in Table 6.5.[22,38,45,48,49]

6.3.4 Fusing distortion

Fusing distortion (Fig. 6.7) means that garment panels are distorted during the fusing process. This problem should be prevented, as such distorted garment panels cannot be corrected and must be discarded as waste. Fusing distortion may be caused by inadequate fusing conditions, improper handling of fusing panels, poor stability of the fabric and wrong fusing directions. The causes and solutions of fusing distortion are summarised in Table 6.6.[22,38,45,48,49]



Strike-through in a fabric

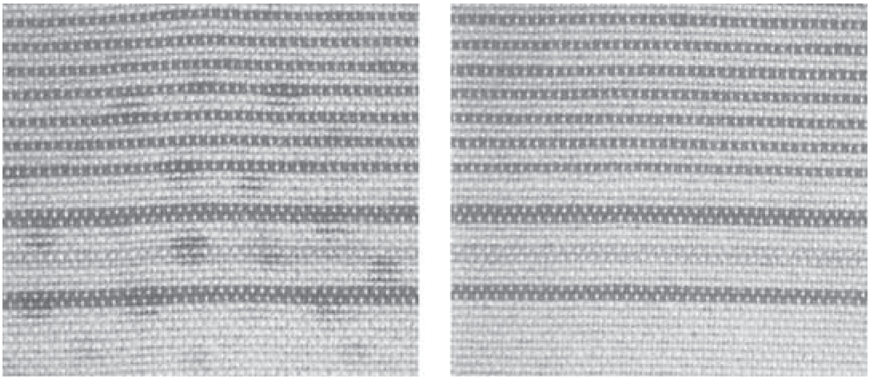


Ideal fusing in a fabric

6.4 Strike-through. Source: Vilene Fusing Guide, 1999[49]

Table 6.3 Causes of, and solutions for, strike-through

Causes	Solutions
Too long fusing time	• Reduce fusing time. • Shorten fusing time for thinner fabrics. • Carry out a fusing test before bulk production.
Too high fusing temperature	• Reduce fusing temperature. • Carry out a fusing test before bulk production. • Use a temperature measurement strip to find the optimum fusing temperature.
Too high fusing pressure	• Fusing test should be carried out to check for the bond, surface and handle of fabrics before bulk production. • Pressure setting should follow machine manufacturers' instructions. • Reduce the pressure for lightweight and loosely constructed outer fabrics.
Incompatible fusible interlining (too much adhesive on interlining)	• Avoid using interlining with excessive adhesive. • Reduce size of the adhesive dots on the interlining. • Reduce the weight of the adhesive dots on the interlining. • Carry out a fusing test before bulk production.
Inappropriate fusing method for thin and loosely constructed fabrics	• Use frame fusing for thin and loosely constructed fabrics. • Carry out a fusing test before bulk production.

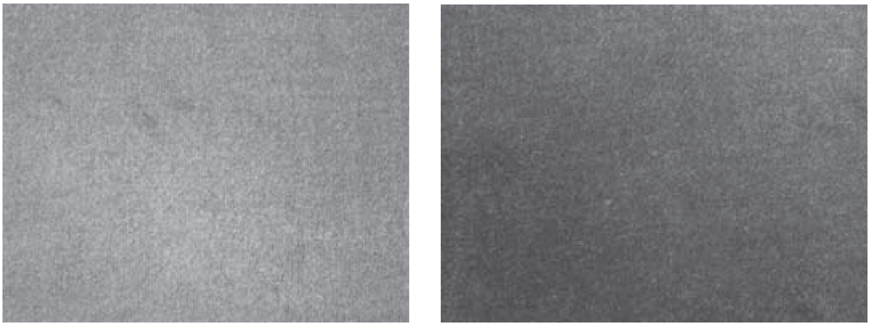


Strike-back in a fabric   Ideal fusing in a fabric

6.5 Strike-back. Source: Vilene Fusing Guide, 1999[49]

Table 6.4 Causes of, and solutions for, strike-back

Causes	Solutions
Inappropriate fusible interlining	• Avoid using too light substrate materials. • Avoid using interlining with excessive adhesive. • Reduce size of the adhesive dots on the interlining. • Reduce the weight of adhesive dots on the interlining. • Carry out a fusing test before bulk production.
Too long fusing time	• Reduce fusing time. • Carry out a fusing test before bulk production.
Too high fusing temperature	• Reduce fusing temperature to avoid adhesive becoming too fluid. • Carry out a fusing test before bulk production. • Use a temperature measurement strip to find the optimum fusing temperature.
Too high fusing pressure	• Fusing test should be carried out to check the bond, surface and handle of fabrics before bulk production. • Pressure setting should follow machine manufacturers' instructions. • Reduce the pressure for lightweight and loosely constructed outer fabrics.



Discoloration after fusing   Normal fabric

6.6 Discoloured fabric after fusing. Source: Vilene, 2000[51]

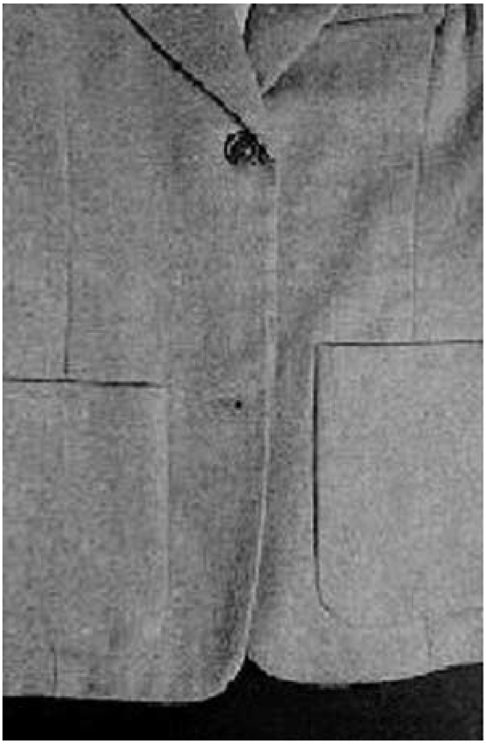
Table 6.5 Causes of, and solutions for, colour changes during fusing

Causes	Solutions
Some synthetic fabrics change colour temporarily after heat press/iron heat	• Regulate the pressing temperature, pressure and time to avoid overheating and over pressing. • Allow fused fabrics to cool down for a while to regain their colour.
Excessive temperature, pressure and time during the fusing process	• Select Multivariable Adhesive (MVA) that requires lower temperature, pressure and time for fusing. • Put a cloth (same material or cotton) to cover the fusing material during heat pressing.

6.4 Appearance issues in garment dyeing

The demands of both quick response and manufacturing flexibility have prompted the need for garment dyeing, as opposed to using coloured yarns or fabrics.

Garment dyeing may be defined as the application of colour to fully fashioned apparel articles, and these articles may be in the following forms (i) Garments cut and sewn from either prepared (e.g. bleached and scoured) or unprepared knitted fabrics and then dyed. (ii) Garments and/or components knitted from either prepared or unprepared yarn and then dyed. (iii) Garments manufactured from either prepared or unprepared woven fabric and then dyed. (iv) Mixed fabric garments, i.e. woven and knitted fabrics manufactured from prepared fabrics and then dyed.[51]



6.7 Fusing distortion caused by mismatched left and right front panels. Source: URL[23]

Garment dyeing has a cost advantage over conventional dyeing, particularly for sportswear and casual wear. Garment dyeing also offers flexibility for rapidly changing markets, quick response and rapid turnaround, low inventory, etc. There are, however, some disadvantages associated with garment dyeing, in that it is labour intensive, produces poor fabric appearance, provides poor reproducibility of shade, and requires special care in the selection of fittings and more material handling.[51–53]

6.4.1 Conditions for garment dyeing

Garment dyeing can utilise different kinds of dyestuffs and can dye into different texture appearance.[54] A good quality garment should have good appearance that complies with customers' demands. Since the fibre does not change its inherent characteristics when converted into the garment, the considerations for garment dyeing and other types of dyeing, e.g. fabric

Table 6.6 Causes of, and solutions for, fusing distortion

Causes	Solutions
Poor fusing machine setting and conditions, e.g. speed of the continuous fusing press, temperature, pressure and setting time.	• Reduce the speed of the fusing press. • Reduce the pressure of the fusing press. • Establish optimum fusing machine setting by consulting the interlining supplier. • Allow time for the fused parts to cool before handling. • Test the fusing conditions before bulk fusing.
Bad orientation of fusing panels.	• Change orientation of panels in order to avoid the corner of the garment panels being caught first by the pressure rollers of the fusing press. • Pre-set the fusing panels by hand-ironing before passing the fusing panels to the fusing press. • Use flat-bed fusing press, if available.
Unstable fabric/substrate properties	• Use stable fabrics – avoid fabrics which have low shear rigidity. • Take extra care in fabric handling during the fusing process.
Wrong fusing directions	• Interlining and outer fabrics should be fused in the same direction, with similar dimensional changes.

dyeing or yarn dyeing, are similar. Each garment type will have its own specific processing requirement, depending upon fibre type or fibre blends and the required end-result.[55] Good garment dyeing depends on the optimal selection of machinery and equipment, dyes, fabrics and chemicals, and the control of pH, temperature and handling.[53]

Preparation and handling before dyeing

All the finishes and residues on the fabrics and garments must be removed before the garment dyeing process. In some cases, it may be advisable to invert the garment and join seams by tacking or by the use of tag fasteners. Generally, the best appearance of the garment is preserved if the garment is inverted prior to dyeing and then reversed to the correct side after drying. Generally, a significant amount of processing and testing must be done prior to actually dyeing the garments. It is very important that a reputable dyer is selected, and the customer must be aware that this is often a time-consuming process.[54]

Machinery

Garment dyeing processes now generally use energy efficient, labour-saving machines which are easy to operate. Paddle machines and rotary drums are the two types of machine regularly used for garment dyeing. A high liquor ratio is required for paddle machines, which is less economical and limits shade reproducibility.[54,56] Many garments are dyed in open-chamber rotary machines, where the primary concerns are tangling and abrasion prevention. Rotary drum machines are sometimes preferred for garments such as sweaters, which require gentler handling.

Selection of dyes or pigments

Dyes or pigments are selected based on the type of fibre and fabric (or combination of fibres and fabrics) to be dyed, the garment type, and the desired colour, consistency, texture and feel of the finished garments.

The type of dye or pigment selected can also impact upon the shade range and light fastness of the finished garment. Therefore, it is important to consider the function of the finished garment. For example, light fastness would be an important consideration for summer wear to be worn mostly in the sun, whereas light fastness may not be an issue for undergarments.

Table 6.7 describing some of the factors to be taken into consideration when selecting dye types.[54]

6.4.2 Problems and solutions in garment dyeing

Although garment dyeing is more responsive and provides cost saving, many inherent defects will only show up after the garment has been dyed.[57] The solutions to some of the most prevalent problems encountered in garment dyeing[51,54,55,57–61] are summarised in Table 6.8.

Table 6.7 Performance of garment dyestuffs. Source: URL[54]

	Reactive dyes	Direct dyes	Pigments
Shade range	Excellent Bright colours	Excellent	Very limited Earth tones
Light fastness	Good	Good to excellent with selected dyes	Good
Wet fastness	Good to excellent	Good with selected dyes	Poor
Colour-on-white	Excellent	Limited	Poor
Chlorine fastness	Moderate to poor	Poor	Good

Table 6.8 Solutions for appearance problems during garment dyeing

Problems	Solutions
Poor dimensional stability	• For woven fabrics the relaxation shrinkage in both warp and weft direction should not exceed 5%.
Seam puckering	• Conduct a laundering shrinkage test on the fabric. Then make a sample garment for further testing by the standard laundry test. • When knitted and woven fabrics are mixed, pre-relax knitted fabric and at the same time preshrink woven fabric part. • Select low shrinkage threads for sewing. • Select sewing thread with the same shrinkage behaviour as that of the material. • Reduce sewing thread tension during sewing.
Shade variations of garments	• Fabrics and yarns should be scoured and bleached to the same degree of whiteness, and additives (e.g. softeners) should be avoided. • All the finishes and residues from the fabrics and garments should be removed before the garment dyeing process. • No optical brighteners should be used in bleaching to further reduce yellowing of fabrics. • Garments from mercerised and non-mercerised fabrics should be separated. • Development of fabric twisting or spirality should be duly considered, and accessories applied to the garment before dyeing should be resistant to high temperatures.
White, undyed or light seam	• Avoid too tight stitching and seaming. • Raise dyeing temperature for getting better diffusion, penetration and running of cloth and facilitating liquid flow.
Chafe marks/creases (exist particularly on delicate garments due to mechanical stress in drum dyeing machines, which degrade the final product)	• Turn garment inside out and dye in the presence of non-foaming lubricant. • Avoid overloading of dyeing drum.
Corrosion or breakage of accessories	• Metal components should be resistant to corrosion, preferably non-ferrous and nickel-plated. • Use of inhibitors based on phosphate ester/triazole gives protection against metal component corrosion but care should be taken to avoid the retardation of dye build-up.

6.5 Appearance issues in pressing

Pressing often represents the final opportunity to enhance garment shape, and to smooth or flatten creases in the garment. Good pressing also can help to preserve the shape and fit of a garment. Pressing performance can govern the appearance of a garment, as presented to a potential customer. Well-pressed garments make a good impression on potential customers, and can command a higher price. Good pressing appearance gives an overall smooth and undisturbed appearance, and the absence of shine, scorching, melting, clamp marks and water marks. There should be no unplanned creases or pleats, pressed wrinkles, or hems pressed on the wrong side. Seams and side seams of pants and shorts should be pressed seam-on-seam with a smooth centre crease.[52] Fabrics should be engineered to have optimum pressing perfomance, and garments should be pressed under the proper pressing conditions, which will differ depending on the types of fabrics and garments. Garments should be stored and packaged adequately to avoid creasing during storage and transportation.

6.5.1 Preparation and handling

Before pressing, remove all the tacking threads and pins so as to avoid leaving any marks on the garment.[62] In order to prevent scorching, melting, hardening or shrivelling, first test the heat (temperature) of the iron prior to pressing so as to ensure that it is suitable for the garment to be pressed. Test the heat on a spare piece of the actual fabric before applying the iron to the garment, so that a suitable heat can be found.

When placing a garment onto a pressing machine, make sure the grain of the fabric is not pulled out of line, so as to ensure that the garment is not unnecessarily creased. Keep all seams in a straight line. To avoid shine or iron marking on the right side, press on the wrong side of a garment. If necessary, slip a strip of paper underneath seam turnings to prevent their marking the right side of the fabric or garment.[62–64]

6.5.2 Pressing conditions

In practice, pressing can be conducted either with industrial or domestic irons (with or without steam) or else with a heavy press. Whatever the pressing method chosen, pressing consists of five components: heat (temperature), moisture (usually as steam), pressure, time and equipment (e.g. an ironing board). When pressing low-volume, high-fashion or highly structured garments, an industrial flat iron is usually used, which is similar to those used by the consumers at home. For pressing performed on high-volume ready-to-wear garments, presses or pressing machines, such as flat-bed, buck presses, form presses and upright presses, are normally used, these being more efficient than hand pressing. Generally, the garment is slipped over the machine; steam and pressure are applied automatically and then a vacuum extracts any excess moisture.[17,52,65] Ideal pressing conditions vary for different types of fabrics and garments.

6.5.3 Evaluation of fabric pressing performance

Since consumers judge garment quality according to appearance, the aim of pressing is to produce smooth, flat seams and sharp, crisp edges. Rounded edges and blown seams detract from the appearance of a high-quality garment. Successful pressing is the result of the correct steam press operation and good fabric pressing performance. Nevertheless, presses vary in their operation and effects and are therefore not good for testing fabric performance. It is in the light of this that the Sirolan-press Test (Fig. 6.8) was developed and commercialised for measuring fabric pressing performance. The lower the crease angle (control limit: less than 20°), the better the pressing performance. The test procedure is as follows:

- Condition the fabric sample.
- Cut specimens (4 cm × 2 cm in size).
- Fold each specimen back to back.
- Place the specimens in the setting jig.
- Place the jig on the press and clamp it.
- Place the jig in boiling water for 3 and a half minutes.

6.8 Sirolan-press Test

- Put the jig in cold water (20°C) for 3 and a half minutes.
- Open the jig and condition the specimens for 24 hours.
- Measure the crease angle.

6.5.4 Effect of fibre content and properties on pressing performance

Different fibres have different properties, which require different pressing conditions.[64] For example, microfibre garments have poor resistance to heat and can be hard to press and finish without any shine, marks or glazes. In order to solve this problem, it is recommended that garments comprising microfibres or extremly light fabrics be pressed from inside using form finishes. If they need to be pressed from the 'right side' of the fabric, the temperature has to be very low (e.g. around 130°C), whilst the steam has to be perfectly dry since synthetic cannot take any moisture.[66]

Wang *et al.*[67] studied the press performance of a range of wool and wool blend fabrics. Their results showed that the effect of iron temperature on the pressing performance of wool and wool polyester fabrics can be related to the glass transition temperature of the wool and polyester fibres. The fabric crease angle is much lower when pressing at 180°C iron temperature than when pressing at 100°C iron temperature, the press duration being 10 seconds in both cases. The press duration has a significant effect on the pressing performance of the fabrics tested, especially when pressing at 100°C iron temperature. The ambient relative humidity for both pre-conditioning and post-conditioning of the fabrics also has a significant influence on the pressing performance.

The general pressing conditions for different fabrics, such as cotton, linen etc., are compared in Table 6.9.

6.5.5 Effect of fabric properties on pressing performance

The pressure during pressing should vary depending on fabric type. Any fabric which is prone to shine or iron marks (e.g. rayon) should be subjected to a light pressure.[62] Less pressure should also be applied to a fine fabric than to a heavy fabric.

Fabric ageing/annealing

Ageing of wool fabrics may change pressing performance, especially with respect to deformation characteristics such as wrinkle recovery.[68] Research by Taylor[69] showed that, similarly to fabric ageing, annealing (rapid ageing) wool fabric can also change wrinkling behaviour under certain conditions.

Table 6.9 Degree of heat and moisture for different types of fabric. Source: Butler, 1972[62]

Fabric type	Heat	Moisture level
Synthetic fabrics	Cool iron	Little, usually no moisture
Lace	Cool iron	Little, usually no moisture
Silk	Moderately hot iron	Moisture rarely used
Wool	Moderately hot iron	Moisture usually required
Linen	Hot iron	Moisture probably required
Cotton	Hot iron	Moisture probably required

Maximum annealing was obtained when the fabric was heated at 15% regain (the time taken depending on the temperature of heating) and then slowly cooled. The annealing mechanism is believed to involve molecular rearrangements via labile hydrogen bonds to give a lower energy network. Wetting out of the sample changes this arrangement and results in a lower recovery during subsequent wrinkling. The work of Robinson *et al.*[70] showed that different annealing conditions produced fabrics with similar wrinkling performance but different pressing performance.

Fabric dimensional stability

Biglia *et al.*[71] studied the relationship between fabric press angles and dimensional properties and other low-stress mechanical properties. It was found that higher hygral expansion and relaxation shrinkage resulted in better pressing performance in wool fabrics.

Fabric finishing

Le *et al.*[72] studied the effects of decatising at various temperatures and regains on the pressing performance of wool fabrics. The pressing performance was strongly affected by fabric regain and the level of set imparted during decatising. It was proposed that the pressing performance of wool fabric comprised two components, namely temporary and permanent. The temporary component depends on the fabric regain during the last setting treatment, and the permanent component depends on the level of permanent set imparted to the fabric by all previous treatments.

6.6 Storage and packaging

After pressing, the garment should be free from wrinkles and creases, and have a good shape. Garments need to be stored and packed for delivery to the potential customers. Nowadays, there are manual or semi-automatic packaging machines available in the industry, but careless or inappropriate storage and packaging will cause a deterioration in the appearance of the final product.

The pressed garments should be stored in a cool, dry place. The storage should have sufficient room to accommodate the garments without their being too closely packed. Should the garments be too closely packed it could not only cause wrinkles in the garments, but also block the air circulation (causing a moisture build-up leading to mildew on the garments), or result in excessive heat which could cause the plastic bags to bond to the fabric. Also, the storage area should be as clean as possible so that dust and dirt, the acids present in atmospheric pollution, as well as the presence of moths or other pests do not cause garments to deteriorate during storage. A garment in storage should not be subjected to any strain or movement which could cause the fibres to become weak and break. Avoid pressing in sharp folds. Different types of garment should have different conditions of storage and packaging. Knitted or stretched garments should preferably be folded rather than hang, and should be stored in a plastic bag. Nylon hosiery should be stored and packed in plastic bags which can prevent snagging. Sweaters should also be stored in plastic bags to keep them from becoming contaminated by lint. Clothing containing wool should be stored in a moth-free or mothproofed place. When storing or packaging small, flat apparel articles, such as lace, lay the article flat, smooth and unfolded with plenty of acid-free tissue paper above and below each piece. If the pieces are not heavy and are quite flat, they can lie on top of each other. Large pieces, which have one side short enough to fit onto a storage shelf or into a drawer, and small, long pieces, such as ribbons or strips of embroidery, should be stored rolled, not too tightly and right side outermost, around a cylinder of some sort, using acid-free tissue paper to protect each side of the article.[65,73,74]

Vacuum packing is recommended for tailored jackets; this not only reduces the storage space required for the packed garments, but also prevents re-introducing creases during storage and transportation. This packing is also reusable which can reduce environmental pollution. Vacuum packaging is now commonly used in households, and provides different sizes for different kinds of garments. Vacuum packing also saves space, and protects the garments against dirt, moisture and insects (because they are waterproof and airtight).[75]

6.7 Concluding remarks

Between garment making and delivery to end-users, many manufacturing and delivering processes are involved. As discussed in this chapter, garment appearance can be affected by and during all these processes. Therefore, the appropriate selection of the use and handling of the fabric, the manufacturing components (e.g. sewing thread), machinery, and conditions and techniques are important in order to maintain or even improve the garment appearance.

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7
Durability of fabrics and garments

L. HUNTER

Abstract: This chapter covers the measurement of properties such as fabric flat, edge, flex and tumble abrasion resistance, fabric tensile, tear and bursting strength and seam strength, and their effect on fabric and garment durability. Ways of predicting and improving durability are discussed. The effects of fibre, yarn, fabric and garment parameters on durability are treated, as are the effects of dyeing and finishing conditions.

Key words: fabric durability, garment durability, flat abrasion, flex abrasion, edge abrasion, tensile strength, tear strength, bursting strength, seam strength.

7.1 Introduction

Consumer studies[1] have shown that durability or serviceability (i.e. acceptable or reasonable wear life) is one of the main requirements for clothing, along with ease-of-care performance, elegance (aesthetics) and comfort. The performance and appeal, or perceived 'quality' (including durability), of fabrics destined for apparel depend upon a number of mechanical and physical properties, such as making-up and handle (Chapter 1), resistance to abrasion (Chapter 7), pilling (Chapter 3), drape (Chapter 5), wrinkling (Chapter 2), bagging/loss of shape (Chapter 4), and change in colour, snagging, soiling and comfort (Chapters 8 and 9), the relative importance of these depending upon the intended end-use and the customer's expectations as well as on the customer's wear conditions and garment fit. In addition to these, garment wear also involves factors such as size/fit and seam strength, 'wear' referring to the deterioration of the physical and aesthetic properties of textiles in use.[2] Durability is a measure of the reasonable wear life of a product[3] and is the consequence of a number of factors which reduce the serviceability and acceptability of the product, including abrasion, tearing, bending, stretching, rubbing (abrasion), laundering and cleaning (see ASTM D3181). Stoll,[4] for example, stated that the wear of army uniforms comprised 30% plane (flat) abrasion, 20% edge and projection abrasion, 20% flexing and folding, 20% tear and 10% other mechanical actions. He defined a Wear Index (*WI*) as follows:

$$WI = 0.50(\text{flex abrasion}) + 0.20(\text{flat abrasion}) + 0.30(\text{tear resistance}) \quad [7.1]$$

Alternatively:

$$WI = 0.40(\text{warp flex abrasion}) + 0.20(\text{flex abrasion}) + 0.30(\text{flat abrasion}) + 0.20(\text{tear strength}) \quad [7.2]$$

Elder[5] suggested the following:

$$\text{Wear resistance} = 0.3(\text{flat abrasion}) + 0.2(\text{edge abrasion}) + 0.3(\text{flex abrasion}) + 0.2(\text{tear resistance}) \quad [7.3]$$

These need to be assessed within the context of the requirements of the specific end-use for which the fabric and garment are destined within the broad categories of clothing (apparel) textiles. With respect to clothing, aspects relating to the fabric and garment aesthetics or appearance generally dominate.[6] Not only does the 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), as well as during laundering.

Fabric and garment durability and wear performance are determined by the fibre type and properties, yarn, fabric and garment construction and any chemical and mechanical treatment applied to the yarn, fabric or garment.[7] The wear and care (e.g. laundering, drying, ironing) conditions have a major effect on durability; laundering can account for as much as 50% of the abrasion damage in worn fabrics,[8] and Buisson *et al.*[9] showed that wet cotton fabrics tumble dried with heat suffered much more damage than those tumble dried dry or without heat. In practice, however, mechanical damage or break-down is generally much more important than chemical damage (including that due to laundering and light) in determining wear life.

Kothari[10] divided fabric properties into six different groups, as shown in Table 7.1. Table 7.2[11] provides a more specific example for a shirt.

The useful life of a garment is in many cases one of the most important quality factors and properties to estimate by means of laboratory tests, and to predict or engineer. Various laboratory instruments (more than one hundred)[5] and test methods, particularly for fabric abrasion resistance, have been developed over many decades in an attempt to simulate and predict, or at the very least estimate, wear performance and durability.[4,5,12–17] Many of such tests have, for various reasons, been discontinued, it being notoriously difficult to simulate the great variety and complexity of the conditions that a fabric and garment experience in the diversity of possible end-use applications. Patton[18] discussed some of the pitfalls and complexities involved in wear testing. Galbraith[14] assessed and compared the various

Table 7.1 Classification of different properties. Source: Kothari, 1999[10]

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

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

Table 7.2 The utility-value analysis graphics. Source: Özcan, 2003[11]

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
		3.8 The cloth should not include toxic materials
	Criteria	
1.1.1 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)
1.5.1 Tearing strength (BS 4304–1986)		3.4.1 Dimensional stability to washing (DIN 53920)
1.5.2 Abrasion resistance (BS 5690)		3.5.1 Colour fastness to ironing (ISO 105 B01)
		3.6.1 Colour fastness to perspiration (ISO 105 EO4)
		3.7.1 Colour fastness to rubbing (ISO 105 × 12)
		3.8.1 Aromatic amine test (MAK Amin IIIA-1.2)

abrasion and wear testers. During its use in apparel, 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 the garment no longer being acceptable, either from an appearance or functional point of view. 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 relatively low and random abrasive forces. Hearle and Lomas[19] concluded that the common form of wear in garments equates to failure in a laboratory biaxial rotation fatigue test by the mechanism of multiple splitting arising from combined bending and twisting. During wear, actual fibre fibrillation is often responsible for failure, which contrasts with laboratory tests.[20]

Laboratory tests are probably most useful for comparing different fabrics, i.e. for comparative purposes. It is a well known fact that moisture content, and to a lesser extent also temperature, affect fabric strength and abrasion properties, both in wear as well as in laboratory tests. Such tests always need to be carried out under 'standard' atmospheric conditions (either 20 ± 2°C and 65 ± 2% RH or 27 ± 2°C and 65 ± 2% RH), after carrying out the necessary pre-conditioning and allowing sufficient time for the samples to reach equilibrium within the laboratory. It is also important to bear in mind that the direction in which the abrasion occurs can play a role in determining the abrasion resistance.[21]

This chapter discusses the measurement of fabric and garment abrasion resistance and strength, and the various factors which influence them.

7.2 Abrasion resistance

7.2.1 Introduction

Abrasion is the mechanical deterioration and progressive loss of substance of a fabric resulting from the fabric rubbing against itself or another surface, usually in turn resulting from the removal of damaged/broken fibre fragments and complete fibres, and to some extent due to frictional wear (fibre wearing away). During wear, the fabric is subjected to a complex combination of forces acting at various rates, in various intensities, in various directions and for various periods. This is one of the main causes of a fabric and garment becoming unacceptable for further wear.[8] Laboratory abrasion tests often impose abrasion forces more uniform and severe than those encountered during actual wear, and frequently also do not include laundering, which is an important source of wear in real life.[8] In the main, those abrasion tests that involve less severe conditions (i.e. gentle abrasion), but include laundering, correlate best with actual wear; however, they present a problem in terms of the prolonged time required for testing. These shortcomings have been addressed in tests developed in recent years by, for example, reducing and varying the abrasion forces and including laundering. The preferred option would be to combine wearer trials with laboratory testing but this is not practically feasible. In spite of the above-mentioned shortcomings, testing of abrasion resistance has remained an important measure of fabric durability, as abrasion is one of the main factors involved in fabric and garment wear and failure. It is, however, generally not possible to draw a meaningful conclusion on the expected wear life (durability) of a fabric based upon abrasion resistance alone. During laundering, for example, both chemical and mechanical actions (damage) are involved in the fabric wear or damage. Abrasion tends first to change the fabric surface characteristics and appearance before affecting the internal structure of the fabric. Certain fabrics, notably worsted serge, develop a shiny (polished) appearance when subjected to abrasion. Examination of the fibres from the shiny area shows their surfaces to be abraded away (flattened).

Abrasion during use not only contributes to the failure of the fabric and garment; it more commonly contributes to changes in fabric appearance (making it look 'old' or unattractive) such as fuzzing, pilling, frosting (colour change) and 'shine'. It also changes 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 appearance-related properties rather than on the basis of fabric mechanical failure, such as tearing or rupturing. Factors which affect abrasion resistance include fibre content and properties, yarn structure (e.g. spinning system, yarn twist and yarn linear density), fabric structure (e.g. weave, float length and yarn crimp) and weight, and chemical and mechanical treatments imposed during dyeing and finishing processes, particularly in as much as the latter affect the fibre friction and resistance to flexing.

One or more of three forms of abrasion occur most frequently, namely flat (plane or surface) abrasion, edge abrasion (e.g. at collars and folds) and flex (flexing and 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 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. The durability and performance of the fabric will often depend upon the type of abrasion and other conditions to which it is subjected during wear.

7.2.2 Abrasion resistance testing

Most abrasion test instruments and methods attempt to provide a measure of one or more of the three different types of abrasion mentioned. In practice, however, the fabric may be subjected to all three forms of abrasion.

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 and scale removal), with the first two generally the main components of fabric and garment failure in practice. The abrasion resistance of the fabric, as measured in the laboratory, is generally quantified by the number of cycles required to produce either a hole, a certain loss in strength or weight, a change in colour (appearance), a change in air permeability or a change in thickness.

Various types of laboratory testing (and their combinations) are used to measure fabric abrasion resistance, including:

- Flat (or relatively flat) abrasion (usually the fabric is rubbed against a fabric or other abradent, such as emery paper, under various pressures)
- Flex abrasion
- Combination of flat and flex abrasion
- Edge abrasion
- Tumble abrasion.

The above tests, for example flex and edge abrasion, are not always highly correlated, and changes in fibre, yarn, fabric and finishing parameters often affect them differently, and even oppositely. Thus, for example,[14] fabrics woven from finer yarns have better flex abrasion but poorer edge abrasion. Furthermore, plain weave and Oxford weave fabrics have been found to have the best flex abrasion resistance but the poorest simulated cuff laundry resistance,[22] while basket weave, mock leno and warp rib fabrics had poor flex abrasion resistance but good edge wear resistance during laundering.[14]

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 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 (ISO 5470, ASTM D3884) and Schiefer (ASTM D4158). Probably one of the most popular flat abrasion testers is the Martindale Abrasion Tester, also used for testing pilling propensity, which was devised by Dr R.G. Martindale in 1942, in which a test specimen is rubbed against an abradent (usually an abradent fabric) at a 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).

Edge abrasion and the tumble test

Edge abrasion takes place when the wear or abrasion occurs along the fabric edge, generally a folded edge, such as on the edge or fold of the collar of a shirt or the cuff of a sleeve or trousers. Tests include AATCC 119, 120, ASTM D3514, D3885 and D3886.

The AATCC 'Accelerotor' test (AATCC93), a rapid tumble test where the sample is folded and stitched prior to testing to accentuate abrasion of edges. Accelerotor edge abrasion results tend to correlate well with abrasion behaviour at the edges of sleeves, collars of shirts and the folds in pants. This test also correlates well[14] with laundering and tumble-drying of mock trouser cuffs, followed by usual evaluation of the fabric, and with the actual wear occurring in the use and laundering of sheets. The test 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, causing frictional abrasion, fabric flexing, rubbing, impact, compression stretching, etc. Mass loss and edge abrasion are often used as a measure of abrasion.

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).

Because of the effect of lubricants and softeners on flex abrasion results, which may not be reflected in actual wear performance, it is often advisable to remove (extract) such lubricants and softeners from the fabric prior to testing.

7.2.3 Effect of fibre properties on abrasion resistance

The fibre properties generally play the major role in fabric and garment abrasion resistance, their relative importance depending to some extent upon the particular type of abrasion (e.g. flat or flex) which predominates during testing and/or wear. Nevertheless, fibre strength, elongation and elastic recovery during and after repeated stress application are generally important, followed by the fibre flexural and shear properties, length and diameter, with fibre shape also playing a role. Low initial modulus, high extensibility and high energy-of-rupture are all desirable for good abrasion resistance,[5] the energy absorbing capacity of the fibre assembly playing a major role in determining abrasion resistance. Fibre loop strength and resistance to flex abrasion provide a good measure of fabric abrasion resistance.

Hamburger (quoted in Ref. 14) listed the following fibre properties required for high abrasion resistance:

- Low modulus of elasticity
- Large immediate elastic deflection
- High ratio of primary to secondary creep
- High magnitude of primary creep
- High rate of primary creep.

Nylon and polyester are considered to have excellent abrasion resistance followed closely by the polyolefin[14] fibres, being characterised by high strength, elongation and elastic recovery. Acrylic and mod-acrylic fibres do not have as good abrasion resistance, but are better than most natural and regenerated fibres.[14] Wool and cotton have moderate abrasion resistance.[14] Viscose, rayon and acetate fibres exhibit the lowest abrasion resistance, probably due to their relatively low strength and elastic recovery, with low energy absorption during repeated stress cycles.[14]

Most studies have reported that fabric abrasion resistance increases with an increase in fibre diameter, linear density and length. Thus, for example, longer polyester and combed cotton improve abrasion resistance.[23] The effect of fibre length on abrasion resistance can largely be ascribed to an increase in length reducing fibre removal (transfer)[24] from the fabric, thereby reducing the loss of fibres from the fabric. In general, combining hard-wearing synthetic fibres, such as polyester and nylon, with natural fibres, such as wool and cotton, will improve fabric abrasion resistance. For example, according to Stroot and Raidt,[25] the mass loss during abrasion decreased by about 30% when 100% wool was replaced by 55/45 polyester/

wool in uniform fabrics. In the case of wool, the cell-membrane complex (CMC) at the boundary of the cortical and cuticle cells has been shown to play an important role in the abrasion resistance.[26] Fabric flex abrasion will increase as the fibre flexibility and resistance to flexing increase (i.e. as the fibre brittleness decreases).

When fibres differing greatly in their physical and mechanical properties are blended, differential wear and abrasion will take place, with associated changes in appearance and colour (e.g. frosting). Care must therefore be taken to avoid the problem of 'frosting', where fibres that differ in both colour and abrasion resistance are blended and which leads to 'differential wear' and associated changes in colour, as well as problems with pilling.

7.2.4 Effect of yarn properties on abrasion resistance

It is important to mention that, where different yarns are used in the warp and weft directions, the abrasion resistance will be determined by the properties of the yarns exposed to the most wear, for example the yarns predominating on the fabric surface in the case of flat abrasion. The abrasion resistance can also depend upon the direction in which the abrasion is applied to the fabric.

The yarn structure, such as twist, linear density, friction, crimp, number of plies (e.g. singles, two-ply, etc.), smoothness, and the presence of wrapper or binding fibres, can affect fabric abrasion resistance. The effect of the yarn structure on fabric abrasion resistance depends upon the type of abrasion test, and is affected by the fabric tightness (compactness) and structure, being greater for looser fabric structures and longer float lengths. If the yarn structure enables the abrading load (stress) to be more evenly spread over a large surface area and more energy to be absorbed, it will increase abrasion resistance. Furthermore, if the yarn mobility within the fabric can be increased by, for example, using coarser yarns at a constant fabric mass per unit area, abrasion resistance can be improved. In general, abrasion resistance will improve as the fibres are better aligned and more securely bound within the yarn structure by, for example, increasing the yarn twist factor or using two-ply (as opposed to singles) yarn, or by using compact spun yarns. Nevertheless, there is likely to be an optimum twist factor (±38 tex twist factor for short staple yarns) above which the abrasion resistance will start to decrease. Knitted[27,28] and woven[29] fabrics containing ring spun yarns tend to have slightly better resistance to abrasion than those containing open-end yarns. Fabrics containing compact ring-spun yarns generally have superior abrasion resistance to those containing conventional ring-spun yarns. Tyagi and Kumar[30] found that woven fabrics containing MJS yarns (polyester/cotton and polyester/viscose) had poorer abrasion resistance than the corresponding fabrics containing ring-spun yarns. Fabrics containing woollen yarns generally have a lower abrasion resistance than fabrics containing worsted yarns, largely due to the associated differences in fibre length and yarn structure. Coarser yarns also tend to improve fabric abrasion resistance. Where laundry type abrasion (i.e. fibre removal) predominates, an increase in the fibre binding by increasing yarn twist will have a beneficial effect on fabric durability (wear life). Where a flat abrasion action predominates, with low friction, a lower twist may be preferable since the yarn will deform more easily at the fabric surface and spread the load more evenly over a greater fabric surface (contact area).

7.2.5 Effect of fabric properties on abrasion resistance

In general, an increase in fabric tightness (compactness), thickness and weight per unit area and a decrease in float length (i.e. an increase in yarn cross-over points) increase fabric flat abrasion resistance, but not necessarily flex abrasion resistance.[22]

Increasing fabric sett will improve flat abrasion until an optimum is reached, when yarn mobility is restricted and jamming occurs, after which abrasion resistance will deteriorate. Nevertheless, where such increases in tightness lead to very prominent and 'rigid' crowns ('knuckled' effect), it will cause a deterioration in flat abrasion resistance.

Any fabric structural modification that spreads the abrasion load over the largest contact area (i.e. reducing the pressure), for example over a greater number of yarn crowns, will improve flat abrasion resistance. In the main, such increased fabric abrasion resistance is due to the more even distribution of the abrading load over a greater number of fibres (and yarns) and reduced fibre removal/transfer from the fabric. Clearly, in flat abrasion, those yarn segments (e.g. crowns) that protrude highest from the fabric surface will suffer abrasion damage first and most. Protecting the stress bearing yarns in the fabric, for example, by means of the floats of the non-stress bearing yarns, should improve abrasion resistance when assessed in terms of fabric strength, but not necessarily when assessed in terms of fabric appearance and/or mass loss. Increasing fabric crimp tends to increase fabric frictional (Accelerotor) abrasion,[31,32] probably due to the yarn crowns becoming more prominent at the fabric surface. The 'ribbed effect' needs to be avoided, i.e. any changes in weave structure that cause a concentration of abrasion loads and actions on fewer yarns and/or yarn surfaces will adversely affect fabric abrasion resistance. Generally, the surface yarns with their float lengths perpendicular to the direction of the abrasion will suffer the greatest abrasion.

Flat abrasion resistance is more dependent on good fibre binding than on fibre and yarn mobility, whereas the reverse is true for flex abrasion. High yarn mobility is reportedly[14] advantageous in edge wear but less important than good fibre binding and balanced distribution of abrasive stress over both warp and weft yarn systems in flex abrasion. Any change in fabric construction that reduces the possibility of fibre removal, i.e. increases fibre cohesion, or increases fabric mass, will increase fabric abrasion resistance. Nevertheless, an increase in fabric surface roughness and friction will decrease abrasion resistance.[33] Aswani *et al.*[34] found that Stoll flat abrasion resistance was linearly related to the total yarn slippage force as measured on the Instron. Abrasion resistance so measured increased with the pick density, with plain weave fabric showing the highest and the matt weave fabric the lowest abrasion resistance, twill and warp rib weave fabrics being intermediate. Sateen and twill weave cotton fabrics woven from either ring-spun or wrap-spun cotton yarns were found[35] to have a slightly lower flex abrasion resistance than the corresponding plain weave fabrics. The use of yarns of the same linear density, crimp and sett in warp and weft will generally produce the best resistance to flat abrasion.

Results obtained by the IWS[36] indicated an approximately linear relationship between the number of abrasion cycles to end-point (Martindale Abrasion Test) and fabric mass for wool and wool/polyester intimate blend double jersey fabrics, with pure wool and wool/polyester feeder blend fabrics behaving the same. They concluded that, for men's suiting and trousers and possibly ladies' suits and slacks, a 300 g/m^2 pure wool fabric would provide acceptable Martindale Abrasion resistance (25 000 cycles), while 260 g/m^2 would be sufficient for 60/40 wool/polyester intimate blends and 275 g/m^2 would be adequate for 70/30 wool/polyester. Slinger and Robinson[37] found that, for 2/2 twill weave all wool worsted fabrics, fabric abrasion resistance was approximately linearly related to fabric mass per unit area.

Candan and Önal[28] found that tuck stitches (e.g. Lacoste fabric) had an adverse effect on the abrasion resistance of cotton and cotton blend knitted fabrics, with the resistance deteriorating with an increase in course length.

De Castellar *et al.*[38] modelled the Martindale Abrasion kinetics of woven fabrics, and showed, by means of regression analysis, that fabric (fibre) composition, thickness and weave interlacing coefficient had the main effect on abrasion resistance.

7.2.6 Effect of garment design and fit

The garment type, size and fit, as well as the type, position and abrasion resistance of the seams inserted, can all influence the performance of garments during wear. Clearly, the wear conditions, including the size, shape, occupation and activities of the wearer, laundering, drying, etc. can all affect the wear life of a garment, and it is often difficult to distinguish between such factors and fabric shortcomings ('defects') when attempting to identify the causes of garment failure during use. Often, variations amongst wearers and wear conditions are more important than variations in the fabrics or garments themselves in determining wear performance (durability).

These factors all impact on the degree or severity of the abrasion and wear of the garment. Furthermore, such wear generally occurs at localised regions of the garment, such as at the seat of pants, elbows of jackets and jerseys, and collars and cuffs of shirts, depending upon the abrasive forces (magnitude, frequency and duration) imposed on the garment by the wearer, and the wear conditions, including those prevailing during laundering. The moisture and perspiration content of the garment can also affect the wear and abrasion experienced.

7.2.7 Effect of dyeing and finishing on abrasion resistance

Any dyeing and finishing treatment which damages the fibre (e.g. causes a deterioration in fibre tensile, bending, torsional and flexing properties) will adversely affect all forms of fabric abrasion resistance. A good example of this is the resin treatment (cross-linking) of cotton fabrics to produce wrinkle resistance, easy-care and durable press, which can decrease abrasion resistance, particularly edge, flex and tumbling abrasion, by embrittling and weakening the cotton fibres. Nevertheless, this is dependent upon the pressure (severity) of the abrading action and the particular treatment applied. Where the pressure is low, a resin treatment may even improve abrasion resistance.

The application of a lubricant or softener (e.g. silicone) generally improves both flat and flex abrasion resistance of fabrics, particularly the latter as measured in the laboratory, the implication being that anything which reduces fibre/yarn/fabric friction and increases fibre and yarn mobility will improve flat and flex abrasion. Nevertheless, such improvement is not necessarily reflected in the actual wear performance, particularly after laundering which can remove much, if not all, of the lubricants and softeners. The effect of dyeing, finishing and laundering on friction and fibre and yarn mobility will therefore be reflected in fabric abrasion resistance, flex abrasion in particular. It should be noted that chemical treatments which bind the fibres more securely within the fabric structure can improve flat abrasion resistance by reducing the effect of the fibre transfer mechanism on mass loss.

Chatterjee *et al.*[39] found that wet processing of cotton fabrics improved fabric abrasion resistance and ascribed this to the associated increase in fabric weight per unit area and softness.

Applying a tough thin flexible polymer coating or film (e.g. polyacrylate or polyurethane) to fibres can improve flat, flex and edge abrasion resistance, particularly that of durable-press cotton fabrics.

7.3 Fabric and garment strength

7.3.1 Introduction

Fabric strength, as a characteristic in determining wear performance and durability, is generally not as important in apparel as in applications such as upholstery, sheeting and shirting material, and industrial 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 and ultimately garment quality and deterioration during use. It also provides a basis of comparison for similar fabrics and a means of assessing any damage caused by chemical and mechanical treatments, for example dyeing and finishing.

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. Tear strength is generally regarded as a better measure of the serviceability of woven fabrics than tensile or bursting strength. For knitted fabrics, bursting strength is almost solely used as a measure of the fabric strength. Tensile strength and bursting strength tend to be fairly highly correlated, but fabric elongation has an important effect on bursting strength and therefore on the correlation. This is not the case for tensile strength and tear strength, which are generally poorly correlated, with fabric cover factor (tightness) affecting the correlation. 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.[40,41]

In the case of tight fitting non-stretch clothing, the bursting strength of the fabric, whether knitted, woven or non-woven, is important.

7.3.2 Strength testing

Various test methods are used in practice to determine fabric tensile, bursting and tear strength, respectively, these often giving different results. In general, the more rapidly the load is applied during the test, the higher the value obtained.

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 a grab test (ASTM D5034), carried out on what is generally referred to as a 'Universal Tester', e.g. Instron, Micro-CX, or 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 (sometimes constant rate of traverse), with the rate of extension variable according to the test method and the requirements. The tensile strength, also termed 'breaking strength' or 'breaking load', is the force required to rupture (break) the fabric, with the breaking elongation or breaking extension being the elongation (usually in per cent) at that point. Test methods include ASTM E-4, D5034, D5035, BS 1610/0.5, BS 2576, BS EN 10002-2, DIN 51221/1 and DIN ISO BS EN 13934-1.

According to Pan,[42] the grab test is simpler to perform and better reflects tensile failure in wear than does the strip test, although the latter provides more accurate and interpretable results. Grab strength values are always higher than strip strength values (up to twice as high), with the fabric breaking extension affecting the relationship as follows:

$$\frac{\text{Grab Strength}}{\text{Tensile Strength (per inch)}} = 1 + \frac{\text{Breaking Extension (\%)}}{40} \qquad [7.4]$$

The grip width also has an important effect on the differences between the results of the two tests.

Pan[42] and Wu and Pan[43] derived and experimentally verified the following relationship between strip and grab tensile strength ratio (λ) for standard sample and grab sizes:

$$\lambda = \frac{Fg}{Fr} = 1 + 1.5\left[1 - \frac{\tanh\left(2\sqrt{\frac{Gxy}{Ex}}\right)}{2\sqrt{\frac{Gxy}{Ex}}}\right] \qquad [7.5]$$

where:

Gxy = Shear modulus
Ex = Tensile modulus
Fg = Grab tensile breaking strength
Fr = Tensile breaking load (strip strength) applied to the gripped portion of the specimen through machine clamps = $2b\sigma_x$
b = Half the width of machine clamps
σ_x = External tensile stress applied directly on the entire width of the specimen through machine clamps.

The strength difference between grab and strip samples will be greater for a tighter fabric.

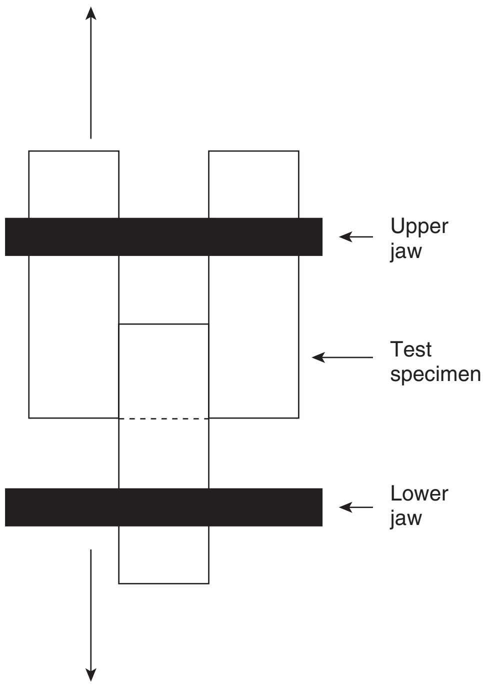
Bursting strength

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 an elastic diaphragm (e.g. Mullen Tester). In the diaphragm test, the fabric specimen, mostly circular in shape, is 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, DIN 53861, BS 3137, BS 3424-38 and BS 4768, and ISO 13938-1/2960 2758/2759/3303/3689/13938-2). It is important to relate the values obtained to the specific test conditions, for example testing speed and size of specimen. Thus, for example, for a circular specimen, the bursting strength is approximately inversely proportional to the specimen diameter.[44] Automatic digital and 'intelligent' bursting strength testers, which measure both the displacement and strength at rupture and carry out the necessary calculations, have come onto the market. The size and shape of the specimen, as well as the rate of pressure increase, affect the bursting strength value obtained.

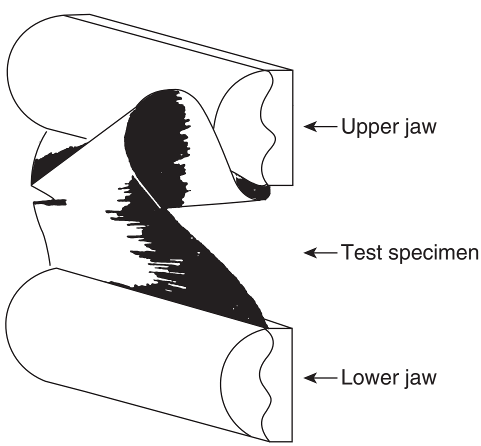
Tear strength

A tear is defined[16] as a rupture, progressively along a line (thread by thread), caused by a moving fabric being caught in a sharp object that is sufficiently fixed in position to exert a tensile force on the fabric as it is moved away. Tearing strength is defined[45] (ASTM D1682) as the force required to start or to continue to tear in a fabric, in either weft or warp direction, under specified conditions. Several methods are used[46] to measure tear strength, e.g. double tongue rip (tear) test (Fig. 7.1),[47] trapezoid tear test (Fig. 7.2)[47] (ASTM D5587), and single tongue tear test (Fig. 7.3) (ASTM D2661, BS 4303).[47] 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 D1424 and D5734, ISO 1974 and 9290, BS 4253/4468/3424, DIN 53862/53128 and BS EN ISO 13937) which, essentially, measures the tear energy. Because of the very short tearing time, about one second, the Elmendorf test approaches an impact tear test, also referred to as a ballistic (pendulum test method), the test result representing the energy to tear a fixed length of fabric.

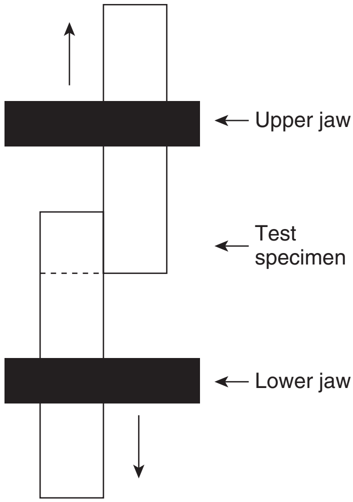
Specific tear strength is defined as the sum of warp and weft tear strength divided by the fabric mass per unit area. Ganatra *et al.*[45] compared the results of different tear strength tests and concluded that the correlation between the Elmendorf and ballistic tear testers was higher than that between the ballistic and tongue tear testers or that between the



7.1 Double tongue rip test. Source: Creswick, 1947[47]



7.2 Trapezoid tear test. Source: Creswick, 1947[47]



7.3 Ballistic tear test. Source: Creswick, 1947[47]

Elmendorf and Tongue Tear Testers, with the correlations in the weft direction always greater than in the warp direction.

Witkowska and Frydrych[46] found a generally good correlation between the various static and dynamic tear strength tests, but a poor correlation between tear strength and tensile strength.

Sharma and Adhikary[48] compared the various tear strength tests on polyester/viscose blends. They concluded that the single rip test was the most suitable, with single rip, double rip and impact tear (Elmendorf) tests showing similar performances, while the wing rip tests differed only marginally. The trapezoid test showed a relatively poor correlation with the aforementioned tests, while the wound bursting method differed widely from them.

7.3.3 Effect of fibre properties on fabric strength

Fibre tensile properties will, to a lesser or greater extent, be reflected in fabric tensile, bursting and tear strengths, with fibre elongation playing a different role according to the fabric structure and type of strength test.

All other factors being constant, fabric bursting, tensile and tear strength will be approximately proportional to the fibre strength, increasing fibre elongation (extension) also increasing fabric tear and bursting strengths. It should be mentioned, however, that fibre elongation will affect this relationship somewhat, and that differences in other fibre parameters, notably length and fineness, will in practice play a role as well. According to Stroot and Raidt,[25] replacing 100% wool by 45/55 wool/polyester in uniform fabrics virtually doubled the fabric tensile and bursting strength. Vatsala and Subramaniam[49,50] showed that adding polynosic fibres to either cotton or polyester decreased fabric tensile and tear strength, with laundering also decreasing both.

Finer and longer fibres will improve fabric strength, the magnitude of the effect decreasing as the fabric tightness factor (i.e. density and compactness) increases, and also as the twist factor of the yarns increases. Essentially, what this means is that the beneficial effects of increases in fibre fineness and fibre length will largely be manifested in relatively loose fabric and yarn structures.

Stronger cottons have been shown[51] to produce stronger greige fabrics and also flame-resistant (FR) and durable-press (DP) finished fabrics, although the differences between the different fabrics were much smaller after FR + DP finishing.

7.3.4 Effect of yarn properties on fabric strength

Tensile strength

The degree of yarn strength utilisation in the fabric depends upon a number of yarn and fabric structural parameters, with the relationship between yarn and fabric strength being highly complex.

Ukponmwan[44] and Seo *et al.*[52] discussed the factors which influence fabric tensile strength and its prediction from the yarn properties. The fabric assistance factor represents the factor by which fabric strength is higher than that predicted from the yarn strength as measured at the same gauge length as used to test the fabric strength and for the same number of yarns as involved in the fabric test. This factor depends upon the fabric density (compactness), inter-yarn friction and contact pressures at yarn crossovers and the yarn twist, being highest for low twist (or no twist) yarns. The mechanism of yarn failure is strongly influenced by the fabric geometry at the instant of failure, and by yarn properties both mechanical and topological.[52] Realff *et al.*[53] showed that testing yarn tensile properties at a long gauge length and then applying the weak link theory to predict short gauge length strength (as is applicable to fabric tensile strength testing) is not accurate. In as much as the yarn structure improves the binding of fibres and reduces the number and length of projecting fibres, it will increase yarn and fabric strength. A good example is the increased fabric strength of compact yarns.[54] The tensile properties of fabrics produced from ply-spun yarns (e.g. Sirospun and Plyfil) tend to be very similar to those produced from conventional two-ply ring-spun yarns.

In general, and within practical limits, increasing yarn twist factor, up to a certain point (38 to 45 tex twist factor for cotton yarns) will increase fabric tensile, bursting and tear strength, with the effect being greatest for looser structures, fewer yarn intersections and shorter fibres. Nevertheless, the yarn twist required for maximum fabric strength is generally lower than that required for maximum yarn strength.[55] Fabric extension at break generally increases with increasing yarn twist. For cotton yarns, Bhargava[56] found maximum fabric tensile strength when using two-ply, as opposed to singles or three-ply, yarn in the weft.

Tear strength

Yarn failure during tear strength tests is generally due to fibre breakage rather than fibre slippage[40] (i.e. short gauge ≈ 3.2 mm failure). Therefore, a weakest link scaling factor needs to be applied to yarn tensile tests in order to make the results applicable to fabric tear strength modelling. The easier the yarns can slip (slide) within the fabric, the higher will be the tear strength, since the yarns bunch up and support each other, and break 'collectively' rather than individually. Yarn strength, and by implication fibre strength, therefore have a major effect on fabric tear strength. An increase in twist should generally have a beneficial effect on tear strength, as it increases yarn strength (up to a maximum) and decreases yarn hairiness and diameter, thereby increasing the ease of sliding (i.e. yarn mobility). Tyagi and Kumar[30] found that woven fabrics containing MJS air-jet yarns in polyester/cotton and polyester/viscose blends had poorer tear strength than the corresponding fabrics containing ring-spun yarns. Dhamija and Chopra[57] found that fabrics from compact yarns had higher tear strength than those containing ring-spun yarns.

7.3.5 Effect of fabric properties on fabric strength

Tensile strength

Within practical limits, fabric tensile strength will generally increase with increasing fabric cover factor (tightness), mass per unit area and with the number of interlacings. At a constant cover factor, weave structures such as plain weave, with the greatest number of yarn intersections and shortest float lengths, will generally have the highest tensile strength[44] although this may not always be the case,[58] their distribution also playing a role. There is approximately a linear relationship between fabric assistance factor and fabric cover factor,[44] the former being about 6% higher for plain weaves than twill weaves, with that of twill weaves being about 8% higher than for hopsack weaves. Generally, fabric assistance will increase as the yarns become finer and the number of interlacings increases. Thus, for example, a plain weave fabric will be stronger than a twill weave, which in turn will be stronger than a hopsack fabric. This may not be the case for plied and cabled yarn twisted to obtain maximum yarn strength. Slinger and Robinson[37] found that for 2/2 twill weave all-wool worsted fabrics, fabric tensile strength was approximately linearly related to fabric mass per unit area.

An Intrinsic Strength Value (ISV) has been defined[50] as follows:

$$\text{ISV} = \frac{\text{Warp plus Weft Breaking Strength}}{\text{Fabric Mass per Unit Area}} \qquad [7.6]$$

Yarn crimp (i.e. weave crimp) and its distribution play an important role in determining fabric tensile strength and elongation, with fabric extension at break increasing with increasing crimp in the direction of the test.[59–61] The crimp in the longitudinal threads affects fabric strength,[44] the latter decreasing by about 1% for every 1% (absolute) increase in crimp.[44]

Tear strength

Fabric deformability and tensile properties largely determine tear strength. In essence, fabric tear strength will increase as the number of 'load bearing yarns' in the direction of the tear increases and as the strength of such yarns increases. In general, an increase in woven fabric tightness (density) increases tensile strength (i.e. increases the fabric assistance factor) but decreases fabric tear strength, since it causes an increase in the yarn packing factor but causes a concomitant decrease in yarn mobility, the latter playing a major role in decreasing tear strength. There is also an approximately linear relationship between fabric strength and fabric mass, although yarn crimp and fabric cover factor will affect this relationship, particularly with respect to tear strength. Increasing the number of cross-over points per unit area and decreasing yarn float length[62] (by changing the weave structure) decrease fabric tear strength. Increasing fabric weave crimp generally has a beneficial effect on tear strength. Decreasing the sett (number of yarns) in the other direction to that being tested increases fabric tongue tear strength,[63] but could decrease the strength slightly in the other direction. Increasing yarn strength in the direction across which the tear strength is to be tested will increase tear strength. Sharma and Adhikary[48] concluded that increasing the fabric density (number of yarns per unit length) along the tear direction increased trapezoid and bursting tear strength but decreased single rip, double rip, wing rip and Elmendorf tear strength. Increasing the fabric (yarn) density across the tear direction increased all the tear strength values, except for the bursting tear strength which showed a marginal decrease. They concluded that the single rip test was the most suitable and that single rip, double rip and impact tests showed similar performance and provided almost identical values of fabric characteristics, while the wing rip test differed marginally. The trapezoid method showed a relatively poor correlation with the above test methods, while the wound bursting method differed widely from them. Teixeira *et al.*,[64] using the tongue tear test, found 2/2 (basket) weave to be more than twice as strong as plain weave and 3/1 (twill) weave to be more than 1½ times as strong as plain weave.

Twill and matt weave structures tend to have higher tear strength than plain weave fabrics, which contrasts sharply with what occurs for tensile strength.[44] Tear strength has also been found[65] to be negatively correlated with the fabric assistance factor (*FA*):

$$FA = \frac{Fs - Ms}{Ms} \times 100 \qquad [7.7]$$

where:

Fs = Strength of yarns in parallel
Ms = Strength of same yarns in the fabric

Taylor[40,41] derived the following stress-based model for fabric tear strength (rip test):

$$T_R = \left[\frac{\left(\dfrac{\log f/fs}{\log \beta} + n \right)(1 - D\theta)}{p} + 2 \right] = f/2 \qquad [7.8]$$

With certain assumptions[40,41] this can be written as:

$$T_R = f/2\left(\frac{nStf}{fs} + 2 \right) \text{ for the single rip test} \qquad [7.9]$$

and

$$T_R = f\left(\frac{nStf}{fs} + 2 \right) \text{ for the tongue test} \qquad [7.10]$$

where:

T_R = Predicted rip tear strength
f = Mean single thread breaking strength (force) of the yarn in the del zone (i.e. triangular shape at the point of tear) with n cross yarns
fs = The sliding (slipping) force (pull-out force) past n crossing yarns
$\beta = e^{u2\theta}$ (from capstan equation)
$1 - D\theta$ = Straight section of yarn between each cross yarn
D = Sum of warp and weft yarn diameters

p = Inter-yarn spacing
u = Inter-yarn friction
θ = Weave angle (half of the arc of contact or wrap angle in radians)
t = Threads/in in the direction of the tear
S = The average distance by which the space between the threads may be reduced

Experimentally[66] it was found for plain weave fabric that:

$nS = 7e^{-0.2x}$ where x is weft cover factor
$nS = 9.8e^{-0.01x}$ where x is warp cover factor

Seo[67] (quoted in Ref. 40) developed a similar, but strain-based, model as follows:

$$T_R = \left[\frac{\left(\frac{p - D\sin\theta}{\cos\theta} + D\theta \right) \varepsilon\gamma B}{(e^{u2\theta} - 1)\, p \tan\alpha} + 1 \right] f/2 \qquad [7.11]$$

where:

$\varepsilon\gamma B$ = Average yarn strain at break, and the other symbols are the same as for Taylor's model given above
α = Del apex angle (a floating variable)

Scelzo *et al.*[40] found that there are three components of tear that must be included in any model if it is to be accurate:

(i) Resistance to pull-out (as included in the models of Taylor and Seo)
(ii) Resistance to jamming (alluded to by Taylor and Seo, but not included in their models)
(iii) Resistance to yarn breakage (included in the models of both Taylor and Seo)

A high resistance to tear requires a large number of 'load bearing' yarns to be incorporated into the del zone[40] (i.e. triangular shape at the point of tear, see Fig. 7.4),[41] which represents the region devoid of longitudinal yarns.

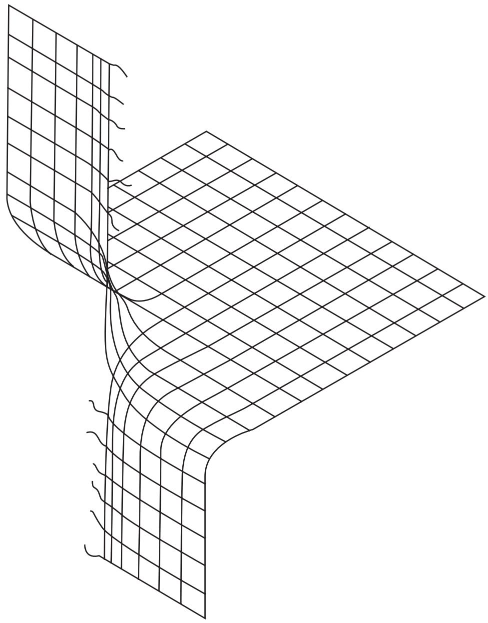
Hager *et al.*[68] showed that the trapezoid tear strength results were a function of yarn breaking strength and extension, the effective specimen length and the number of threads per cm.

Steele and Gruntfest[69] concluded that, for the trapezoid test, the tear load (F) is given by the following equation:

$$F = \frac{ghL_0}{2\cot\alpha} f(E) \qquad [7.12]$$

where:

g = Fabric modulus
h = Fabric thickness



7.4 Triangular zone (del) at the point of tear. Source: Taylor, 1959[41]

L_o = Gauge length
α = Trapezoid angle
E = Elongation of the material at break

The form of the term $f(E)$ is determined by the shape of the force–elongation curve. Scelzo *et al.*[70] concluded that further work was necessary to improve the accuracy of the various models developed to predict fabric tear strength.

Bursting strength

Fabric bursting strength is related to yarn strength and is greatly affected by fabric extensibility, being approximately proportional to the square root of the fabric extensibility, which is largely determined by fabric structure[44] and fibre/yarn extensibility.

7.3.6 Effect of garment properties on strength

In the main, the properties, positioning, etc. of seams, together with the fabric properties, determine the strength characteristics of garments. In addition, clearly, the design and fit of the garment will determine the stress (load and extension) applied to the fabric assembly during wear. Therefore, tight fitting garments containing low stretch (rigid) fabrics will be subjected to large forces, particularly around the knees, elbows and seat regions and could therefore burst or tear if not sufficiently strong or extensible.

Seam strength

Various studies (e.g. Ref. 71) have been undertaken on the role of seams on the tensile behaviour of fabric assemblies. Seam failure can be caused by the sewing thread wearing out or breaking before the fabric, seam slippage (e.g. when the yarns are smooth or the fabric loose) and the breakage of the yarns by the sewing needle during the sewing operation. Ng *et al.*[72] recently reviewed the effect of the sewing thread properties on fabric and garment quality.

A seam joins two garment panels/fabrics together by the use of a sewing thread for garment making. In order to maintain a good overall appearance and fit of a garment, seam strength should be adequate. Different types of garments have different seam strength requirements. Frederick[73] recommended in 1952 that the seam strength in United States military cotton fabrics should be 80% of the fabric strength or in other words have 80% seam efficiency. Crow and Dewar[74] found that the double-lap seam used in Canadian Forces combat clothing had a seam efficiency of 80 to 100%. However, many factors govern the level of seam strength, and these will be discussed below.

Effects of fabric structure and properties:

Fabric type and weight can affect the seam strength, with fabric types that are prone to fraying, such as loosely woven fabric, always requiring better constructed and more dense seams.[75]

The seam direction can also affect the seam quality. Domingues *et al.*[76] studied wear simulation from a different perspective, using standardised seams on 40 fabrics which were submitted to a series of fatigue-simulation cycles including washing, drying, a static mechanical load under determined characteristics, and steam ironing. The results showed that seam strength is greater for seams following the warp direction than for those following the weft direction.[76]

Fabric weight also affects seam strength. Lightweight fabrics require relatively stronger seams and seam strength efficiency than heavy fabrics. According to the research of Crow and Dewar,[74] lightweight fabrics used in Canadian Forces combat clothing require higher seam efficiency than heavy fabrics.

Effects of fibre, yarn and fabric processing parameters:

- *Stress location of a garment.* As a result of body movements, e.g. bending and sitting, it is inevitable that certain locations of a garment (such as the crotch area) have to withstand greater stresses during wear. Nestler and Schlegel[77] noted that donning and doffing a garment can cause considerable stresses in certain parts of the garment. Consequently, stronger seams are required in those parts of the garment.
- *Thread type, construction, finish and properties.* The type of thread used and its construction, size and finishing can influence the seam strength of a garment. Different threads, such as cotton, polyester, nylon and silk, are available. Generally, threads made from synthetic fibres are more durable and have better abrasion resistance and resistance to chemical degradation, such as that due to bleach, than cellulosic fibres. However, cellulosic type threads have better heat resistance than synthetic threads. Thus, the type of thread to be used depends on the fabric being used.[78,79]

  There are different types of thread constructions, such as multi-filament, core, spun and textured. Continuous filament core threads usually provide better seam strength than other constructions of threads. Different thread sizes are available on the market but the finest threads are preferred because a longer length of thread can be accommodated on the lockstitch machine, and they do not acquire much space in the seam, which can prevent puckering.[78–80] Nevertheless, the thread linear density to be used also depends upon the fabric weight and type of sewing thread. For example, lightweight denim fabrics could be sewn with either finer polyester threads, or coarser cotton threads, while heavyweight denim fabrics should be sewn with either coarse corespun threads or coarse polyester threads.[81]

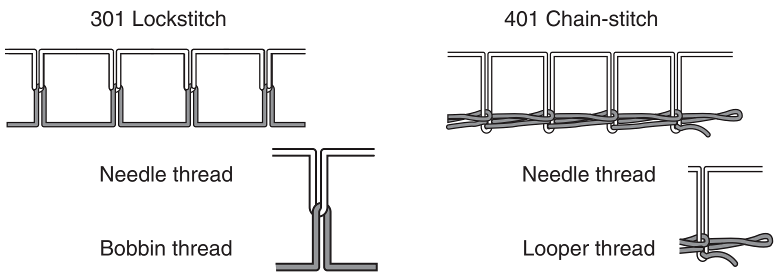
  There are many thread finishes, including soft, mercerised, glaced and bonded, which can affect the seam strength. Glaced or bond finished threads generally have better abrasion resistance than soft finished threads. Mercerised threads are stronger than soft cotton threads of the same thread type and size.[78]

  It is also important that the sewing thread elasticity should match that of the fabric. If it does not match, it could result in tearing of fabric or thread and seam breakage in the garment. Different fabrics require threads of different elasticity.[79] For example, knitted fabrics are more elastic than woven fabrics; therefore, more elastic threads should be used when sewing knitted fabrics. The entire length of the thread on the reel should also have the same elasticity which ensures proper stitches.
- *Sewing machine tension.* The thread tension on the sewing machine should be correctly adjusted before sewing commences. Low thread

tensions usually generate lower seam strength while too high a thread tension can result in seam puckering; a medium thread tension is to be preferred. All the relevant parts of the sewing machine should be well oiled and smooth enough to ensure a low thread waste, smooth and flawless stitching, and no damage to the thread.[79]

- *Sewing needle*. The diameter of the sewing needle, the shape of its point and the size of the needle eye can all affect the seam construction. The size of the needle eye should be in accordance with the thickness of the thread. If it is smaller than the thread and does not enable effortless passing of the thread, there is the possibility of thread abrasion during sewing and thread failure during garment wear. If the needle eye is too large relative to the thread, miss-stitching might result due to poor loop formation and thread control. Therefore, the proper ratio of size and type of sewing needle and thread is required. In order to avoid fabric damage due to excessive heating of the needles while stitching, special needles, such as titanium nitride coated needles, have been developed.[79]
- *Stitch type and stitch density*. In general, the more thread consumed in a stitch, the stronger the seam. For example, 301 lockstitch and 401 chain-stitch seams (Fig. 7.5)[78] are used to increase seam strength by interlocking the threads. Lockstitch seams are commonly used in the industry because of their comparatively low cost, but they are more susceptible to shearing.[78,79]

  Generally, the greater the stitch density in a seam, the greater is the seam strength. As previously mentioned, when more thread is used in the seam, the seam is stronger. Nevertheless, too great a stitch density can damage some kinds of fabrics by cutting the yarns and can also cause seam puckering; it also reduces the speed through the sewing machine.[78]
- *Seam type*. There are various types of seam constructions for sewing different types of garments:[78]



7.5 Features of 301 lockstitch and 401 chain-stitch. Source: URL[78]

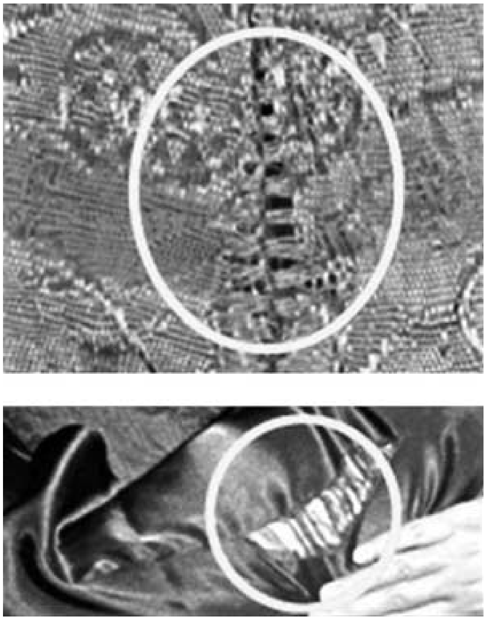
(i) Decorative seam. This seam is used for decorating a garment. It is applied to one or more than one layer of fabric, using many rows of stitches.
(ii) Superimposed seam. This is the simplest and most widely used type of seam construction. The border of one fabric piece is kept on another piece of fabric, and then the two are sewn together.
(iii) Applied seam. An applied seam is when another material other than the fabric itself, such as lace and patch, is sewn on the seam or edge of the garment fabric.
(iv) Bound seam. This seam is also used for decorative purposes. Here the edges are attached by means of tapes or through self binding.
(v) Single ply construction seam. This is constructed from a single layer or piece of fabric. It is generally used for manufacturing belts and belt loops.
(vi) Edge neatening. Here the edges of the fabric are trimmed, hemmed and folded and stitched.
(vii) Lapped seam. This is the strongest type of seam, and it is generally used for denims. Here the seam is on the overlapped fabrics. Chmielowiec[82] investigated the effect of the seam type and sewing thread on seam efficiency for two types of work-wear fabrics. He found that lapped seams were stronger than safety stitched seams. Top stitching (of the lockstitch type) at safety seams weakened the seams, but the third row of stitching at the lap seams had no significant effect on seam strength.

- *Effect of laundering*. Laundering has an adverse effect on the seam strength of a fabric. Mukhopadhyay and Sikka[83] studied the impact of laundering on the seam tensile properties of suiting fabric and found that the seam strength and seam efficiency of the fabric decreased after repeated laundering (tensile properties, including initial and secant moduli, were reduced after laundering).[83]

Seam slippage

Seam slippage[84] (Fig. 7.6) is defined as that which occurs when the yarns in the fabric pull out of the seam at the edge[84–86] or, alternatively, where the threads of a fabric begin to pull away from the stitching in a seam. It will create a laddered effect at the seam, and eventually the fabric will break down completely. The stitches of the seam remain intact; it is the fabric on either side of the seam that tears.[87]

Factors that can increase the occurrence of seam slippage are discussed in the following pages.



7.6 Seam slippage on rayon fabric. Source: URL[84]

Effects of fibre composition, structure and properties

In general, fibres with a lower surface friction or smooth structure, such as silk and polyamide (nylon), are more likely to lead to problems with seam slippage.

Effects of yarn structure and properties

Smooth yarns and/or continuous filament yarns and/or those having a slippery surface are more likely to lead to problems with seam slippage, since such yarns will slide more readily over other yarns.[84,85,88] Also, a lower number of ends and picks per inch or cm (i.e. lower sett) with relatively coarse yarns increases seam slippage problems.[88] Yarns with lower crimp are less inclined to slipping when the seam is sewn perpendicular to them.[89]

Yarn-to-yarn friction, yarn-to-sewing-thread friction and yarn flexural rigidity[90] can also influence seam slippage.

Effects of fabric structure and properties

- *Fabric structure.* Woven fabrics tend to suffer more from seam slippage than knitted fabrics because of the floats in the weave structure and the interlocking nature of the knitted loops. Kalaoglu and Meric[91] investigated the performance of different linings that demonstrated this.

The seam direction can also affect the seam quality. Domingues *et al.*[76] found that seam slippage is higher for seams in the weft direction than for seams in the warp direction.[76]

- *Fabric density.* Seam slippage occurs more readily for fabrics with a low density (i.e. loosely constructed fabrics) because such relatively open (loose) fabric constructions allow the threads a greater freedom of movement.[84,85,88] Miguel *et al.*[89] concluded that wool fabrics generally have a high density and cohesion, with compact and/or strongly interlaced yarns, which makes yarn separation during seam slippage more difficult. Generally, internal cohesion of the fabrics can be increased by increasing the type of finish, which leads to greater wool felting and, consequently, to more fibre entanglement. This makes it more difficult for the yarns to separate or slip, and therefore reduces seam slippage potential.
- *Cover factor*. Fabrics with a high cover factor are less inclined to seam slippage, but usually have low air permeability. Fabrics having a much higher warp cover factor than weft cover factor exhibit lower slippage of the weft against the warp, as there is a greater number of contact points between them, and the adjacent warp yarns are highly crimped. On the other hand, warp slippage through the weft yarns is easier when there are few contact points and the weft crimp is lower.[89]
- *Stretchability.* Body movement and bending will induce fabric stretch, with some fabrics, such as linings, having no stretchability. When the garment (i.e. outer fabric) is stretched but the lining fabric cannot, the lining will start coming apart at the seams since the threads used to stitch the lining pieces together are generally stronger than the lining fabric. Therefore, the linings should be slightly larger than the garment.[87]

Effects of fibre, yarn and fabric processing parameters

Seam slippage can also occur because of the stress location of a garment, thread type and properties, sewing needle, stitch type, stitch density, seam type, and sewing machine condition. The explanations are similar to those given for seam strength, which were discussed in the section on seam strength. As in the case of the effect of sewing thread on seam strength, lightweight fabric should be sewn with finer threads.[81] Regarding the seam type, Morris and Brain[88] found that lockstitch and chain-stitch seams produce similar effects but safety stitching, with needles closely spaced, may increase seam slippage. Apart from the above factors, the following factors can also affect seam slippage:

- *Finishing*. Some finishing processes, such as lubricants and softeners, that are applied to the fabric may reduce yarn-to-yarn friction and allow the yarns within the fabric to move more freely, which can increase the risk of seam slippage.[88]
- *Laundering*. Behera *et al.*[81] investigated the sewability of denims and found that the seam slippage decreased after laundering, for all the fabric–thread combinations they studied. This is due to the relaxation taking place during washing, which results in stronger gripping of thread by the fabric, providing high frictional resistance during the tensile loading of the seam, and hence less slippage.
- *Seam allowance*. One reason for seam slippage is insufficient seam allowance, especially for slippery fabrics or fabrics that easily fray, such as linings.

Measurement of seam strength and seam slippage

As discussed above, researchers have proposed seam efficiency and seam strength guides for different types of fabric. Nevertheless, the technology of maximising seam strength has been developed (e.g. more durable sewing thread) and the measurement of seam strength has been reviewed. A fabric tensile test on fabrics containing a seam is a commonly used method to determine seam quality. There are many national and international seam strength and/or slippage test methods and standards for textiles and apparel. They have been developed to evaluate different kinds of garments. The principles of these test methods and standards are reviewed briefly below.

ASTM D434, Standard test method for resistance to slippage of yarns in woven fabrics using a standard seam (Withdrawn 2004)

This test method covers the determination of the resistance to slippage of filling (weft) yarns over warp yarns, or warp yarns over filling (weft) yarns, using a standard seam. It is not intended for upholstery fabrics. The test involves a tensile testing machine, a pair of dividers, metal rule, metal clamp and sewing machine. When doing the test, the load–elongation curve of the fabric is superimposed upon a load–elongation curve of the same fabric with a standard seam sewn parallel to the yarns being tested. Resistance to yarn slippage is reported as the load at which a pre-determined slippage is observed [ASTM D434, 1995].

BS EN ISO 13935-2, Textiles – Seam tensile properties of fabrics and made-up textile articles – Part 2: Determination of maximum force to seam rupture using the grab method

This test is for the determination of maximum seam force of sewn seams when the force is applied perpendicularly to the seam. This part of EN ISO 13935 describes the method known as the grab test. The test method is mainly applicable to woven textile fabrics although it may be applicable to fabrics produced by other techniques. It is, however, not normally applicable to woven elastic fabrics, geotextiles, non-wovens, coated fabrics, textile-glass woven fabrics and fabrics made from carbon fibres or polyolefin tape yarn. The sewn fabrics may be obtained from previously sewn articles or may be prepared from fabric samples, as agreed by the parties interested in the results. This method is applicable to straight seams only and not to curved seams. The test involves a CRE machine, equipment for sewing defined seams and equipment for cutting test specimens. A fabric test specimen, having a seam in the middle, is gripped in its centre part by jaws of specified dimensions and is extended perpendicular to the seam at a constant rate until the seam ruptures. The maximum force to seam rupture is recorded [BS EN ISO 13935-2].

ASTM D1683, Standard test method for failure in sewn seams of woven apparel fabrics

This test method measures the sewn seam strength in woven fabrics by applying a force perpendicular to the sewn seams. This is used when a breaking force to rupture, a minimum elongation, or both, are required to determine the sewn seam strength, seam slippage, or seam integrity of a particular fabric for a specified end use. This test method is applicable whenever a determination of effective sewn seam strength, that is, the optimum seam interaction, is required. The breaking force of the seam and fabric will permit determination of seam efficiency. This method can aid in determining optimum seam interaction for any given fabric by comparing the properties of the fabric with and without a seam. The test involves a tensile testing machine, sewing machine, sewing threads, dividers and metal rule. While doing the test, the breaking force required to effect rupture of the sewn seams is measured using the grab test method. The applied force is longitudinal and perpendicular to the seam. It can also be used to measure seam slippage by subtracting the elongation of the fabric from that of the fabric with a seam in it. The difference is indicated as seam slippage, which can be considered one mode of failure of a seam assembly [ASTM D1683, 2007].

BS EN ISO 13936-1, Textiles – Determination of the slippage resistance of yarns at a seam in woven fabrics – Part 1: Fixed seam opening method

This part of ISO 13936 is intended for the determination of the resistance offered by thread systems of woven fabric to slippage at a sewn seam.

However, this method is not suitable for stretch fabrics or for industrial fabrics, e.g. beltings. The test uses a constant-rate-of-extension (CRE) machine (i.e. tensile testing machine), sewing machine, needles, throat-plate and feed-dog, sewing thread, and calibrated rule. An unseamed and a seamed part of the test specimen are separately extended by using a tensile testing machine fitted with grab test jaws, to produce, in the case of the use of a chart recorder, two force/extension curves originating from the same abscissa. The force required to produce a specified distance between the curves, equivalent to a specified seam opening, is determined [BS EN ISO 13936-1, 2004].

BS EN ISO 13936-2, Textiles – Determination of the slippage resistance of yarns at a seam in woven fabrics – Part 2: Fixed load method

This part of ISO 13936 is intended for the determination of the resistance offered by thread systems of woven fabric to slippage at a sewn seam. This method is suitable for all apparel and upholstery woven fabric and stretch fabrics (including those containing elastomeric yarn). However, the method is not suitable for industrial fabrics, e.g. beltings. The equipment used is the same as in Part 1. A strip of fabric is folded and stitched across its width. The strip is cut near the fold and a force is applied to the strip at right angles to the seam using grab-test jaws. The extent to which the seam opens is measured [BS EN ISO 13936-2, 2004] and used as a measure of seam slippage.

ASTM D3940, Test method for bursting strength (load) and elongation of sewn seams of knit or woven stretch textile fabrics (Withdrawn 1995)

This test method is for the determination of the bursting strength and elongation of sewn seams in knitted or stretch fabrics. The sewn seams may be obtained from previously fabricated articles, such as garments, or may be prepared from fabric samples. This test method requires a straight seam line, and is not applicable if the seam line is curved. The preparation of test specimens in this test is from fabric samples, which require prior specification of sewing details as agreed upon by the purchaser and seller. Equipment used in this test includes a tensile testing machine, ball burst device, sewing machine and sewing thread. The prescribed sewn seams taken from an already sewn item or prepared in accordance with a specification are tested for force to rupture and for extensibility using the ball burst procedure [ASTM D3940, 1983].

7.4 Effects of dyeing and finishing on fabric strength

Fabric tear strength is generally susceptible to changes during processing[92] (dyeing and finishing), due to the changes in fibre and yarn friction and mobility, particularly the latter. Nevertheless, any fibre damage or tendering during such mechanical and/or chemical treatment processes will have a detrimental effect on all three measures of fabric strength. Furthermore, chemical, photo-chemical, biological (e.g. micro-organisms) and heat damage can reduce fabric strength.

Chatterjee *et al.*[39] found that wet processing of cotton and rayon fabrics tended to increase tensile strength but decrease tearing strength, ascribing these changes to the increased fabric consolidation and mass per unit area. Fabric tear strength is very sensitive to lubricants and softeners in as much as they affect inter-fibre and inter-yarn friction, tear strength increasing as inter-yarn friction decreases.[50]

It is a well known fact that most traditional durable press (DP) treatments of cotton, involving cross-linking, adversely affect the fabric durability, strength in particular.[93] In many cases they also release formaldehyde, a carcinogen. Considerable research has been directed towards developing new DP treatments which do not have these disadvantages, one example being ionic cross linking.[93] Although most dyeing and chemical finishing treatments applied in practice decrease fabric tensile strength by chemically degrading/damaging the fibres, certain finishing treatments, such as the mercerisation of cotton fabrics,[54] increase fabric tensile strength. Furthermore, where the treatment increases inter-fibre friction and bonding, e.g. by a polymer coating, fabric tensile strength can be improved.

Chiweshe and Crews[94] found that neither dryer sheet softeners nor cellulose-enzyme-containing laundry detergents affect cotton and polyester fabric tensile strength, whereas rinse cycle softeners increase fabric strength loss. Kut *et al.*[95] found that the softeners they studied (polysiloxane, fatty acid and quaternary ammonium) decreased the breaking strength of polyester fabrics by increasing fibre slippage.

7.5 Modelling and predicting fabric strength

Various researchers have used multiple regression analysis, artificial neural networks,[96] and expert systems in attempts to engineer and predict fabric tensile strength and other related properties. Chen and Ding[97] reviewed the different approaches to modelling and predicting woven fabric tensile strength. From their investigation, Ertugrul and Ucar[98] concluded that both the multi-layer feed-forward neural network and adaptive network-based fuzzy inference system can be used to predict the bursting strength of plain knitted cotton fabrics. They found that fabric weight, yarn breaking strength and yarn breaking elongation affected bursting strength.

Chen and Ding[97] used the chain-of-bundles model and Monte Carlo method to simulate and predict the tensile strength of woven fabrics. They concluded that the shear-lag analysis was more suitable than the local loadsharing rule for predicting the strength of woven fabrics under uni-axial tensile load.

7.6 Sources of further information and advice

The reader is referred to the following for further reading:

- Abrasion and wear[5,12,13,14,16,17,34,99]
- Fabric surface wear[15]
- General[10,59–61,100–103]
- Fabric strength[17,40,44,93,105,106]
- Fabric and garment quality assessment[49,72,104]

7.7 Concluding remarks

Further technological developments in the area of fabric/garment abrasion and strength can be expected through the following:

- Improved modelling and prediction of fabric strength and abrasion resistance
- Improved and integrated testing
- Instrumental measurement of fabric appearance related properties, such as changes in fabric appearance during abrasion
- 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

7.8 References

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8
Physiological comfort of fabrics and garments

J. FAN

Abstract: This chapter first provides the definition and scope of clothing comfort. It then focuses on the various aspects of clothing physiological comfort, including tactile comfort, thermophysiological comfort, garment fit and ease of body movement, and pressure comfort. The assessment of these different aspects of clothing physiological comfort and their relationship to the properties of clothing materials, fabric and garment design, as well as environmental conditions, are discussed.

Key words: clothing comfort, tactile comfort, thermo-physiological comfort, ease of body movement, pressure comfort.

8.1 Introduction

Comfort is arguably the most important requirement of mankind. Human beings are constantly striving to maintain or improve their level of comfort. Even before birth, the human embryo attempts to find a more comfortable location by embryonic motion. Throughout different stages of life, from baby to elderly, the needs may change but the comfort demand is always there. It was said that from cradle to grave, for old and for young, for rich and poor alike, comfort is the major need in life and to the edge of death.[1]

Although everyone has an experience of comfort, it is such a subjective phenomenon that a unanimously agreed quantitative definition is almost impossible to achieve, as a situation which is perfectly comfortable for one person may be very uncomfortable for another. In the literature, comfort is defined qualitatively or conceptually. In the *Oxford English Dictionary* and *Webster's Third New International Dictionary*, comfort is defined as 'freedom from pain, trouble and anxiety; therefore, comfort is a contented enjoyment in physical or mental well-being'. Mehta and Narrasimham[2] defined comfort as an experience caused by the integration of impulses in the brain passed up by the nerves from peripheral receptors. In the context of clothing, it means a neutral sensation when the wearer is physiologically and psychologically unaware of the clothing.[3] It may also mean adequate warmth and a dry skin, freedom from pressures and restrictions of movement, and absence of a cold shock when putting on a garment.[4]

Slater[1] defined comfort as a pleasant state of physiological, psychological and physical harmony between a human being and his environment. He classified comfort into three interrelated aspects, viz. physiological comfort, psychological comfort and physical comfort. Physiological comfort refers to the human body's ability to maintain life. It depends on such factors as the temperature of body and skin, tactile sensations, neural responses, lung function, body mechanical efficiency, blood pressure, visual or aural stimulation, taste or smell sensations, and skin hygiene. Psychological comfort refers to the mind's ability to keep itself functioning satisfactorily without external help, and is influenced by such attributes as the presence or absence of other human beings, fear, stress, pleasure, embarrassment, or pain.[1] Physical comfort refers to the effects of the external environment on the body's physiological and psychological equilibrium.

In this book, the subject of comfort is dealt with in two chapters: a chapter on physiological comfort and a chapter on psychological comfort. Since physical comfort invariably relates directly to either physiological or psychological comfort, it is discussed from the point view of how physical properties of clothing relate to physiological comfort and psychological comfort in the respective chapters.

8.2 Different aspects of clothing physiological comfort

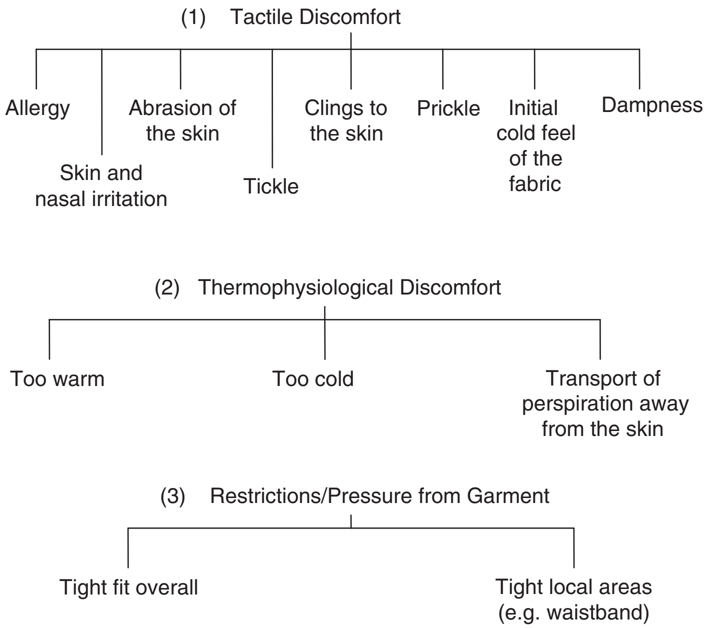
Smith[3] classified physiological discomfort sensations into three categories, viz. sensorial discomfort (i.e. what the fabric/garment feels like when it is worn next to skin), thermophysiological discomfort, and garment fit.

The sensorial discomfort referred to by Smith[3] may be better termed tactile discomfort since the thermal and pressure sensations referred to in the other two categories can also be regarded as sensorial. The category referred to as garment fit may be better termed as restrictions or pressure imposed by garments. The modified classification is illustrated in Fig. 8.1.

8.3 Tactile comfort

Tactile sensations arise through the triggering of sensory receptors in or near the skin surface by the contact of the fabric surface with the skin. The nature of the fabric surface therefore has a marked effect on the sensations experienced.[5]

There are three basic categories of skin-sensory receptors, viz. the touch group, the thermal group and the pain group. There are several different types of touch receptors which respond to mechanical displacement of the skin. They are extremely sensitive and supply us with good spatial and temporal discrimination of stimuli. Tactile sensations associated with soft-



8.1 Classification of clothing physiological discomfort sensations. (Modified from Smith, 1986[3])

ness, stiffness, and clingingness are examples of information likely to be conveyed by these receptors. The thermal group responds to cold and warmth, and monitors for us the transfer of heat to or from the skin. Thus, we can gauge whether our clothing is appropriate for the climate, and they also provide us with those cold sensations that are perceived initially on placing some types of fabric against the skin.[5]

Skin tactile sensations range from the relatively mild tickle and wet-cling sensations through to the more severe discomfort associated with an allergic reaction. In the following sections, the different types of tactile sensations are described and their association with fabric and garment properties are discussed.

8.3.1 Effects of fabric and garment properties on tactile sensations

Allergies

A fabric that is uncomfortable to wear next to the skin can cause a rash or an allergic reaction. Skin inflammation that follows prickle in some people is sometimes also described by clinicians as an allergy.[5]

Allergies can be physiological, psychological or physical. For example, some people may think that they have allergy to a fibre, when in fact the rash is caused by the fabric rubbing against the skin. Prickle-sensitive people who cannot tolerate wearing some types of wool garments (e.g. those made of inferior coarse wool) next to the skin tend to believe that they are allergic to wool.

The presence of excess levels of certain chemical finishes on a fabric surface (e.g. formaldehyde on some wrinkle-free garments) is of particular concern in terms of allergies associated with clothing.[6]

Skin and nasal irritation

Skin and nasal irritation is caused by loose fibres that have been released from the fabric surface. These loose fibres will cause nasal irritation and tickle or prickle sensations at the skin. All these will cause discomfort. Moreover, the loose fibres may roll up and entangle with other protruding fibres to form pills and may also attach themselves to other garments in an unsightly manner that causes annoyance.[6]

Local irritation

Local irritation can be caused by sewn-in garment labels and to a lesser extent by abrasion associated with seams. Most of the cases of 'label prickle' have been attributed to the hard, sharp corners that are sometimes present on labels, the edges of which are heat-sealed or folded. Moreover, the label may stick onto the skin and cause discomfort. Besides, it may cause psychological discomfort when the label is hanging outside the garment. Therefore, it is better to remove the label (especially from infant wear) or sew it to an area that minimizes the discomfort, i.e. at the side seam of an outer garment.

Abrasion

Skin abrasion is a common cause of tactile discomfort when the relative movement between fabric and skin is frequent during physical activity.

When clothing fabrics touch the skin surface, sensations of softness or roughness are aroused. These sensations can be modulated by moving fabrics across the skin surface, which alters the contact forces.

Skin abrasion is not only related to the fabric–skin contact area, but also to the moisture on the fabric surface. Smith[6] pointed out that the presence of perspiration aggravates the situation, promoting abrasion of the skin. Both perspiration and water externally applied to the skin surface have been reported to increase skin surface friction. The increased friction due to skin moisture alters the perception of fabric pleasantness (or acceptability) and texture. Skin moisture and skin friction therefore contribute much to the discomfort and unpleasantness of clothing in damp, warm environments. Clothing for babies and the elderly, who have sensitive skins, should therefore be engineered to minimize skin wetness by using water absorbent and moisture permeable fabric and be designed with enhanced ventilation between skin and clothing.

Tickle

Tickle is caused by fabric hairiness and is influenced by garment fit.[6] Hairiness, an important attribute of yarn quality, is caused by the protrusion of fibres from the body of the yarn, imparting a fuzzy appearance. The protrusion of fibres will irritate the skin-sensory receptors' touch group.[5] The fit of the garment is also an important contributor, as garment fit determines the amount of relative movement between the fabric and the body. It has been reported that the more often the fabric moves over the skin, the more frequently will a tickle sensation be experienced by the wearer.

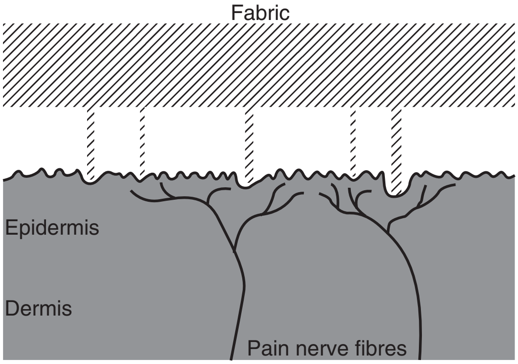
Clinging to the skin

There are different types of clinging, including wet cling, tacky cling and cling due to static charge.[3] Wet cling is caused by perspiration; tacky cling is associated with the presence of damp and sticky perspiration residues on the skin. The main factor influencing the degree of wet and tacky cling is the area of fabric in contact with the skin, which is influenced by the fabric structure.[3,6]

Cling due to static charge is formed when the electrostatic forces on the garment are greater than the gravitational force.[2] The static electrical effect of a fabric manifested in sparking and clothing clinging to the body is unpleasant and detrimental to a person's comfort. The amount of charge generated depends on the chemical nature and electrical resistance of the materials, surface finishes and additives, the pressure and degree of rubbing, and the area of contact. Thus, the degree of clinging also depends largely on weight per unit area of the fabric. The charge can be eliminated or minimized by the use of conductive fibres, chemical finishes to make the material more electricity conductive (e.g. hydrophilic finishes, metal coatings), or creation of conductive paths.

Prickle

Prickly sensations are caused by coarse and therefore stiff fibres protruding from the fabric surface. Prickle is a pain sensation arising through the



8.2 The mechanisms in fabric-evoked prickle. Source: Mayfield, 1987[5]

triggering of the pain group of the skin-sensory receptors. Prickle sensations from fabrics occur well after tactile sensations from the touch group of receptors have failed.[5] The prickle sensations, in fact, disappear about the same time as thermal and painful sensations are diminishing, which indicates that prickle is mediated by nerve fibres of the thermal or pain groups.

Experiments on single-nerve fibres in rabbits[5] showed that some skin-pain receptors are activated by forces as small as 0.75 mN exerted at the end of a 30 μm glass fibre against the skin. In other words, the prickle stimuli on the fabric surface are fibre ends that can support (without buckling) loads of about 0.75 mN or more against the skin. Figure 8.2 illustrates the mechanisms in fabric-evoked prickle.

Garnsworthy *et al.*[7] found that the subjective magnitude of the prickle sensation depends on the prickle stimulus intensity measured as the number of protruding fibres with buckling loads greater than 75 mN per 10 cm,[2] viz.

$$R_p = 0.54 S_p^{0.66} \quad [8.1]$$

where R_p is the subjective magnitude of prickle sensation and S_p is the prickle stimulus intensity, measured as the number of protruding fibres with buckling loads greater than 75 mN per 10 cm^2.

According to buckling theory, the critical buckling load is proportional to Ed^4/l^2 (E: bending modulus, d: diameter of the fibre and l: length of the protruding fibre). It was shown that a fibre diameter of 30 μm and a protruding length of 2 mm will give a critical buckling load of 0.75 mN.[8,9] Therefore, the percentage of coarse fibres (i.e. fibres > 30 μm) is important in terms of prickle sensation. Naylor[9] showed that prickliness is very different for a fabric having 1% of fibres coarser than 30 μm and for a fabric having 2.4% of fibres coarser than 30 μm; Dolling *et al.*[10] also found that fibre diameter distribution is a critical factor in terms of the prickliness of a fabric. Based on the buckling theory, He and Wang[11] further showed that fibre irregularity decreases the critical buckling load of fibres since thinner fibre segment will buckle more easily.

Moisture is also a factor, Mayfield[5] observing that moisture applied to the skin before application of a prickly fabric significantly raised the level of activity of a skin-pain receptor. This is because water softens the hardness of the outermost layer of the skin (the *stratum corneum*). The finding was consistent with the known enhancement of prickle intensity caused by wetting the skin or perspiration during physical activity or under hot and humid conditions.

Individuals can vary considerably in their sensitivity to fabric-evoked prickle. Psychophysical measurement of prickle threshold in a group showed that the mean threshold-stimulus intensity was lower for females and progressively increased with age. Therefore, a soft skin is most sensitive to prickle, especially in babies.[5]

Prickle can be prevented. Use of finer fibres, chemical processes which reduce the bending modulus of the fibre, and the finishing processes of brushing and raising, which increase the length of protruding fibres, will reduce prickle. In contrast to this, the finishing process of cropping, which shortens the protruding fibres, tends to worsen the prickle discomfort. All the above can be explained in terms of buckling theory.

Initial warm/cool feeling

Initial warm or cool feelings are experienced when a garment is first donned or a fabric is first touched. This sensation is determined by the heat transfer between the skin and the fabric surface. It is therefore predominantly influenced by fabric surface contact with the skin and fibre content.[6]

In general, surface hairiness and loose arrangements of fabric layers containing more air create a warmer feeling; more compact and less hairy fabrics create a cooler feeling. Hes *et al.*[12] investigated the effect of mutual bonding of textile layers on the thermal contact properties of fabric assemblies, and showed that spotbonding the outer fabric interlining and lining together increases the thermal absorptivity (i.e. makes the material feel cooler to the touch).

Dampness (or wetness) perception

Liquid or moisture on the skin, or in clothing, leads to dampness discomfort sensations during wear, such as clamminess and stickiness. Through a dynamic surface wetness test, in which the surface wetness of the fabric was measured by the cobaltous chloride colour index, Scheurell *et al.*[13] showed that the intensity of discomfort sensations is directly influenced by the amount of moisture at the clothing–skin interface, and that comfort level decreases with the build-up of moisture on the clothing next to the skin.

The sensation of moisture in clothing was further investigated by Sweeney and Branson[14] by applying a psychophysical method. They placed a sample of pre-prepared water content onto the back of human subjects and asked the subjects to make a magnitude estimation of the moisture sensation in comparison with a control sample of fixed water content. Then they correlated the magnitude estimates of wet sensation with the water content of the fabric sample and found

$$S = 31.62\phi^{0.53} \quad [8.2]$$

where S is the moisture sensation and ϕ is the moisture stimuli value (i.e. water content). This shows that Steven's power law of psychophysics applies to the moisture sensation.

The water concentration at the fabric–skin interface (the direct stimulus of dampness discomfort) is influenced by the fibre type. By a simulated sweating experiment, Scheurell *et al.*[13] showed that the water concentration (as indicated by the colour change of cobaltous chloride) at the surface of a polyester fabric increased much faster than that at the surface of cotton/polyester and cotton fabrics. The better wicking property of cotton fibre slowed the build-up of water concentration at the fabric–skin interface. Plante *et al.*[15] further investigated the relationship between dampness perception and fibre type. They evaluated four fabrics of different fibre types (viz. wool, cotton, polyester, wool/polyester blend) at five levels of moisture content and three levels of relative humidity. They found that dampness perception is related to fibre hygroscopicity. The dampness sensation is produced by the water content in excess of the equilibrium regain of the fabric. Highly hygroscopic fibres, such as wool, are perceived to be significantly drier than weakly hygroscopic fibres, such as polyester.

Despite the evidence that dampness perception is related to the water concentration at the skin–fabric interface, there is an argument that dampness perception is caused by the skin temperature drop when the skin is in contact with the wet fabric,[16,17] as no specific moisture detector in humans has been identified by neurophysiologists.

8.4 Assessment of tactile comfort

Tactile comfort of clothing can be assessed through subjective wearer trials by using psychological scaling or psychophysical magnitude estimation. It can also be evaluated through objectively measuring the physical stimuli directly causing a specific tactile discomfort sensation.

8.4.1 Psychological scaling

With the psychological scaling method,[18] human subjects are directed to undertake a wearing protocol and are then asked to rate the intensity of a specific discomfort sensation on a defined scale, defined in the prospective raters' language of perception, for example, 1 for totally to 4 for partially having a specific tactile sensation.[19]

8.4.2 Psychophysical scaling

Psychophysical scaling involves the measurement of a single sensation in relation to its initiating physical stimulus. Physical stimuli of known intensities are used to evoke the sensations under investigation.[14,20] With a psychophysical scale, the rater is asked to make simple judgements, such as to detect whether a sensation is present or absent, or to detect whether two sensations are equal in intensity or different. It avoids the problem of using words that may have different meanings for different persons to name the intensities of sensations or to name polar adjectives of comfort sensations. It also avoids the difficulty of having to choose the number of categories or points on a scale. Therefore, psychophysical scaling is considered to be more reliable than psychological scaling. Nevertheless, psychophysical scaling applies only to the assessment of comfort sensations, which have direct physical correlations.

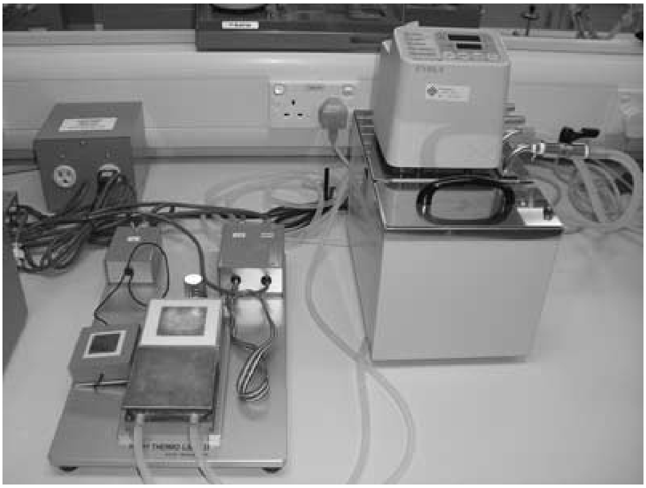
8.4.3 Objective evaluation methods

Characterisation of surface mechanical stimuli

Many of the tactile discomfort sensations, such as irritation, skin abrasion, tickling and prickling, are related to the surface characteristics of the fabrics, which can be evaluated by the Fabric Surface Property Tester of the KESF system. The instrument, which has been described in Chapter 1, measures the fabric roughness (or the variation in fabric thickness) and surface frictional forces.

With regard to prickle, a technique has been devised for objectively measuring the prickle propensity of fabrics. In this method, a fabric under a pressure of 4 gf/cm^2 is placed on a thin PTFE skin spread over a glass slide. The pliability and poor elasticity of the PTFE skin result in fibre ends with buckling loads of about 100 mg or more leaving imprints on the skin. The number of imprints are counted under a microscope and used as a measure of prickle propensity.[5]

Sakaguchi *et al.*[21] developed a novel technique for assessing the contacting behaviour of a fabric. In their technique, transparent silicone rubber is



8.3 KES Thermo Labo II.

used as a substitute for the human skin. The contact condition between the rubber and the fabric is observed through the rubber, using photomicrography. This provides a measure of the deformation to the body caused by the fabric under pressure.

Characterisation of thermal contact properties

The warm–cool contact feeling of the fabric can be physically evaluated by measuring the heat flow from a hot surface to a fabric surface. There are two commercially available instruments for this purpose: KES Thermo Labo II[22] and Alambeta.[12] In the KES Thermo Labo II (see Fig. 8.3) test, a fabric specimen is placed on a water box of constant temperature 20°C (the temperature is kept constant by water circulation). A so-called BT-Box, the temperature of which is initially set at 30°C, is then placed on the fabric specimen, and the heat loss from the BT-Box is measured. The maximum rate of heat flux from the BT-Box, termed Q-max, is used as a measure of the warm/cool contact property of the fabric. The greater the Q-max value, the cooler the initial contact feeling of the fabric.

Hes *et al.*[12] later developed a new instrument, called Alambeta, in which a heat flux sensor having a thermal inertia similar to that of the human skin is used to measure the heat flow from the measuring head to the fabric specimen. Alambeta therefore has the advantage that its warm–cool feeling sensitivity approximates to that of the human skin. Hes *et al.* also proposed a new parameter, called thermal absorptivity, to measure the warm–cool feeling. It is defined as:

$$b = \sqrt{\lambda \rho c} \qquad [8.3]$$

where b is thermal absorptivity ($Ws^{1/2}/m^2K$), λ the surface thermal conductivity (W/m.K), ρ density (kg/m^3) and c specific heat capacity (J/kg K).

Measurement of formaldehyde content

Excessive amounts of formaldehyde (CH_2O) present on the fabric or released from the fabric is believed to be one of the causes of skin irritation or even skin cancer. National and international standards have been established to determine the formaldehyde contents on textiles.

BS EN ISO 14184-1:1999[23] specifies a method for determining the amount of free formaldehyde and formaldehyde extracted partly through hydrolysis, by means of a water extraction method. Formaldehyde is extracted from a textile sample with water at 40°C, and the amount of formaldehyde is then determined colorimetrically. The result is expressed in ppm (parts per million), i.e. milligrams of formaldehyde per kilogram of textile sample.

BS EN ISO 14184-2:1998[24] specifies a method for determining the amount of formaldehyde released under conditions of accelerated storage from textiles in any form by means of a vapour absorption method. A specimen is suspended above water in a jar, using a wire mesh basket or other means. The jar is sealed and placed in an incubator at 49 ± 2°C for 20 h ± 15 min. The formaldehyde concentration of the water in the jar is then determined colorimetrically.

The British Standard Institution (BSI) also has another standard, viz. BS6806,[25] for determining the total and free formaldehyde. This method is not compatible with BS EN ISO 14184-1[23] and EN ISO 14184-2[24] because of the different chemistry used to determine the formaldehyde.

8.5 Thermophysiological comfort

Thermophysiological comfort, simply referred to as thermal comfort, is defined by ASHRAE as that condition of mind which expresses satisfaction with the thermal environment.[26]

The expression of thermal comfort depends on the thermal physiological conditions of the human body. The human being is a homeotherm, which means the temperature of its central core must be maintained within a narrow limit. The central core includes the contents of the skull, thorax and abdomen, i.e. most of the vital organs, and a variable amount of the deep tissues within the body. According to many physiological studies, for a person under extended exposure, maintaining the core temperature within 37 ± 0.5°C is vital for survival. The maximum deviation of the core temperature which can be tolerated is about 2°C from its normal level. Beyond this, serious physical threats, such as hyperthermia and convulsions from a high core temperature, and hypothermia and cardiac fibrillation from a low core temperature, can result. More extreme variations in core temperature may result in death.

To maintain thermal comfort under extended exposure, apart from core temperature, a person's skin temperature should also be maintained within certain limits, and the body temperature regulation should be completely accomplished by vasomotor control of blood flow to the skin, viz. an absence of sweating and shivering.[27] The mean skin temperature should generally lie between 33°C to 34.5°C for men and 32.5°C to 35°C for women, and the local skin temperature between 32°C and 35.5°C.

The contribution of clothing towards thermal comfort is to assist the human body to maintain comfortable thermal physiological conditions over an extended range of environments. Thermophysiological comfort of clothing is therefore the ability of clothing in assisting the human body to maintain thermal comfort. As will become clear and can be understood from the discussion in the next section, thermophysiological comfort of clothing is largely determined by the thermal resistance (or insulation), moisture permeability and liquid water transport of clothing.

8.5.1 Humans and their thermal environment

The human body, considered as a thermal dynamic system, produces mechanical work and low temperature heat, using food and oxygen as input. The heat which is generated and which must be dissipated by the body varies from a minimum of about 30 watts per square metre when lying at rest, to a maximum of about 600 watts per square metre or more during extreme physical activity. The body has a human thermoregulation system to control loss of heat, partly by varying the flow of blood to the blood vessels near the skin and so varying the skin temperature within limits, and partly by varying the amount of perspiration, which can produce evaporative cooling (about one-third of the heat loss from a resting person is due to evaporation). Cooling by the evaporation of perspiration is the most important means of dissipating the body heat in hot conditions or under conditions of high physical activity.

Fanger[26] described the energy balance between human and environment, per unit body surface area, as follows:

$$S = M - W_k - H_d - H_e - F_r \quad (\mathrm{W/m^2}) \qquad [8.4]$$

where S is the rate of body heat storage (under thermal equilibrium, S = 0); M is the metabolic rate, i.e. internal energy production of the body; W_k is the external work; H_d is dry heat loss from the skin induced by conduction, convection and radiation; H_e is evaporative heat loss from the skin; and E_r is the sum of the latent and sensible respiration heat loss.

For a clothed person, H_d and H_e may be determined by:

$$H_d = \frac{(T_s - T_d)}{I_t} \quad \mathrm{W/m^2} \tag{8.5}$$

$$H_e = \frac{(P_s - P_a)}{R_t} \quad \mathrm{W/m^2} \tag{8.6}$$

where $(T_s - T_a)$ and $(P_s - P_a)$ are the temperature difference and difference of water vapour pressure between the skin and environment respectively; I_t and R_t are the total thermal insulation and total water vapour resistance of the clothing system, respectively.

The combined equations [8.4], [8.5] and [8.6] are used to determine the heat stress of a clothed person in terms of the required evaporation for thermal equilibrium, required perspiration rate, and skin wettedness.[28,29] They are used to determine the cold stress in terms of the required insulation for thermal comfort,[30] and evaluate the functional design and the range of environmental conditions in which the clothing can be worn comfortably.[31]

The combination of equations [8.4], [8.5] and [8.6] clearly explains the importance of clothing in assisting the human body to maintain thermal comfort and survival. The equations appear simple, but the accurate determination of I_t and R_t is no easy task. The total thermal insulation I_t and vapour resistance R_t of a clothing system are the results of complex heat, moisture and liquid water transport through the clothing materials. They are also not constants. They vary depending on the way the garments are worn, body posture, body movement, and environmental conditions such as wind, rain and radiant heat.

8.5.2 Thermal insulation properties of fabrics and clothing

Measurement of thermal insulation properties of textile fabrics

The thermal insulation properties of textile fabrics can be expressed in terms of thermal conductivity or thermal resistance. The ISO unit for thermal conductivity is W/mK and that for thermal resistance is Km^2/W. In addition, there are two popularly used units for thermal resistance or insulation, viz. Tog and clo.

A 'Tog' is defined as the approximate insulation of light summer clothing.[32–34] Physically, 1 Tog = 0.1 Km^2/W.

Another unit, 'clo', is defined as the insulation required to keep a resting person (producing heat at the rate of 58 W per square metre) comfortable in an environment of 21 degrees Celsius, and air movement of 0.1 m/s, or roughly, the insulation value of typical indoor clothing. The clo is intended to express the insulation provided by a total clothing ensemble, not a single item. The relationship between the clo and tog is that a thermal resistance of 1 clo is equivalent to a thermal resistance of 1.55 Togs or 0.155 Km^2/W.[34]

Less commonly, the thermal insulation property is expressed as the thermal transmittance or warmth keepability rating, which is the ratio of the difference in heat loss between the uncovered hot surface and covered surface to that of the uncovered hot surface, expressed as a percentage.

Several instruments are available for determining the thermal insulation properties of fabrics or fabric assemblies, including:

- Guarded Hot Plate[35]
- KESF Thermo Labo-II
- Alambeta instrument.

In general, these methods determine heat flux by measuring the energy required to maintain a set temperature of a heated device when it is covered by a textile, as well as the temperature difference across the textile material. The thermal conductivity is then calculated by:

$$k = \frac{W \times D}{A \times \Delta T} \, (\mathrm{W/m.^\circ C}) \qquad [8.7]$$

where W is the heat flow, D is the thickness of the fabric sample, A is the area of the hot plate covered by the fabric specimen, and ΔT is the temperature difference across the fabric specimen.

The thermal resistance or insulation I is:

$$I = \frac{D}{K} = \frac{A \times \Delta T}{W} \quad (\mathrm{Km^2/W}) \qquad [8.8]$$

The thermal transmittance U is calculated by:

$$U = \frac{W}{A \times \Delta T} \quad (\mathrm{W/m^2K}) \qquad [8.9]$$

The Warmth Keepability Rating Q is calculated by

$$Q = \left(1 - \frac{b}{a}\right) \times 100 \qquad [8.10]$$

where a is the heat emanated from the blank emanater or test plate (W) and b is the heat emanated from the emanater or test plate with the test specimen mounted (W).

8.4 Sweating fabric manikin Walter.

Measurement of thermal insulation properties of clothing

The thermal insulation properties of garments or clothing ensembles can be measured using heated thermal manikins.

The earliest manikin reported in the literature[36] was that made by the US Army in the early 1940s. Based on their development and functionality, thermal manikins can be grouped into three generations.[37] The first generation were standing (not walkable) and non-perspiring ones.[38–40] The second generation manikins were moveable (walkable), but non-perspiring ones, such as the copper manikin 'Charlie' in Germany[31] and those in Denmark[41] and Japan.[42] The third generation manikins were moveable and perspiring. Although there are more than 100 thermal manikins in use worldwide, the third generation movable and perspiring manikins are still rare in the world. Strictly speaking, only 'Coppelius' in Finland,[43] 'SAM' in Switzerland[44] and 'Walter' (see Fig. 8.4) in Hong Kong[37] belong to this category.

By testing on the thermal manikin, the thermal insulation of garments or clothing ensembles on the manikin can be determined by:

$$I_t = \frac{A_s(\bar{T}_s - T_a)}{H} \qquad [8.11]$$

where I_t is the total thermal insulation of the clothing plus air layer, H is the total dry heat loss from the manikin, A_s is the surface area of the manikin, T_s is the mean skin temperature and T_a the mean ambient temperature.

Factors affecting the thermal insulation of fabrics and clothing

Many researchers[45–51] have studied the thermal insulation of different types of fabrics, and the following general conclusions can be drawn:

(i) The thermal insulation of textile fabrics is primarily due to the still air contained (trapped) within the fabric and yarn. Factors which help the trapping of still air will improve the thermal insulation of fabrics. Texturizing, for example, produces loops, curls or crimps to smooth filament fibres so as to create a fuzzy or natural appearance and impart more air spaces within their structures.[33] Another method of trapping still air in fibres is to imitate wool's medulla and create a hollow fibre, Dupont's Dacro 88 being an example. It is a hollow polyester fibre developed for insulation of clothing and backpacking applications.[33]

(ii) Due to the relatively low bulk density of textile fabrics, differences in the thermal conductivity of the fibres have little effect on the overall thermal insulation of the fabric.

(iii) The thermal transmission of textile materials increases with density. In general, the greater the bulk density for a given thickness, the greater the thermal transmission and the lower the warmth, due to the replacement of air by fibres having a greater heat conductivity. However, if the bulk density is very low, or if the fabric construction is sufficiently open, radiant heat from the skin can pass through the garment, reducing its warmth.

(iv) Fabric thickness is the most important factor governing thermal insulation. There is a linear relationship between thermal insulation and the fabric thickness.

(v) When two fabrics are of equal thickness, the lower density fabric has the greater thermal insulation, but there is a critical density (about 0.6 g/cc) below which convective effects become important and thermal insulation falls.

(vi) The thermal insulation of fabrics increases significantly when two fabrics are placed one above another as compared to a single fabric of similar thickness. This is because the trapped air between the two fabrics provides additional thermal insulation.

(vii) Thermal insulation decreases with an increase in the water content in the fabric.

(viii) Thermal insulation can be increased by increasing the air gap between the body and the fabric, but it starts to decrease beyond a gap of about 7.5 to 10 mm, because of convection effects.
(ix) Increased wind velocity reduces the thermal insulation of a fabric compared to that in still air. The effect is minimized for closely woven fabrics.
(x) The thermal insulation of a fabric is improved significantly if covered with a fine closely woven outer fabric.
(xi) A slight increase in thermal insulation value is observed with an increase in the weight of fabric.

The thermal behaviour of fabric can be affected by the mean temperature of the fabric and the surrounding air pressure. Harold and George[52] observed that thermal conductivity increases linearly with an increase in both sample fabric mean temperature and its surrounding pressure. Additionally, they noticed that thermal conductivity increased with sample density and decreased with an increase in the molecular weight of the surrounding gas.

8.5.3 Effects of garment design

Up to 75% of total heat is not lost through the fabric layers of the garment, but through the openings of the garment.[53] Furthermore, the temperature[35,54,55] of the human body is different for different parts of the body, and the sensitivity of the different sections of the body towards heat and cold is different.[56] Therefore, garment design plays a vital role in the overall thermal insulation of clothing systems. The following design factors[57–59] affect the thermal insulation of a garment or clothing ensemble:

(i) Properties of the fabric used in the garment
(ii) Amount of the body covered
(iii) Looseness or tightness of fit
(iv) Amount of air space between body and garment
(v) Ensemble weight
(vi) Layering of fabrics in the garment
(vii) Garment opening
(viii) Body parts covered
(ix) Body movement.

The fabric from which the garment is made always has a significant effect on the thermal insulation of the garment. The higher the insulation of the fabric, the higher the insulation of the garment of similar type, but the increase is not of the same degree,[60] as other factors play a role. Furthermore, the amount of trapped air between the layers of fabrics in a garment also plays a vital role in determining the thermal insulation.

Another important factor which affects the thermal insulation is the extent to which the body is covered by the garment. Generally, garments that cover a greater portion of the body have higher clo values than those garments that cover less. However, when a garment covers only a part of the body and an overgarment of lower thermal resistance is used, then the garment contribution to the body insulation is reduced.[61]

Garment fit also affects clothing thermal insulation. Loose fit garments trap more air and provide greater insulation as long as the air remains stationary, as the conductivity of air is lower than that of the fibre. This process continues until the thickness of the air layer reaches about 1 cm, after which the thermal insulation reduces due to convective heat loss.[62,63] Body movement or atmospheric air movement can provide movement to the air layer and thereby reduce the insulation of the garment.[64] Fanger[26] showed that for very loose fitting garments, body movement has a greater impact on the insulation property of the garment.

Layering of fabric in a garment increases the amount of trapped air, which normally increases the insulation of the garment if it covers the whole garment. If the proportion of layering in the whole garment is too small and does not sufficiently insulate appropriate body regions, the effect is not so marked. A greater number of layers[65] in appropriate places of the garment can increase the thermal insulation of the garment significantly.

Garment openings play an important role in thermal insulation. Researchers[66] observed a significant difference in the thermal insulation of a winter jacket when open or closed during walking. Research[67] has also shown that ventilation in a raincoat reduces the thermal insulation substantially, with the size of the ventilation gap playing a vital role.

The clothing factor of a garment is also important from a thermal insulation point of view. The clothing factor is defined as the ratio of the total area of the body surface covered by a garment to the nude (i.e. total) body surface. The higher this factor, the higher the proportion of body covered by the garment. This factor is affected by fabric properties such as stiffness, drape and elasticity. If the clothing factor increases, it indicates that the surface area of the body covered by the garment increases, which means that for the same amount of body heat, the cover is greater. Hence the thermal insulation will increase if other factors remain constant.

Body movement changes the volume of micro-climate between the body and the garment. Additionally, body movement adds apparent motion to the stationary air between the garment and the body, which generally increases the heat exchange from the human body towards the outside air. When seated, the inside air is compressed by the garment and the intrinsic thermal insulation of the fabric decreases. Research,[47] using a thermal manikin, has shown that a reduction of 10–15% in thermal insulation can take place due to body movement.

8.5.4 Moisture transmission properties of fabric and clothing

Under high activity or in a hot climate, evaporative heat loss is the most important means of body cooling. However, even under indoor sedentary conditions, the human body has a requirement to lose water from the skin by 'insensible perspiration'.[34] If water vapour cannot escape sufficiently fast through clothing, even under normal conditions of atmospheric temperature and humidity and at low levels of body activity, there will be a build-up of moisture at the skin surface and within the clothing which will result in uncomfortable sensations, such as dampness and clamminess.

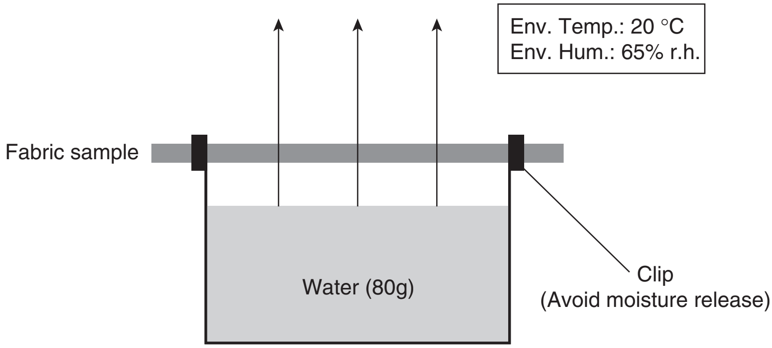
Measurement of moisture transmission properties

The moisture transmission properties of fabrics and clothing may be measured in terms of water vapour transmission rate (WVTR), moisture vapour resistance, or moisture permeability index.

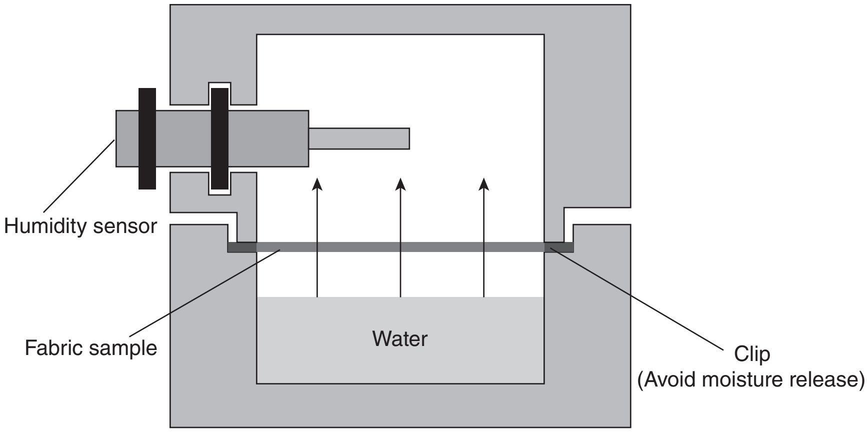
Measurement of moisture transmission of fabrics

ASTM E96E[68] describes a Cup Method, which is commonly used for testing the moisture transmission properties of fabrics. It measures the rate of water vapour transmission perpendicularly through a known area of a fabric within a controlled atmosphere. In this method, as shown in Fig. 8.5, a cup containing distilled water is covered with a specimen and placed in a controlled environment of 20°C and 65% relative humidity. The water vapour transmission rate (WVTR) in grams per hour and per square metre is calculated by using the following equation:

$$WVTR = G/tA \qquad [8.12]$$



8.5 The principle of ASTM E96 water vapour transmission test.



8.6 Construction of the moisture transmission tester.

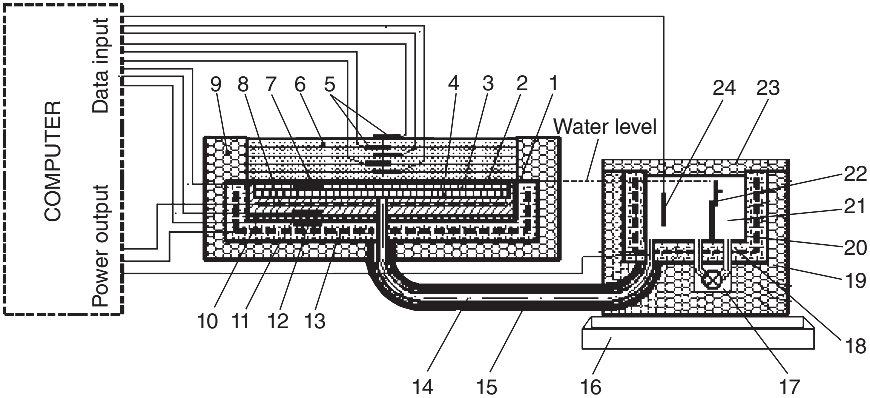
where G is the weight change of the cup with fabric sample in grams, t is the time during which G occurred in hours and A is the testing area in square metres.

Moisture transmission rate can also be measured by the Moisture Transmission Tester (see Fig. 8.6) developed by Ludlow Corp,[69] which is a much faster method than the ASTM E96 Cup Method.[68] Samples are clamped between two halves of a cell, with the lower half of the cell containing distilled water and the upper half dried by a drying agent at the beginning of the test. The air gap between the water surface in the lower half of the cell and the lower fabric surface is 10 mm. The cell is placed in a controlled temperature and humidity chamber (20°C, 65% R.H.). Water vapour from the wet side transfers through the sample to the dry side. The humidity sensor detects the humidity changes in the upper half of the cell. The humidity rise is recorded every 3 minutes, when the humidity changes from 50% to 60%. The moisture vapour transmission rate in grams per hour and per square metre is calculated by:

$$T = (269\times10^{-7})(\Delta\%RH\times60/t)(H)/(100\times0.0225^2) \qquad [8.13]$$

where $\Delta\%RH$ is the average of the differences in relative humidity between the lower and upper halves of the cell, t is the time between successive readings (t = 3 minutes) and H is the water content in the air at the cell temperature (H = 45.74 g/m^3).

The measurement of moisture vapour resistance using a sweating guarded hot plate (See Fig. 8.7) is described in ISO 11092[70] and ASTM F1868.[71] From the measurement of the evaporative heat loss, the total moisture vapour resistance of the fabric sample on the plate, together with the surface air layer, can be determined by:



1. Shallow water container
2. Manmade skin
3. Porous plate
4. Water
5. Measuring sensor
6. Layers of specimen
7. Temperature sensor
8. Heating element
9. Insulation foam
10. Insulation pad
11. Temperature sensor
12. Temperature sensor
13. Heating element
14. Water supply pipe
15. Insulation layer
16. Electronic balance
17. Water pump
18. Water tank
19. Insulation foam
20. Heating element
21. Warm water
22. Water level adjustor
23. Cover
24. Temperature sensor

8.7 Sweating guarded hot plate.

$$R_{et} = \frac{A(P_{ss} - P_{sa}H_a)}{H_e} \qquad [8.14]$$

where R_{et} is the total moisture vapour resistance, A is the sample covering area (A = 0.0444 m^2), P_{ss} is the saturated vapour pressure at the skin temperature (controlled at 35°C), R_{sa} is the saturated vapour pressure at the ambient temperature, H_a is the ambient relative humidity (%) and H_e is the evaporative heat loss.

To obtain the intrinsic moisture vapour resistance of the fabric, the following experimental procedure is recommended. First, place five layers of the fabric sample on the instrument. After stabilization, the R_{et} value with the five layers of fabric is measured. Then one layer of fabric is removed and the R_{et} value with four layers of fabric measured. This is repeated until the R_{et} values for one, two, three, four and five layers of samples have been obtained. The R_{et} value is then plotted against the number of layers. After fitting the data with a straight line, using linear regression, the slope of the line is taken as the intrinsic moisture vapour resistance of a single layer of fabric.

Measurement of moisture transmission properties of garments or clothing ensembles

The moisture transmission properties of garments or clothing ensembles can be measured using a sweating manikin. With the sweating manikin

'Walter',[37] the total moisture vapour resistance is determined using the following formula:

$$R_{et} = \frac{A(P_{ss} - P_{sa}H_a)}{H_e} - R_{es} \qquad [8.15]$$

where A is the surface area of the manikin, P_{ss} is the saturated vapour pressure at the skin temperature, P_{sa} is the saturated vapour pressure at the ambient temperature, H_a is the ambient relative humidity (%), R_{es} is the moisture vapour resistance of the fabric skin which is calibrated in advance (R_{es} = 8.6 m^2Pa/W), and H_e is the evaporative heat loss. H_e is calculated from the measurement of evaporative water loss, $H_e = \lambda Q$, where λ is the heat of evaporation of water at the skin temperature (λ = 0.67 W hr/g at 34°C), and Q is the rate of evaporative water loss per hour.

Moisture permeability index, I_m, is a dimensionless parameter first proposed by Woodcock and included in BS EN ISO 9920.[72] It provides a relative measure of the efficiency of moisture transmission. It can be calculated from the thermal insulation (R_t) in m^2°C/W and moisture vapour resistance (R_{et}) in m^2Pa/W, i.e.:

$$I_m = 60.6 \times \frac{R_t}{R_{et}} \qquad [8.16]$$

In addition to the above described methods for measuring the moisture transmission properties of the fabrics, there are other test methods of water vapour permeability. Overington and Croskell[73] reviewed and summarised the various standard test methods used for fabric breathability, and summarized them into a table (see Table 8.1). They concluded that the test parameters of the different tests are variable, producing different values that are not always correlated.

Factors affecting moisture transmission

The movement of water vapor through a fabric depends greatly on the micro-porous nature of the material, and this movement can therefore be modified by any means that brings about a change in this structure. It includes changes in fibre properties, fabric construction, texturising, and different yarn twist, finishing treatment, blending and mechanical treatment.

Effects of fibre properties

Moisture transmission through a fabric is affected by the hygroscopicity of the fibres. Hygroscopic fibres, such as wool and cotton, absorb moisture

Table 8.1 Summary of current standard testing methods for water vapour permeability. Source: Overington and Croskell, 2001[73]

Standard Test Method	Principle	Temperature of Test Environment	R. Humidity % of Test Environment	Reagent	Air Gap	Air Flow Speed	Measuring Interval	Units
BS 3546: Part 4 BS 3424 Part 34, Method 37	Control dish method with a reference woven fabric	20 ± 2°C	65 ± 5%	Distilled water, 20°C	10 mm	Not exceeding 6 m/min	At least 16 hours	WVP (g/m²/24 hr)
BS 7209	As above	20 ± 2°C	65 ± 5%	Distilled water, 20°C	10 mm	Not exceeding 6 m/min	At least 5 hours	WVP; WVPI (%)
JIS L 1099 85 (A-1)	Upright dish	40 ± 2°C	50 ± 5%	Distilled water, 40°C	10 mm	0.5 m/s	1 hour	WVP (g/m²/hr)
JIS L 1099 85 (A-2)	Upright dish	40 ± 2°C	90 ± 5%	Desiccant calcium chloride	3 mm	0.5 m/s	1 hour	WVP (g/m²/hr)
JIS L 1099 85 (B)	Inverted cup method	30 ± 2°C	NA	Potassium acetate solution, 23°C	Sample floating in the water	0.5 m/s	15 minutes	WVP (g/m²/hr)
ASTM E96-90 (A)	Upright dish	23°C	50 ± 5%	Desiccant calcium chloride	¼″ (6 mm)	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT (g/m²/hr) permeance (g/Pa.s.m²)
ASTM E96-90 (B)	Upright dish	23°C	50 ± 5%	Distilled water	¾″ (19 mm)	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT (g/m²/hr) permeance (g/Pa.s.m²)

Table 8.1 Continued

Standard Test Method	Principle	Temperature of Test Environment	R. Humidity % of Test Environment	Reagent	Air Gap	Air Flow Speed	Measuring Interval	Units
ASTM E96-90 (BW)	Inverted water method	23°C	50 ± 5%	Distilled water	NA	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT ($g/m^2/hr$) permeance ($g/Pa.s.m^2$)
ASTM E96-90 (C)	Upright dish	32.2°C (90°F)	50 ± 5%	Desiccant calcium chloride	¼″ (6 mm)	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT ($g/m^2/hr$) permeance ($g/Pa.s.m^2$)
ASTM E96-90 (D)	Upright dish	32.2°C (90°F)	50 ± 5%	Distilled water	¾″ (19 mm)	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT ($g/m^2/hr$) permeance ($g/Pa.s.m^2$)
ASTM E96-90 (E)	Upright dish	37.8°C (100°F)	50 ± 5%	Desiccant calcium chloride	¼″ (6 mm)	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT ($g/m^2/hr$) permeance ($g/Pa.s.m^2$)
CAN/CGSB 4.2 N249-99 (CANADA)	Control dish method	20°C	65%	Distilled water	Control dishes: 4, 9, 14 mm; Sample dishes: 9 mm	0.1 m/s	Several hours	Resistance in cm of equivalent air layer thickness
CAN/CGSB 2-4.2 M77 Method 49-1977 (CANADA)	Modified control dish method	20°C	65%	Distilled water	NA	4 ± 0.5 m/s	Every 30 minutes Total time: less than 3¼ hours	Resistance in cm of equivalent air layer thickness

AS 2001.2.24-1990 (AUSTRALIA)	Control dish method	20°C	65%	Distilled water	Control dishes: 9, 14, 19 mm; Sample dishes: approx. 14 mm (37 ml of water)	0.01 m/s to 0.1 m/s	Not less than 12 hours	Water vapour diffusion resistance expressed in mm air layer thickness
DIN 53 122 part 1 (GERMANY)	Gravimetric method upright dish	20–38°C	75–90%	Desiccant calcium chloride	3–4 mm	0.5–2.5 m/s	Several hours	Water vapour transmission rate expressed in g/m^2.day
BS (DIN) EN 31092 ISO11092	Sweating guarded hot plate test	35°C	40%	Distilled water	NA	1 ± 0.05 m/s	Several hours	Thermal resistance Rct (m^2K/W) Water vapour resistance Ret (m^2Pa/W)

and at the same time release heat of absorption. The absorption of moisture and release of heat change the the moisture concentration and temperature profile across the fabric, and consequently change moisture transfer through the fabric.

Kim *et al.*[74] investigated the influence of fibre type on vapour pressure and temperature at the fabric surface which are directly related to sensations of clothing comfort. The study revealed significant fibre influences on vapour pressure and surface temperature changes at the inner fabric surface during dynamic moisture transfer. The findings indicate that a cotton/cotton assembly would result in a dryer, warmer feeling at the onset of sweating than would a polyester/polyester mixed assembly. Conversely, the polyester double layer assembly might be perceived as cooler but wetter.

More recently, Wu and Fan[75] showed, both experimentally and theoretically, that placing hygroscopic battings in the inner region and non-hygroscopic battings in the outer region of a clothing assembly is advantageous in terms of thermal comfort, as it reduces condensation within the assembly and the associated dry heat loss.

Effects of fabric construction

Based on the analysis of experimental data, Whelan *et al.*[76] showed that the volume percentage of fibre in the fabric is a dominant factor in terms of moisture transmission. Dense and thick fabrics tend to have a greater resistance to moisture transmission.

Effects of types of breathable fabrics

The water vapour transmission properties of waterproof breathable fabrics (or beathability) are affected by the type of coating or membrane.[77] For example, the water vapour transfer rate of polyurethane laminated fabrics was greater under isothermal conditions, whilst the water vapour transfer of hydrophilic laminated fabrics was greater under non-isothermal conditions, when condensation takes place. This topic is discussed in more detailed in Chapter 11 concerning waterproofing and breathability.

Effects of garment design

Garment design has a significant effect on moisture transfer, through its affect on the amount of body surface area covered, the looseness or tightness of fit, the wind penetration and the ventilation through the openings.

Fan and Keighley[50] demonstrated that wind penetration is a major cause of reduction in thermal insulation and vapour resistance of garments. Unless the garment is skin tight, a micro-climate is formed between the

Table 8.2 Volume of the micro-climate of some typical clothing ensembles. Source: Crockford and Rosenblum, 1974[78]

Clothing ensembles	Mean volume (l)
Shirt, sweater, trousers and underclothes	26.2
Duck suit, foam lined	23.1
Foam Neoprene coverall (3 mm)	16.3
Duck suit, spacer and fabric lined	43.9

garment and the human body, which affects the vapour transfer from the body. Crockford and Rosenblum[78] employed a trace gas technique to measure the clothing micro-climate volume. Table 8.2 shows the volume of the micro-climate of some typical clothing ensembles.

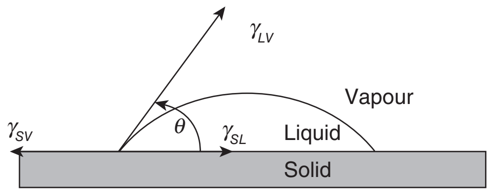
Chen *et al.*[64] investigated the effect of garment fit on the moisture vapour resistance of clothing, and found that moisture vapour resistance of clothing increases with the thickness of the air gap when the air gap is small. The rate of increase gradually decreases as the air gap increases, owing due to increased convection. The air gap thickness at which the vapour resistance reaches maximum depends on the fabric properties and wind conditions. Under windy conditions, the vapour resistance reaches a maximum when the air gap is about 6 mm.

8.6 Liquid water transport properties of fabrics and clothing

Liquid water transport properties of fabric and clothing are important, especially for clothing worn under hot and humid conditions or under conditions of high physical activity, when evaporation of perspiration is a major means of body cooling.[79,80] The ideal fabric should prevent the accumulation of perspiration on the human skin so as to keep it dry by allowing the respired body water to flow to the outer layer of clothing.

8.6.1 Mechanisms of liquid water transport in fabrics

Wetting and wicking are of paramount practical importance for the absorption and transportation of liquids in textiles. A knowledge of the fundamentals of wetting and wicking is necessary for research into water transportation behaviour. There are certain differences between wetting and wicking. Wickability[81] can be defined as the ability to sustain capillary flow, and while wettability refers to the initial behaviour of the fabric, yarn and the fibre, and can be defined as the interaction between the liquid and



8.8 Different forces on a water drop on a solid surface.

the substrate before wicking takes place. Hence wetting can be expressed as a prerequisite of wicking. Wetting is also the displacement of a solid–air (vapour) interface with a solid–liquid interface, and is a dynamic process. Spontaneous wetting is the migration of a liquid over a solid surface towards thermodynamic equilibrium. Forced wetting, on the other hand, involves external hydrodynamics or mechanical forces that increase the solid–liquid interface beyond the static equilibrium.

The interaction between the forces of cohesion and the forces of adhesion determines whether or not wetting takes place and also determines spreading of a liquid over the surface of a solid. The following Young–Dupre equation[82] is commonly used to express the forces in equilibrium at a solid–liquid boundary (see Fig. 8.8):

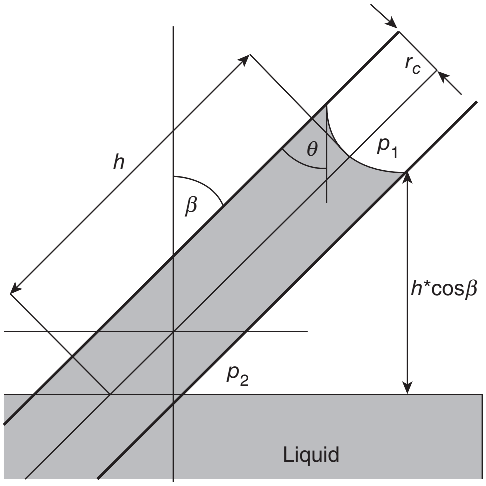
$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \qquad [8.17]$$

where γ_{SV} is the surface free energy of the solid, γ_{SL} is interfacial tension between the liquid and the solid, γ_{LV} is the surface tension of the liquid and vapour, and θ is that equilibrium contact angle.

The term $\gamma_{LV}\cos\theta$ is called 'adhesion tension' or specific wettability. Hence, from the above equation, it can be said that when $\gamma_{SV} > \gamma_{SL}$ then $\cos\theta$ is positive, i.e. the contact angle θ lies between 0 and 90°, and if the reverse is true then $\cos\theta$ will be negative, i.e. the contact angle θ lies between 90 and 180°. Hence, when θ decreases, $\cos\theta$ increases and the fabric becomes more prone to wetting.

The surface free energy of a solid depends on its surface characteristics.[83] Covalent or ion or metal interactions or molecular crystals bonded by Van der Waals forces or by hydrogen bonds of the molecule result in different wetting behaviour. The surface energy of the fibres largely depends on the perimeter, surface purity and molecular orientation of the fibres.[84] It can be changed by various finishing treatments applied to the fabric.[85]

Transport of liquid into a fibrous assembly or textile fabric can be caused by external forces, such as capillary forces. The spontaneous transport of liquid driven into a porous system by capillary forces is termed wicking.



8.9 Liquid flow in a capillary.

The advancing wetting line in a single capillary, as shown in Fig. 8.9, can be described by the Hagen–Poiseuille law of liquid flow:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{\pi(p_1 - p_2)r_c^4}{8h\eta} \qquad [8.18]$$

where $\mathrm{d}V/\mathrm{d}t$ is the flow rate, and p_1 is the so-called capillary pressure, which can be expressed by:

$$p_1 = \frac{2\gamma_1 \cos\theta}{r_c} \qquad [8.19]$$

p_2 is the hydrostatic pressure on the liquid level in the vicinity of the capillary, where:

$$p_2 = \rho g h \cos\beta \qquad [8.20]$$

Washburn first described the capillary flow in a porous material in 1921. The widely known Washburn equation[86] states:

$$L^2 = \frac{\gamma D t}{4\eta} \qquad [8.21]$$

where t is the time for a liquid of viscosity η and surface tension γ to penetrate a distance L into a fully wettable, porous material, the average pore diameter of which is D.

8.6.2 Measurement of liquid water transport properties

Various instruments are used for measuring the absorption and wicking behaviour of fabrics. There are generally four types of test method for measuring the water transport properties of fabrics, namely: longitudinal wicking 'strip' tests, transverse (or transplanar) wicking 'plate' tests, areal wicking 'spot' tests, and syphon tests.

Longitudinal wicking 'strip' tests

Two such tests are established as industrial standards: BS3424 Method 21,[87] Determination of Resistance to Wicking, and DIN 53924,[88] Determination of the Rate of Absorption of Water by Textile Materials (Height of Rise Method). Both these methods use a preconditioned strip of the test fabric, suspended vertically with its lower end immersed in a reservoir of distilled water, to which may be added a dye (of a type known not to affect the wicking behaviour) for tracking the movement of water. After a fixed time has elapsed, the height reached by the water in the fabric above the water level in the reservoir is measured. The difference between the two methods is that BS3424 Method 21 specifies a very long time period (24 hr) and is intended for coated fabrics with very slow wicking, whereas DIN 53924[88] specifies a much shorter time for the test (5 minutes maximum), appropriate to relatively rapidly wicking fabrics. In 1978 Hollies *et al.*,[89] and subsequently other researchers,[90,91] used the latter for their research. Since water transport in clothing is generally transplanar to the fabric plane, the measurement of a fabric's wickability in the fabric plane, as measured by the longitudinal wicking 'strip' test, has only limited implications for clothing comfort.

Transverse (or transplanar) wicking 'plate' tests

A transplanar wicking plate type apparatus was first used by Buras *et al.*[92] The apparatus consists of a horizontal sintered glass plate fed from below with water from a horizontal capillary tube, the level of which can be set so that the upper surface of the plate is kept damp, thereby simulating a perspirating skin surface. A disc of the test fabric is placed on the plate and held in contact with it under a defined pressure, applied by placing weights on top of it. The position of the meniscus along the capillary tube is recorded at various time intervals as water is wicked through the fabric layer. Given the diameter of the capillary tube, the recorded position of the meniscus can be used to calculate the mass transfer rate of water into the fabric. The problem with this method is that the resistance to the flow imposed by the capillary tube, and the hydrostatic head, decrease during the course of the test as water wicks up through the fabric sample.

Hussain and Tremblay-Lutter[93] have also described a test for measuring the transplanar uptake of liquids by fibrous materials when the material is in contact with a liquid. The instrument, called DAMT (Dynamic Absorbency Measurement Technique), has a liquid reservoir which continuously supplies liquid to the sample cells through pipes. The changing weight of the reservoir is measured by an electronic balance which provides a measure of the rate of liquid uptake by the textile material. The problem of this instrument is that the liquid level in the reservoir decreases as the liquid is absorbed by, or transported through, the material, creating a continuously changing liquid pressure.

McConnell has developed[94] an instrument that is commercially known as GATS (Gravimetric Absorbency Tester System). In this instrument, there are broadly two sections. One section contains a vessel hanging from a spring linked to, located on or connected to a balance, and the other section is the sample podium containing a small hole, connecting with the suspended vessel by means of a pipe. In this instrument, the fabric absorbs water through its centre, which is not ideal in terms of what happens in practice for the actual cases. Additionally the accuracy of the instrument depends on the accuracy of the spring from which the vessel is suspended.

Sarkar *et al.*[95] developed a novel instrument to test the transplanar wicking of the entire fabric surface. The water level is controlled at a constant level by the principle of overflowing and syphon action, which makes the instrument more simple and easy to handle. Here, the fabric is placed on a perforated plate to give greater surface contact, imitating the actual sweating, and the amount of absorption is measured by the loss of water in the container placed on the balance.

Areal wicking 'spot' tests

There are two published standards in the spot test category, namely BS 3554,[96] Determination of Wettability of Textile Fabrics, and AATCC Method 79,[97] Evaluation of Wettability. In these standard tests, a drop of liquid (either distilled water, or, for highly wettable fabrics, a 50% sugar solution) is delivered from a height of approximately 6 mm onto a horizontal specimen of the test fabric. The elapsed time between the drop reaching the fabric surface and the disappearance of the reflection from the liquid surface is taken as a measure of how quickly the liquid has spread over, and wetted, the fabric surface. The weakness of this method is that the supply of water is not continuous and does not closely simulate the actual process of perspiring. This method is also not suitable for highly absorptive fabrics, unless a high speed camera[85,98] or electrical sensing device[99] is used for the measurement. A modified procedure has been designed by Fort and

Patterson[100] using the reflected light beam to measure the contact angle. Likewise, Song *et al.*[101] developed a drop length–height method to measure the same.

Another recently patented areal wicking 'spot' testing instrument is the Moisture Management Tester (MMT).[102] This instrument is based on the measurement of the electrical resistance of the upper and lower surface of the fabric.[56] The instrument gives various moisture management indices, which include the accumulated liquid absorption of the upper and lower surfaces of the fabric, maximum difference of the water content between the upper and lower fabric surfaces, initial liquid absorption speeds and spreading rates of water at the upper and lower surfaces. Just like other areal wicking 'spot' tests, this method does not simulate profuse sweating conditions. Furthermore, it presents difficulties in testing long pile fabrics because piles do not touch the copper wires properly.

Syphon tests

The syphon test method was reported by Lennox-Kerr[103] and Phukon.[104] With this method, a rectangular strip of the test fabric is used as a syphon by immersing one end in a reservoir of water or saline solution and allowing the liquid to drain from the other end, placed at a lower level, into a collecting beaker. The amount of liquid transferred at successive time intervals can be determined by weighing the collecting beaker. This is a simple test, but does not resemble the liquid water transport through clothing during continuous perspiring.

8.6.3 Factors affecting the liquid water transport properties

Fibre characteristics

Fabrics made from hydrophilic fibres, such as cotton and viscose, tend to have very good wettability. Fabrics made of polyester/nylon split type conjugated fibre have a very high intrinsic absorption, even higher than that of cotton.[74,105]

Fibre cross-sectional shape has a significant effect on liquid water transport properties. Reed and Wilson,[106] and Rajagopalan and Aneja[107] showed that the vertical liquid wicking height in a bundle of filament yarns increases with an increase in the non-circularity of the fibre and with a decrease in void spaces between the filaments. They also established that, for a constant void area, the maximum wicking height increases with an increase in the diameter of the filament. This means that better wicking takes place when more yarns are bundled together.

Fabric construction

A number of researchers[108–111] have studied both theoretically and experimentally the liquid wetting and transport in capillaries and fibrous materials. It has been shown that smaller pore sizes produce higher capillary pressure and thus enhance the liquid spreading. Furthermore, inter-fibre pores must have the proper dimensions to produce sufficient capillary pressure and inter-connective pathways to transport the liquid, and to have sufficient overall porosity to retain the liquid.

Structural variations in woven and nonwoven fabrics affect the directional variations in water transport behaviour. By examining the shape and position of a radially advancing fluid front in the fabric, Adams and Rebenfeld[112] and Montgomery *et al.*[113] found that the structural heterogeneities in terms of spatial variations in areal density, irregularities in fibre orientation, variations in fibre composition (as in blends), and variations in needle punching for nonwoven fabrics result in the liquid water transport properties being different in different directions. The importance of fibre orientation in terms of the in-plane fluid flow was also acknowledged by Kim and Pourdeyhimi[99] and Mao and Russell.[114]

The effect of fabric construction on the water absorption was investigated by Kim *et al.*,[74] who tested a variety of knitted and woven fabrics produced by using different kinds of yarns in terms of fineness and fibre blend, by using the gravimetric absorbency testing systems (GATS). They observed that:

(i) for similar knitted fabric structures, the greater the fabric weight the faster the intrinsic absorption;
(ii) if a constant weight is maintained for the knitted fabric by varying loop length, absorption increases with a decrease in fabric density;
(iii) the intrinsic absorption of a fabric is proportional to its thickness, if other factors are constant;
(iv) the intrinsic absorption of a non-pile woven fabric is higher than that of a double-sided pile fabric, because of the greater surface contact area with the water.

Many workers[102,115–117] have tried to develop different types of multilayer fabrics so as to achieve good moisture management properties, viz. to facilitate the transport of perspiration to the outer layer so as to keep the skin dry. For example, hydrophobic yarns are used in the inner layer and hydrophilic yarns used in the outer layer to direct the liquid water transport to the outer layer, where it evaporates.

Recently, recognizing the superior water transport system in plants, Fan and his co-workers[118] developed textile fabrics that emulate the branching structure of plants. Fabrics so constructed exhibited excellent initial water absorption and moisture management properties.

Surface treatment and finishing

Surface treatment can modify the liquid water transport properties of fabrics. Spence *et al.*[119] showed that plasma surface treatment can improve the wettability and rewettability of textile materials. Wong *et al.*[120] showed that plasma treatment improves the wicking of linen fabric.

Hydrophilic finishing can improve water absorption.[121] For example, hydrophilic softener applied to wrinkle-free treated garments improved the water absorption rate.[122] For chemically finished fabrics, the durability of the finish after repeated laundering is a concern.

8.7 Garment fit and ease of body movement

Body movement is inevitable for humans. Clothing, as the second skin of the human body, must fit the human body and be adaptable to its movement.[123,124] Well-fitted garments are those that are comfortable to wear, consistent with current fashion and free of undesirable wrinkles, sags or bulges, and which allow sufficient ease for freedom of movement.[80,125]

The importance of garment fit for clothing comfort has long been recognised. Smith[3] stated that the fit of a garment is important as fit determines the amount of relative movement between the fabric and the body, and influences the tactile sensations. (The more times the fabric moves over the skin, the more frequently will tickle sensation be experienced by the wearer since the fabric and skin contact areas are also determined by garment fit.) Mehta and Narrasimham[2] pointed out that no matter how well the fabric is engineered to have optimum values of heat, water or air transmission, any garment made from it cannot be regarded as comfortable if it does not fit properly.

8.7.1 Assessment of garment fit and ease of body movement

Garment fit and ease of body movement during wear of a garment are often assessed by means of wearer trials. Human subjects wearing a garment under assessment are required to perform a series of activities which normally occur in practice. Then they are asked to rate the ease of body movement on a Likert scale; for example, 1 for being very stiff to 5 for being very flexible, or 1 for being very tight and 5 for being very loose. Different assessments should be made for different parts of the body under different activities. Sometimes photographs are taken for subsequent visual assessment.

The method of subjective wearer trials was applied by Huck *et al.*[126] to assess the fit of protective coveralls, by Aldrich *et al.*[127] for assessing the fit of women's tailored jackets and by Chan[128] for assessing the fit of men's shirts.

Different objective methods have been proposed or developed for evaluating garment fit. These include the fitting index, based on the measurement of the space between the body and clothing,[129–131] the symmetrized dot pattern technique, based on the measurement of the changes of the dot pattern, and imaging technology through capturing and analyzing garment images.[132] Nevertheless, their practical use is very limited due to the difficulty in accurately and efficiently capturing the space between the body and clothing or the garment surface, which may be folded or wrinkled.

8.7.2 Factors affecting garment fit and ease of body movement

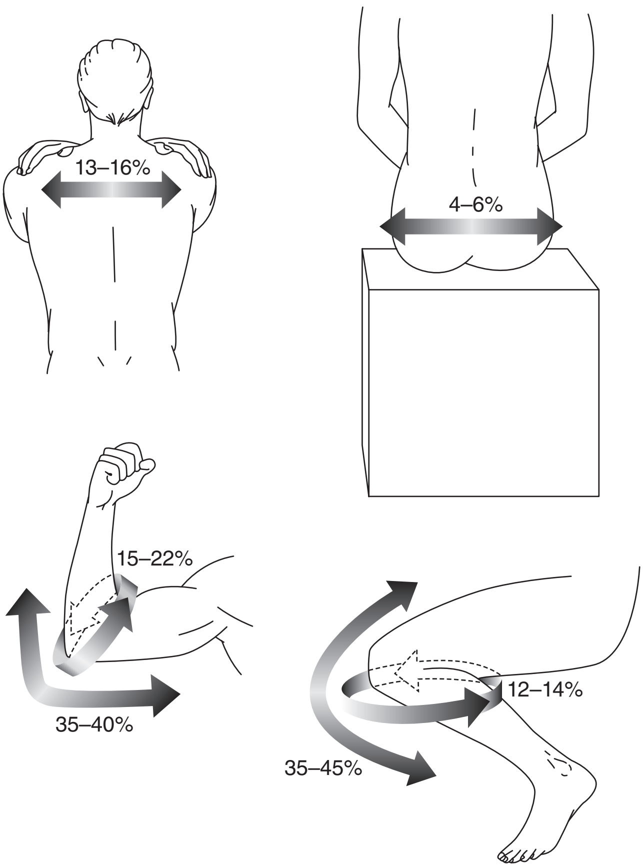
Fabric properties

As illustrated by Fig. 8.10, when people move, the skin will elongate and recover. Skin stretch varies in different parts of the body depending on the activity. Skin elongation can be up to 35–45%. Consequently, garment fit and ease of body movement are very much related to the extensibility and recovery of fabrics.

In general, fabrics with >15% elongation are referred to as stretch fabrics, and fabrics with <15% elongation as rigid fabrics. Most woven fabrics are rigid because the interlacement of yarns allows little extension to occur under a tensile force, unless the yarns (or fibres) themselves stretch. Stretch woven fabrics can therefore be structured from elastic fibres and yarns. Knit fabrics, due to the interlooping yarns, usually possess a minimum of 15% elongation, but they can also be made into rigid fabrics. Knitted fabric is more extensible than woven fabric, hence for tight-fitting garments, e.g. underwear, knitted fabric is preferred. Fabrics having 15–30% elongation are called comfort stretch fabrics. Close-fitting garments made of such fabrics have minimum resistance to body movements, particularly around the elbows, knees, back, and seat. Fabrics having more than 30% elongation are called power stretch fabrics. These fabrics are used for swimwear, foundation garments, stretch ski pants, support stockings and active sportswear, in which high stretchability and body shaping are required.[123] Table 8.3 shows the minimum elongation, minimum recovery and maximum growth recommended for different types of garments.

Garment weight and bulkiness

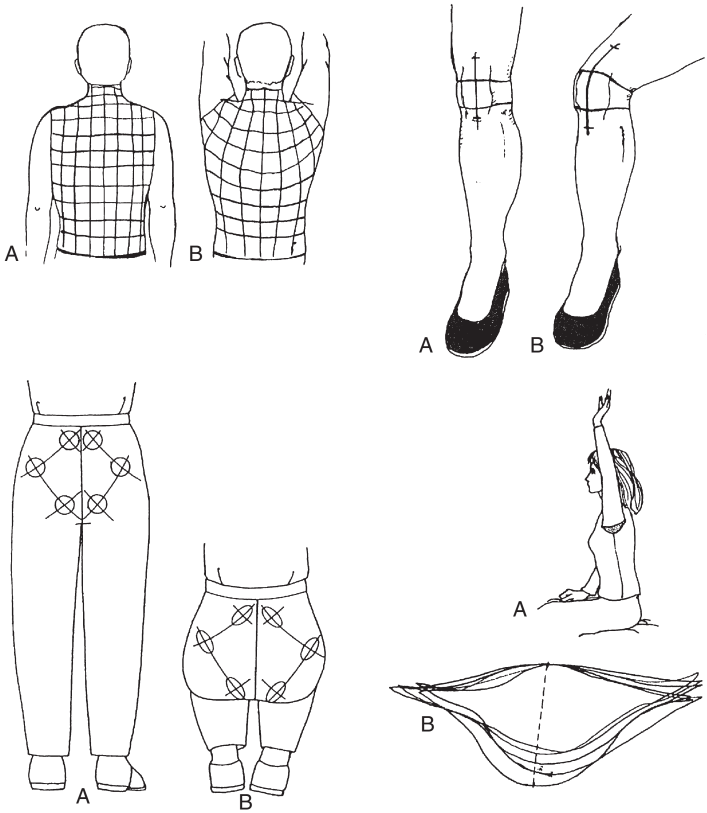
Heavy and bulky garments may provide thermal protection to the wearer in extremely cold or hot conditions. However, the weight and bulkiness of



8.10 Key stretch points on the body. Source: Hatch, 1993[123]

Table 8.3 Minimum percentages of elongation and recovery, and maximum percentage of growth, for comfort and appearance to be acceptable. Source: Hatch, 1993[123]

Garment type	Minimum elongation (%)	Minimum recovery (%)	Maximum growth (%)
Tailored clothing	15–25	98	2
Spectator sportswear	20–35	95	5
Form-fit garments	30–40	95	5
Active wear	35–50	94	6



8.11 Body movement pattern. Note: A: before body movement; B: during body movement. Source: Watkins, 1995[33]

such garments can hinder body movement. For cold protective clothing, such as mountaineers' down jackets and firemen's uniforms, weight and bulkiness are important considerations.

Garment design

During body movement, the body expands and contracts in the area surrounding its joints, so the garments' expansion and contraction should follow the pattern of body movement (Fig. 8.11). For instance, when the knee is bent, the leg increases in length over the kneecap and correspondingly decreases in length along the back of the knee, and the bent area may also increase as muscle tissues and fat move into different positions.

Therefore, if the design is too tight and the fabric is non-stretchable, the wearer may have difficulty in bending at the knee.[33]

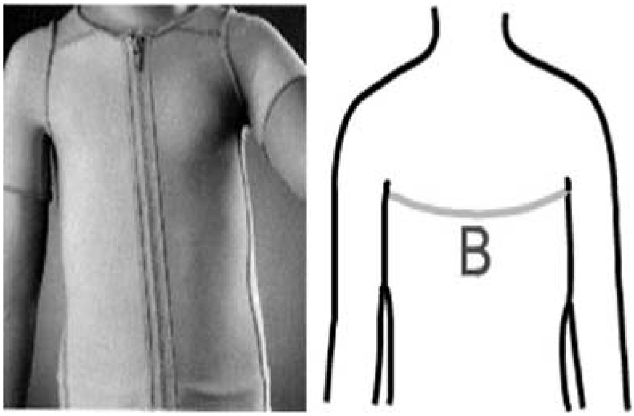
Garments should be designed to facilitate body movement. Smith[3] pointed out that both excessive local tightness and looseness are causes of poor garment fit and associated discomfort. Brown[133] suggested the following features, which can enhance the freedom of body movement:

- Shirt or bodice backs with adequate width. Pleats in back are helpful.
- Blouson bodices with adequate back length to cover curvature.
- Sleeves with adequate shoulder width, not too tight.
- Raglan, dolman, or kimono sleeves to better fit rounded shoulders.
- Waistlines loose enough to expand when the person is seated. If the waist is elastic, be sure it does not cut.
- Yokes or gathers to flatter the bodice.
- Front-opening styles.
- Large neck openings.
- Pants legs that are large enough to pull over a cast, brace, or catheter.
- Two-piece garments. The top and bottom may be of different sizes for better fit.
- Accessible front pockets for carrying personal items.

With respect to body movement, different end-uses of clothing have different requirements in garment design. For example, when people grow older, the skeleton is deformed: the vertebral column becomes more compressed, shorter, and less flexible; the bone mass decreases and bones lose some of their resilience and become lighter.[134] Ageing also leads to slower voluntary movement in the elderly, and the posture alters with a slight backward tilt of the head and varying degrees of flexing at the wrists, hips and knees, leading to the development of a shuffling gait.[135,136] As a result, a hump back often occurs in the elderly. Therefore, the pattern of the garment should be adjusted to accommodate the body change.[137] Also, front fasteners are preferred instead of back fasteners.

8.8 Pressure comfort

Garments impose pressure on the wearer. Excessive garment pressure can cause detrimental physiological effects. Pressure comfort is therefore an important issue, especially for close-fitting garments such as swimwear, body shapers (e.g. ladies' bras, girdles and stockings) and some special functional garments that can generate excessive pressure, for example, pressure garments for skin healing (shown in Fig. 8.12) and baby huggers (shown in Fig. 8.13).



8.12 Redi-Fit™ Vest Pressure garment for burns.
Source: URL[138]

8.8.1 Comfortable range of garment pressure

The effects of garment pressure on physiological responses have been studied by many researchers. Watanuki[140] investigated the effect of girdle pressure on the cardiac output of wearers. He found that the cardiac output decreased linearly with an increase in the pressure applied to the groin by the girdle, and estimated that the minimum pressure that may lead to adverse effects on blood circulation is 14.1 mmHg. Tanaka *et al.*[141] investigated the effect of girdle pressure on the change in skin blood flow. They showed that the skin blood flow increased when the girdle pressure was within the range of 20.4~34.0 gf/cm^2 (or 15.0~25.0 mmHg). Nakahashi *et al.*[142] examined the influence of pressure imposed on the lower leg on the skin blood flow. They found the skin blood flow tended to decrease with increasing pressure.

Many researchers also have studied the effect of clothing pressure on comfort sensations. Makabe *et al.*[143] measured pressure on subjects wearing girdles of various designs, materials, patterns and constructions. They found that subjects complained of discomfort when the pressure reached more than 30–40 mmHg. The relationship between the pressure sensation and clothing pressure was studied by Okada.[144] He noticed that the pressure sensation at the waistline was linearly related to the logarithm of the pressure applied by a waist cuff band, following the Weber–Fechner Law. As for the clothing pressure of girdles, Ito *et al.*[145] observed that there were only weak to moderate relationships between the sense of compression and clothing pressure of girdles at the waist, abdomen, hip and thigh lines. The effects of dynamic clothing pressure were recently investigated by Sasaki

8.13 Baby hugger. Source: URL[139]

et al.,[146] who showed that the measured clothing pressure corresponded to the tightness sensation. Chan and Fan[147] observed that there was a moderate linear relationship between the tightness rating and the logarithm of clothing pressure for a girdle. The tightness rating may not only be related to clothing pressure, but also to factors such as body size, human fat, resilience of muscle and human bone structure. They recommended optimum pressures for a girdle at different points, which are listed in Table 8.4.

After reviewing previous studies on pressure comfort, Lim[148] summarized the comfortable range of girdle pressures at different parts of the body as follows: waist (3.3~6.6 mmHg), abdomen (5.9~9.2 mmHg), hip (4.4~8.1 mmHg), thigh (4.4~6.6 mmHg), and side waist (12.5~20.6 mmHg).

Table 8.4 Optimum pressure for a girdle at various points

Position	Optimum pressure (mmHg)
Front abdomen	7.03
Left front abdomen	9.2
Right front abdomen	9.15
Left side	11.98
Right side	11.57
Left front lower	7.34
Right front lower	7.5
Left hip	4.34
Right hip	4.37
Front waist level	6.47

8.8.2 Assessment of pressure comfort

Pressure comfort may be evaluated by various techniques including:

(i) Conduct subjective wearer trials and ask the wearers to rate the degree of pressure comfort sensation on a Likert scale.
(ii) Measure the physiological responses, such as cardiac output and skin blood flow, of human subjects when wearing the pressure garments and undergoing a sequence of activities.
(iii) Measure the pressures at different body locations using pressure sensors when wearing the pressure garments and undergoing a sequence of activities, and then compare the measured pressure values with the desirable comfortable pressure range.
(iv) Use a soft manikin to replace the human subject. Pressure distribution on the soft manikin when wearing a pressure garment is measured and compared to the desirable range. The use of a soft manikin that mimics the real female body improves the consistency and accuracy of pressure measurement. It also reduces the need for live models, which are expensive to hire.

A review of various methods for the evaluation of pressure garments has been given by Lim.[148]

8.8.3 Factors affecting pressure comfort

The pressure a garment imposes on the body surface can be modelled by:

$$P = \frac{T_1}{r_1} + \frac{T_2}{r_2} \qquad [8.22]$$

where T_1 and T_2 are fabric tensions in each of the two principal directions (e.g. warp and weft) respectively; r_1 and r_2 are the radii of the body contour in the two principal directions, respectively.

From Equation [8.22] it is clear that pressure is dependent on the curvature of the contour and fabric tension. The sharper the body curvature (for example in bony regions), the greater the pressure. Any means of increasing the fabric tension, for example by greater negative ease and using fabrics with higher Young's modulus, will increase pressure on the body.

To minimize pressure discomfort, it is important to avoid pressure concentration at any position of the body.

8.9 Concluding remarks

In summary, a physiologically comfortable clothing ensemble should:

- have adequate thermal insulation so as to keep the body and skin temperature of the human body within a narrow limit;
- be highly permeable to moisture transmission and have good liquid water absorption and transport properties so as to keep the skin dry;
- not cause any tactile discomfort;
- not impose excessive pressure on the human body;
- not restrict movement of the human body.

These requirements sometimes compete against each other. The challenge in the engineering of physiological comfort of clothing is to find the right balance or innovative solutions to different end-uses.

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9
Psychological comfort of fabrics and garments

J. FAN

Abstract: Psychological comfort of clothing is an increasingly important issue in fabric engineering and garment design. This chapter discusses how psychological comfort sensations can be reliably assessed and how they are related to fabric and garment design.

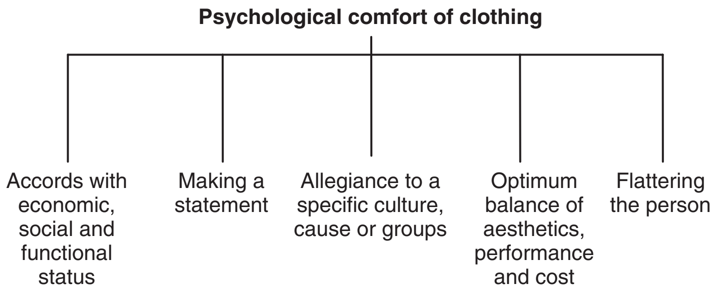
Key words: psychological comfort of clothing, colour emotion, aesthetic factors related to psychological comfort, body cathexis, body image.

9.1 Introduction

Psychological comfort relates to the human mind's ability to keep itself functioning satisfactorily without external help. It may be defined as 'a pleasant state of psychological harmony between a human being and the environment'.[1] It can perhaps be summarised as a combination of feeling both comfortable and good (a feeling of well-being) within a certain 'environment'.

Psychological comfort comes when one has a sense of well-being because one is confident that one's appearance is as good as one can make it.[2,3] With regard to clothing, psychological comfort is the feeling that one is dressed in a style/fashion/manner that is adequate for the purpose of the clothing, and is in accord with one's view of one's economic, social and functional status *vis-à-vis* either one's immediate work colleagues or one's wider group of friends, associates and acquaintances.[4] It can also be when one makes a specific statement or shows allegiance to a specific culture or cause.

Psychological comfort of clothing is an increasingly important issue in fabric engineering and garment design. As emphasized by Smith[5] and Taylor,[6] garment and fabric designers should be aware of the consumer demands for comfort and good performance linked to desirable aesthetics. The consumer looks at a garment to see if it is the right style and colour, if it is fashionable or traditional, and whether it would flatter. Decisions are being made on whether the fabric colour, print and surface properties and garment style are acceptable. Even for protective clothing worn for protection under severe hazardous conditions, there may be strong resistance in a person to wearing any clothing that in some way does not 'look right'.[4]



9.1 Factors related to psychological comfort of clothing

Whether a garment 'looks right' or not is a careful balance of aesthetics, performance, and cost, and whether it conforms to the wearer's perception of what they would like to wear considering the external environment in its totality. Figure 9.1 summarizes the factors related to the psychological comfort of clothing.

Psychological comfort of clothing is a highly subjective matter and an individual choice. It is therefore not the scope of this chapter to recommend 'right' garments for different occasions but, instead, to discuss how psychological comfort sensations can be reliably assessed and how they are related to fabric and garment design. It is believed that such knowledge would provide guidelines for fabric and garment designers to engineer the apparel products for the targeted end use.

9.2 Assessment of psychological comfort

As pointed out by Slater,[1] psychological factors, the ones for which personal idiosyncrasies can be so important, are the hardest of all to measure. He, however, listed a number of parameters for measuring the level of psychological discomfort that do not necessarily involve textile products directly. These include the determination of interpersonal distance, wish for privacy, level of embarrassment or effects of stress, and each of these can be estimated by observation with greater or lesser accuracy.

The influence of apparel products on psychological comfort (involving aspects of adornment, status, or modesty) is even more difficult to assess directly. Yet it is possible to observe such indicators as the style of garment bought, the frequency of purchase, or the size of a respondent's wardrobe in order to check that his or her replies to questioning on the subject are valid.

Psychological scaling is a common technique used to assess what a wearer is thinking or feeling.[7] Hollies[8] summarized six essential elements in psychological scaling:

- Commonly recognized attributes to measure.
- Language (terms) to describe these attributes.
- Assignment of a scale to indicate the level of attributes.
- A rating panel to apply the rating scale to attribute measurement.
- Appropriate data handling.
- Comparison of results from psychological scaling and objective measurement of the same attributes.

Psychological scales have been developed to assess colour emotion, body image and body cathexis (satisfaction with one's own body), which are key indicators to psychological comfort.

9.2.1 Assessment of colour emotion

Bipolar colour-emotion scales are frequently used for quantifying colour emotion.[9–13] In recent work by Xin *et al.*,[12,13] twelve opponent word pairs were used to describe human colour emotions in a visual assessment. These word pairs were 'warm–cool', 'light–dark', 'deep–pale', 'heavy–light', 'vivid–sombre', 'gaudy–plain', 'striking–subdued', 'dynamic–passive', 'distinct–vague', 'transparent–turbid', 'soft–hard', and 'strong–weak'.

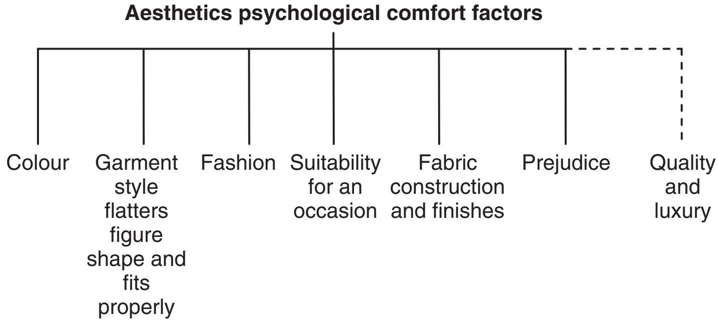
With this method, a score of +1 was given to the selection of 'warm', 'light', 'deep', 'heavy', 'vivid', 'gaudy', 'striking', 'dynamic', 'distinct', 'transparent', 'soft' or 'strong', and a score of –1 was given to the selection of the opposite words (i.e. 'cool', 'dark', 'pale', 'light', 'sombre', 'plain', 'subdued', 'passive', 'vague', 'turbid', 'hard' or 'weak'). After the colour emotions of colour samples were assessed by all the viewers, a colour emotion percentage was calculated for each word pair. For example, for 'warm–cool' colour emotion, a 'warm–cool' percentage (WC) was calculated using the following formula:

$$WC = \frac{x(+1) + y(-1)}{x + y} \times 100\% \qquad [9.1]$$

where WC is the warm–cool percentage, and x and y are the number of viewers selecting warm and cool colour emotions for the colour sample, respectively. If all viewers select 'warm' to describe the colour, WC is 100%. If all viewers select 'cool' to describe the colour, WC is –100%.

9.2.2 Assessment of body image and body cathexis

The perception of one's own body in terms of weight and size is termed 'body image'.[14] A nine-figural scale, initially proposed by Stunkard *et al.*[15] and later modified by Thompson and Gray,[16] is commonly used to assess body image. The scale consists of schematic figures or silhouettes of varying



9.2 Aesthetic factors related to psychological comfort. (Modified from Smith, 1986[5])

sizes, from thin (underweight) to heavy (overweight). The subjects are asked to pick up the ideal figure and their conception of the figure that most closely matches their own. The difference is a measure of the perception of one's own body (i.e. body image). Body image can be significantly influenced by clothing.

The level of satisfaction with one's own body or body parts is termed 'body cathexis'. Five-point,[17] seven-point[18] or nine-point[19] Likert scales have been used to rate body cathexis. It has been reported[20] that people are significantly more satisfied with their clothed bodies than with their nude bodies.

9.3 Factors affecting psychological comfort

Just like the physical and physiological aspects of comfort, psychological comfort is a neutral sensation and is frequently unnoticed by the wearer. Instead, psychological discomfort is more easily sensed. Smith[5] summarized the different aesthetics factors associated with psychological discomfort in a diagram as illustrated in Fig. 9.2. These factors include colour, whether garment style flatters the wearer, shape, fit, sense of fashion, fabric construction and finishes, suitability for an occasion and prejudice. To these could be added factors related to quality and luxury, for example the 'good/special' feeling when wearing clothing associated with quality and luxury, such as cashmere and leather.

9.4 Effects of colour and surface texture

9.4.1 Colour

Many have studied the effect of colour on psychological sensations. The effects have also been summarized by Davis.[21] Here, the effect of colour is discussed in general.

Warm–cool feeling

A warm–cool perception is influenced by one's experience with the colour of warm or hot objects, such as warm sunlight, hot fire or molten metals, and the colour of cool or cold objects, such as blue sky, ice or plants. Hence, reds, oranges and yellows are associated with a warm feeling; violets, blues and greens are generally associated with a cool feeling.

The value and intensity of colour also influence the warm–cool feeling. Pale values tend to feel cooler and dark values warmer. Bright intensities tend to create warmer feelings, dull intensities tend to give cooler feelings.

Emotion

Colour can also influence human emotion. In general, cool hues, dark values and low intensities make people feel calm; warm hues, light values and bright intensities create more active feeling.

Activeness

Colour evokes active or passive feelings. Warm, light and bright colours are more stimulating; cool, dark and dull colours make people more relaxed.

Femininity or masculinity

Warm hues, light values and soft intensities of colour are often associated with femininity, while cool hues, dark values and bright intensities of colour are often associated with masculinity.

Youthfulness

Colour can also create age illusions. Warm, bright colours tend to project a young and resourceful appearance; dark colours tend to give a mature and experienced appearance. Children, for example, wear colourful garments to show their liveliness, office workers may like to wear dark, grey colours to project the mature look, and the elderly may like to wear bright colours to look younger.

The effect of culture in colour connotation

The psychological effect of colour is influenced by culture.[22] In African nations, for example, black is the most unpopular colour as it has a symbolic meaning associated with darkness, corruption and death. However, black is frequently the favourite colour of many designers in developed countries. In Iran, a predominantly Shi'ite Muslim country, gold and yellow colours are not approved, while in countries such as India, Burma, Cambodia and Laos, gold and yellow are preferred colours.

The effect of age in colour connotation

The association of particular colours with specific feelings and emotions can be different for different age groups.[23,24] It was shown by Dove[23] that the association of red with pain and black with fear began with 7 to 8 year olds, while the association of grey with sadness began with 12 year olds (approximately). Zentner[24] recently showed that the association of happiness with yellow colours and sadness with blue colours is already established at three years of age. He pointed out that, in contrast with the consistencies in the emotional connotations of blue and yellow between children and adults, there is a clear difference for black and red. The connotation of black as sad and red as angry develops only after 10 years of age.

9.4.2 Texture

Fabric texture appeals to three types of senses – touch, sight and sound – and hence greatly affects the mood produced by a garment.[21] One garment style made from fabrics of different texture can convey different psychological perceptions. For example, a shirtwaist in denim appears sporty, in gabardine businesslike, in silk crepe graceful. In general, soft textures such as flannel, corduroy and knit felt suggest casualness and relaxation; firm textures such as gabardine and worsted seem businesslike, compact and resilient. Textures such as denim and shark-skin appear sporty and supple, while shiny textures, such as satin, crepe and velvet, appear sophisticated and dressy. Shiny surfaces, which reflect light, and pile surfaces, which add to the volume, also tend to make the figure look larger. Texture, colour and garment style should be in harmony to produce a desirable psychological mood.

While perceptions of texture are largely subjective in nature, attempts have been made recently to quantify the relationship between the perception of textures, sensibilities and consumer preference on one hand and the structural properties of plain knit fabrics on the other.[25] Both conventional statistics (viz. factor and regression analysis) and an adaptive-network-based fuzzy inference system (ANFIS) were applied in the study. It was found that the fibre content and loop length of plain knitted fabric affect the textural perception in terms of roughness, bulkiness, softness and stretch-ability, which in turn, affect the sensibilities as expressed in 'stable/neat', 'natural/comfortable' and 'feminine/elegant'.

Table 9.1 Psychological effects of lines. Source: Davis, 1996[21]

Types of lines	Visual effects	Psychological effects
Straight lines	Emphasize angularity Counter rotundity	Stiff, direct, precise, dignified, tense, masculine
Vertical lines	Draw attention to the face or down to the feet	Taller looking
Horizontal lines	Draw attention to across body	Broader looking
Structural lines	Direct attention to certain body area	Highlighting of the best features of the body
Curve lines	Emphasize body curves Counter thinness	Dynamic, feminine, active, youthful, unrestrained
Thick lines	Add weight	Forceful, aggressive
Thin lines	Minimize weight	Delicate, dainty, calm
Continuous lines	Emphasize bulges Smoothness	Consistent, sure, firm
Broken lines	Emphasize irregularities	Less certain
Sharp lines	Emphasize smoothness	Definite, precise, assertive
Fuzzy lines	Gently increase size	Soft, uncertain
Porous lines	Advance a little, recede a little	Open, delicate, less certain

9.5 Effect of garment design

Garment design is an integration of all the design elements including colour, texture, space, lines, pattern, silhouette, shape, proportion, balance, emphasis or focal point, rhythm and harmony. Each of these contributes towards the visual perception of the garment. Line manipulation, for example, can create different visual and psychological effects in clothing (see Table 9.1).[21]

Principles of illusion can be applied in garment design to flatter the figure of the wearer.[21] For example, the Muller-Lyer illusion (viz. a line with angled extensions at each end appears longer than a line of equal length, but with angled lines at each end doubled back) may be applied in pattern design to lengthen or shorten the perceived figure of the wearer. The lengthening effect may also be created by applying the horizontal–vertical illusion, i.e. a vertical line seams longer than a horizontal one of the same length. The tendency to interpret diagonals and non-right-angles as rectangles seen in perspective, and to misjudge distances as a result, is called the Sander parallelogram. It can be used in dress design to make diagonals look longer than neighbouring horizontal or vertical lines. For example, the diagonal overlapping of the Japanese kimono helps to lengthen the upper bodice area. The effect of the spacing of the surrounding lines on the apparel angle sizes may be utilized in the collar design. For example, a V neck may look wider by having narrow lapels.

9.6 Effects of garment sizing and fit

The perceived body image is also affected by the size of the garment a person wears or how a garment fits their body. Such an effect is different for different body builds and the optimum garment ease is different for different body sizes in order to achieve optimum body image. It was found[26,27] that, for thin persons, wearing garments with bigger garment ease (loose fitting) will make them look thinner. For an obese person, both too loose and too tight fitting clothing tend to make the person look even bigger. In order to have a better appearance for the obese person, the optimum garment ease should be around 2 to 3 cm.

9.7 Fashion and prejudice

Psychological comfort is strongly related to whether the garment is fashionable or not, and whether it fits a certain genre, personal statement, environment and/or age or other grouping. Fashion is dynamic and evolutionary in that it changes constantly from season to season and year to year. For instance, a casual appearance with a loose fitting silhouette was very popular in the 1980s,[28] whereas the cyber-look is in the fashion scene in the present millennium (2000s) to represent the era of high technology. It is almost impossible to define what makes something become fashionable, except that we know that, for something to be accepted as fashionable, a significant number of people have to acknowledge it as such and give it at least minimal signs of approval.

Prejudice is another important factor of psychological comfort. It is defined as an unfair and often unfavourable feeling or opinion, not based on reason or adequate knowledge, and sometimes resulting from fear or distrust of ideas different from one's own. A person may be prejudiced against something when they have had a negative experience with it in the past. Therefore, a person's sense of fashion and their prejudice towards a particular event may affect their choice of clothing in terms of colour, texture, garment style, etc.

9.8 Concluding remarks

Psychological comfort is a state of harmony between wearers and their environment. It is very much affected by the aesthetic factors of clothing, including colour, texture, garment design elements, garment fit, fashionability and prejudice. All these factors should be considered holistically in designing or choosing garments for a targeted end use.

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10
Flammability of fabrics and garments

J. FAN and L. LAU

Abstract: Flammability of garments is a major safety concern. In this chapter, the effects of the properties and processing parameters of fibre, yarn and fabric as well as the effects of garment design on flammability are discussed. Test methods and standards for the flammability of textiles and clothing are also reviewed.

Key words: flammability of garments, burning mechanisms, flame-retardant finishes, Limiting Oxygen Index, burning rate tests.

10.1 Introduction

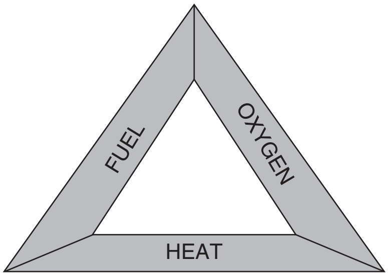
Textile and clothing have been reported[1] to be among the main items causing fire injury and death, and consequently flammability of garments is a major safety concern. In many countries, legislation has been enacted to reduce potential injuries from highly flammable fabrics.

Generally speaking, there are three approaches to produce flame retardant textile products: (i) The use of fibres that are inherently flame resistant. (Except asbestos, glass fibres and metal fibres with mineral characteristics, all other fibres are combustible, although they can be differentiated as either easily combustible or hard to burn). (ii) The use of fibres that have been modified by the addition of flame retardants. (iii) The application of flame retardant finishes to fabrics after manufacturing.[2,3]

In order to achieve desirable safety features and appropriate garment serviceability, it is necessary to optimize the fibre materials and the process of fabrication.[4] In this chapter, the effects of the properties and processing parameters of fibre, yarn and fabric as well as the effects of garment design on flammability are discussed. Test methods and standards for the flammability of textiles and clothing are also reviewed.

10.2 Burning mechanisms

The combustion of a textile is a feedback mechanism in which fuel (from thermally degraded or pyrolysed fibres), heat (from ignition and combustion) and oxygen (from the air) feature as the main components,[5,6] also



10.1 Fire triangle. Source: Wagner, 1996[6]

referred to as the fire triangle (Fig. 10.1). Therefore, there are essentially two main areas, namely 'fuel' and 'oxygen/air', where the textiles or garment *per se* can influence flammability and burning behaviour. In terms of the former (i.e. fuel), the type of fibre, its chemical composition and the application of flame retardant finishes play the dominant roles. In terms of the latter (i.e. oxygen or air), the yarn, fabric and garment structure, in terms of the oxygen/air volume to fibre volume/mass ratio at the fibre/fabric surface and with the yarn/fabric and garment, play the dominant roles. The latter set of properties is dependent upon factors such as yarn and fabric hairiness and density, and fabric weight. By reducing the above mentioned ratio, flammability related hazards can be reduced.

10.3 Index for burning behaviour of textiles

The burning behaviour of fibres is influenced and determined by a number of thermal transition temperatures and thermodynamic parameters. Table 10.1 lists the thermal properties of some commonly available fibres, including their glass transition (Tg) and melting (Tm) temperatures, chemically related pyrolysis (Tp) temperature and auto-ignition (or the onset of flaming combustion) (Tc) temperature. In addition, typical values of flame temperature and heats of combustion are given. Generally, the lower the Tc (and usually Tp) temperature and the hotter the flame, the more flammable is the fibre. This generalisation is typified by natural cellulosic fibres, including cotton, viscose and flax, as well as some synthetic fibres, such as acrylics.[5]

Limiting Oxygen Index (LOI) values represent the inherent burning character of a material and can be expressed as a percentage or decimal. LOI is the minimum percentage of oxygen in the air which is required to sustain the burning of a material. Fibres having LOI values of 21% (0.21) or below ignite easily and burn rapidly in air (containing 20.8% oxygen). Those with LOI values above 21% will not ignite and burn easily in the air.

Table 10.1 Thermal transitions of some commonly used fibres.[8,9] Source: Horrocks *et al.*, 2001, 1983[5,8]

Fibre	Tg, °C (softens)	Tm, °C (melts)	Tp, °C (pyrolysis)	Tc, °C (ignition)	LOI, %	ΔHc, KJg^{-1}	*Flammability
Wool	–	–	245	600	25	27	Supports combustion with difficulty
Cotton	–	–	350	350	18.4	19	Burns readily with char formation, afterglows
Viscose	–	–	350	420	18.9	19	Burns very rapidly with char formation, no afterglow
Nylon 6	50	215	431	450	20–21.5	39	Supports combustion with difficulty, melts
Nylon 6.6	50	265	403	530	20–21.5	32	Does not readily support combustion, melts
Polyester	80–90	255	420–447	480	20–21	24	Burns readily with melting and soot
Acrylic	100	>220	290 (with decomposition)	>250	18.2	32	Burns readily with melting and sputtering
Polypropylene	–20	165	470	550	18.6	44	Burns slowly
Modacrylic	<80	>240	273	690	29–30	–	Melts, burns very slowly
PVC	<80	>180	>180	450	37–39	21	Does not support combustion
Oxidised acrylic	–	–	≥640	–	–	45	–
Meta-aramid (e.g. Nomex)	275	375	410	>500	29–30	30	–
Para-aramid (e.g. Kevlar)	340	560	>590	>550	29	–	–

* Source: Nametz, reprinted with permission from Nametz, 'Flame-retarding Synthetic Textile Fibers', *Ind and Eng Chemistry*, copyright 1970, American Chemical Society.[9]

When LOI values rise above approximately 26–28%, fibres and textiles may be considered to be flame retardant and will pass most of the fabric flammability tests in both the horizontal and vertical orientations.[5,7]

The heats of combustion (ΔHc) in Table 10.1 indicate that there are relatively small differences between the fibres, and indeed some fibres, such as cotton, appear to have a lower heat of combustion compared to less flammable fibres, such as aramid and oxidised acrylic fibres. It is the speed at which this heat is given out that determines the rate of fire spread and severity of burns.[5]

10.4 Effects of fibre composition, structure and properties

Fibre content vastly influences a fabric's behaviour when it burns. According to the study by the UK Home Office,[10] natural and synthetic fibres each accounted for 42% of the total clothing flammability accidents while natural/synthetic blends accounted for the remaining 16%.

10.4.1 Fibre composition

In general, fibres can be classified into three categories: plant/cellulosic fibres, animal/protein fibres and synthetic fibres.[11–13] The burning behaviour of different textile fibres are summarized in Table 10.1.

Plant/cellulosic fibres

These include cotton, flax (linen), hemp, jute, kapok, ramie, sisal and the regenerated cellulosic fibres. These fibres are considered to be flammable because they are readily ignited and rapidly consumed after ignition. However, cellulosic fibres are commonly used to produce apparel due to their excellent performance in terms of drape, comfort and durability. The residue of the cellulosic fibres after burning is ash, which will normally fall away from the remaining unburned fabric/apparel. Rayon tends to be the most flammable fibre among all the cellulosic fibres. Flame resistant chemicals can be applied to fabrics/apparel to make them less flammable; some of these chemicals can withstand repeated washing, but handle is often adversely affected.[11,14,15]

Animal/protein fibres

Wool, alpaca, angora, cashmere, mohair, silk, tussah silk and vicuna are classified as animal/protein fibres. Animal/protein fibres have a tendency to smoulder, so that a fire which is thought to be out can start again. However, they do not catch fire easily. As an example, wool is regarded as one of the most naturally fire-resistant fibres. Wool may be ignited if subjected to a sufficiently powerful heat source, but will usually not support a flame, and it continues to burn or smoulder for only a short period of time after the heat source is removed. The typical elemental composition of wool is C, 48–50%; O, 23–25%; N, 15–16%; H, 6–7%; and S, 3–4%. The relatively high nitrogen content of wool may be responsible for the relatively high natural flame retardancy when compared with other material or man-made non-nitrogen-containing fibres. The natural flame resistant property of wool is also due to its relatively high moisture content, high ignition temperature, low heat of combustion, low flame temperature and high Limiting Oxygen Index of 25.[15]

Synthetic fibres

Nylon and polyester are examples of synthetic fibres which are nominally fire resistant, and which do not catch fire immediately when exposed to an open flame. However, they smoulder much more than animal fibres and can burst into flames when exposed to a cigarette butt for a prolonged period. They also have a very serious problem: they melt as they burn, and they stick, particularly to the skin. In addition, they produce toxic smoke which kills people from asphyxiation, even when present in relatively small quantities.

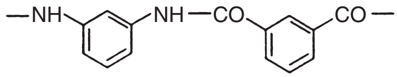
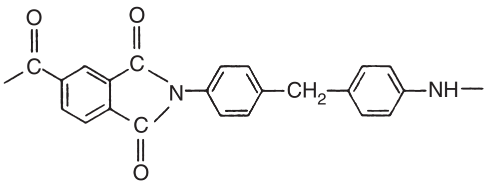
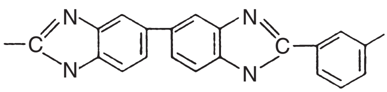
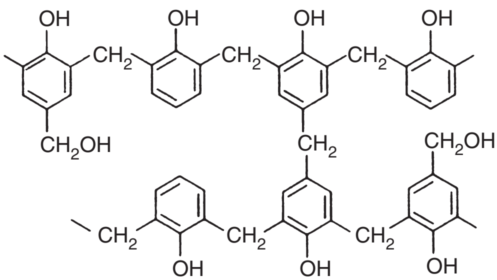
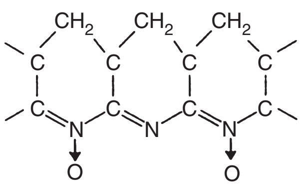
Fibre blends

Fibre blends can affect the flammability behaviour of textile products. Results showed that polyester–cotton blend fabrics appeared to have more potential for causing fire related injuries than 100% cotton or 100% polyester fabrics, with the 100% polyester fabrics appearing to have the lowest injury potential.[15]

10.4.2 Fibre structure

Naturally flame resistant fibres usually contain combustion resistant all-aromatic polymeric structures. Their all-aromatic structures are responsible for their low or non-thermoplasticity and high pyrolysis temperatures. In addition, their high char-forming potential is responsible for their low flammability. Table 10.2 lists the major aromatic fibre-forming polymeric structures currently available, with respective char and LOI values.[5,16]

Table 10.2 Heat and flame resistant fibres based on aromatic polymeric structures. Source: Horrocks A R and Price D[5], Table 4.14.

Generic type	Structure	LOI %	Char %, 850°C
Polyaramid, e.g. poly(m-phenylene isophthalamide) (Nomex)		30	35
Polyamideimide (Kermel)		30	55 30
Polybenzimidazole (PBI)		41	66 59
Novoloid (Kynol)		36	45
Carbonised acrylic (Panox)		55	93

10.4.3 Fibre properties

Fibre length

Relatively short fibres will produce a more hairy or fuzzy yarn/fabric, due to the protruding fibre ends. This increases flammability since it increases the air/oxygen to fibre ratio.

Fibre fineness

Coarse fibres tend to produce a more hairy fabric due to a greater number of fibre ends protruding from the yarn, which may easily catch fire and cause the fabric to burn.

Moisture absorption/moisture regain

The moisture absorption or moisture regain properties of fibres can affect their flammability characteristics since moisture inhibits ignition and burning. Moisture absorption also changes the properties of fibres; it causes the fibres to swell, eventually resulting in changes in fibre dimensions. Consequently, the size, shape, stiffness, and permeability of yarns and fabrics are modified. The higher the moisture absorption, the lower the flammability. For example, bone-dry wool burns much more easily than conditioned wool. Table 10.3 lists the moisture regain of various textile fibres.

Thermal properties

These properties are important in determining fire safety, care instructions, and optimal processing temperatures. Some materials soften or melt with heat, and others ignite and burn without melting. Those materials that soften or melt when exposed to heat are called thermoplastic. Given adequate heat and oxygen, most textile materials will burn; thus the ease with which they burn must be compared in order to make statements about flammability.[12]

Chemical properties

Chemical properties determine the basic burning characteristics of fibres since fire is a chemical reaction.[18] For example, as mentioned in Section 10.4.1, the high nitrogen content of wool is one of the parameters that results in the low flammability of the fibre.

10.5 Effects of yarn structure and properties

The effect of yarn geometry and structure on flammability has not been studied in depth.[5]

Yarn structure

Yarn can be divided into filament and staple/spun types. Filament yarns provide the ultimate in lustre, sheer and smoothness in apparel fabrics.

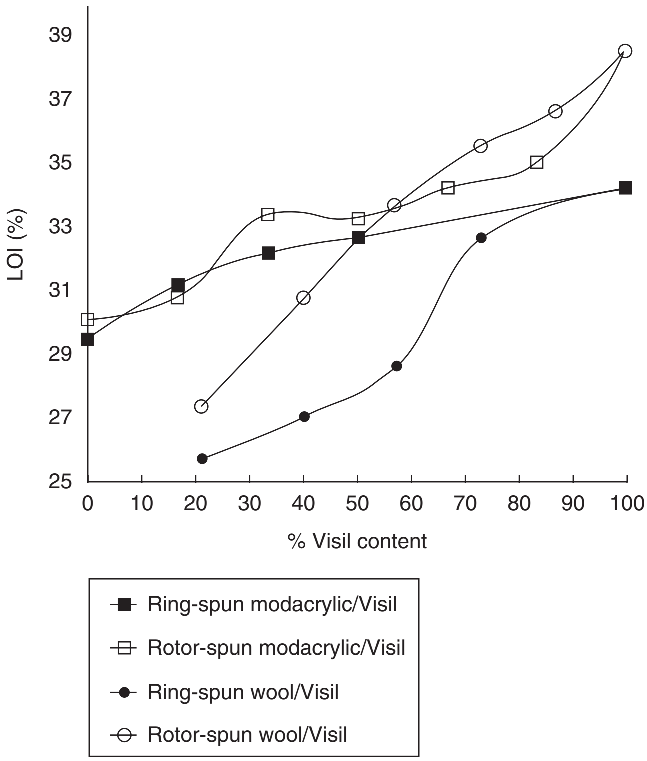
Table 10.3 Moisture regain of textile fibres. Source: Goswami *et al.*, 1976[17]

Fibre type	Name	Moisture regain 65% r.h. (%)
Natural vegetable	Cotton	7
	Flax	7
	Jute	12
	Sisal	8
Natural animal	Wool	14
	Silk	10
Regenerated	Viscose rayon	13
	High-tenacity rayon	13
	Polynosic rayon	11
	Fortisan	11
	Acetate	6
	Triacetate	4
	Casein	14
Synthetic	Nylon 6	2.8–5
	Nylon 6.6	2.8–5
	Qiana (du Pont)	2.5
	Polyester: Dacron (DuPont)	0.4
	Polyester: Kodel (Eastman)	0.4
	Acrylic: Orlon (DuPont)	1.5
	Acrylic: Acrilan (Monsanto)	1.5
	Polyolefin: Polypropylene	0.1
	Polyolefin: Polyethylene	0
	Aramid: Nomex (DuPont)	6.5
	Novolid: Kynol (Carborandum)	6
	Spandex: Lycra (DuPont)	1.3
Inorganic	Glass	0
	Asbestos	1

However, they generally do not provide the same bulkiness, covering power, or soft appearance in fabrics as do staple yarns. No protruding fibre-ends or filament loops are normally associated with filament yarns,[17] although different processes of texturing, such as air-texturing, may do so. The smooth and compact nature of filament yarns generally makes them more fire retardant than staple yarns.

Yarn blending and spinning method

Garvey *et al.*[19] investigated the burning behaviour of blended yarns comprising modacrylic/flame retardant viscose and wool/flame retardant viscose, where the flame retardant viscose is Visil (Sateri Fibres, Finland). Yarns of the same nominal linear densities were produced by both ring-spinning and



10.2 LOI values of knitted fabrics from blended yarns.
Source: Horrocks A R and Price D[5], p. 137 (Fig. 4.3)

rotor-spinning methods and knitted into panels. Figure 10.2 shows that the difference in yarn structure significantly influences the fabric burning behaviour. The less flammable rotor-spun yarns are probably a consequence of their more compact and less hairy structure.[5]

Yarn twist

Twist is inserted in yarns to give them coherence; it affects the bulkiness and the hairiness of the yarns. Bulky and hairy yarn is considered to be more flammable than compact and smooth yarn.

Yarn texture

With all other factors being equal, textiles with the fuzziest texture will catch fire more easily. This is why fuzzy or textured rayon yarn catches fire more easily than flat rayon yarn.[11]

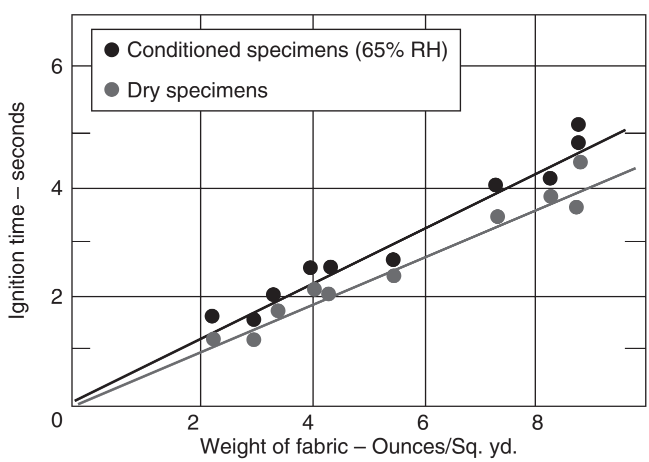
10.6 Effects of fabric structure and properties

Fabric construction

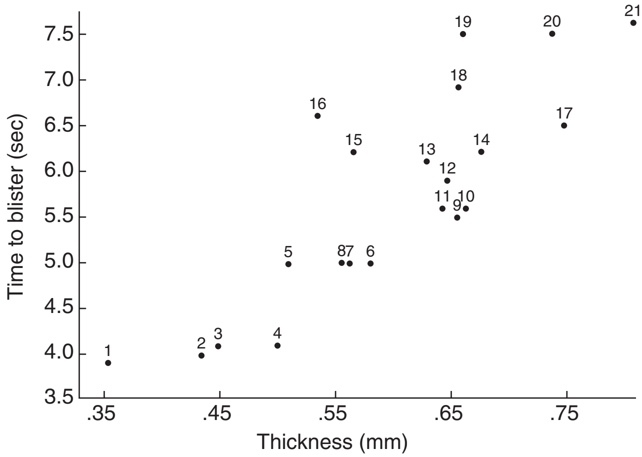
The influence of fabric construction is very important. In brief, any constructional factor that increases the air to fibre surface and/or fibre mass ratio will increase the fabric flammability. Thus, for instance, more open or loosely constructed fabrics will be more flammable. Loose pile fabrics usually also ignite more easily than compact smooth surface fabrics.[20] Increased weave tightness would therefore be expected to reduce flammability.[4] Quilted fabrics tend to spread flames horizontally, more so than other constructions.[14]

Fabric weight and density

Textile materials have very high fibre surface area to mass ratios and hence tend to ignite easily and burn faster than other materials. Once again, the determining factor is the air (i.e. oxygen) volume to fibre surface/volume ratio at or within the fabric. Therefore, lighter and more open fabrics and carpets will ignite and burn more readily than heavier and more compact structures. Figure 10.3 shows that the denser and heavier the fabric, the lower the flammability.[5,15,20] As another example, a conventional wool carpet can pass the American Tablet Test[21,22] without any special treatment, while an open shag wool carpet may not pass the same test. It also follows that lightweight fabrics require higher levels of flame retardants than heavier fabrics.



10.3 Ignition time vs. fabric weight.
Source: Nametz, 1970[9]



10.4 Fabric insulation vs. thickness; flame contact.
Source: Baitinger, 1978[4]

Fabric texture

Between two equal textiles, the one with the fuzzier or hairier texture will catch fire more easily,[11] once again because of the higher air to fibre ratio.

Fabric layer

The number of fabric layers in outerwear–underwear assemblies was shown to affect the burn potential in garment fires.[15]

Fabric thickness

Figure 10.4 shows that thicker fabrics offer more protection against burns.[4]

10.7 Effects of fibre, yarn and fabric processing parameters

10.7.1 Flame retardant finishes

In order to reduce the flammability and burning characteristics of fabrics and garments, flame retardant finishes can be applied. The basic systems of flame retarding applied in the textile industry include halogen-containing flame retardants, phosphorus-containing flame retardants, nitrogen-containing flame retardants, intumescent systems, mineral-based flame retardants, and other flame retardant systems.[23–25]

Halogen-containing flame retardants

The effectiveness of halogen-containing flame retardants increases in the order F < Cl < Br < I. Fluorine and iodine based flame retardants are not used in practice because neither type interferes with the combustion process at the right point, fluorine due to its strong bond with carbon, and iodine due to its weak bond to carbon. Halogens are one of the most effective classes of flame retardant. The majority are bromine-containing products, appearing in approximately 75 different varieties. The principle of action is to interfere with the radical chain mechanism that takes place in the gas phase of the combustion process. However, the use of certain bromine-containing compounds has already been prohibited in the European Union because of their ecological harmfulness.

Phosphorus-containing flame retardants

This class can be organic, inorganic or elemental. It can be active in the vapour phase or in the condensed phase or sometimes in both phases. Phosphine oxides and phosphate esters are thought to act in the vapour phase through the formation of PO* radicals, which terminates the highly active flame propagating radicals (OH* and H*). The condensed phase mechanism arises as a consequence of thermal generation of phosphoric acids from the flame retardant, e.g. phosphoric acid or polyphosphoric acid. These acids act as dehydrating agents, altering the thermal degradation of the polymer, and promoting char formation. In a fire, dehydration takes place and these products form a vitreous layer, which stops further oxygen supply.

Nitrogen-containing flame retardants

These products are used mainly together with phosphorus-containing flame retardants. They stabilise the bonding of phosphorus in the polymer. Furthermore, crosslinked structures are formed, supporting carbonisation during the combustion process.

Intumescent systems

These systems consist of an acid source, a carbon supplier and an expansion agent. The effect of the system is based on the formation of a heat-insulating, carbon-rich layer which is converted to a foam by the expansion agent. This foam attains a thickness of 10 to 100 times the originally applied coating and insulates the substrate material through its low thermal conductivity.

Mineral-based flame retardants

Aluminium or magnesium hydroxide is used in mineral-based flame retardants. Here, chemically bound water is released on heating, resulting in cooling of the polymer and dilution of the combustible gases.

Other flame retardant systems

These include products containing borax and nanocomposites. Borax is used mainly in combination with other flame retardant products. Water is eliminated in case of fire and a vitreous layer is formed. Nanocomposites are mainly layered aluminium silicate (clay) based composites. These systems are predominantly used in the field of plastics, where they support carbonisation and prevent dripping of flame material in case of fire.

10.7.2 Other finishing processes

Many textiles are provided with special permanent finishes intended for such purposes as wrinkle resistance, stain resistance, softness, water repellency and washability. These finishes can influence flammability, once again by either changing the flammability of the fibre directly or by changing the fabric structure, such as hairiness, density, weight and thickness.

Research[26] has shown that shrink resistance finishes can, for example, lower the oxygen index values of finished wool blend fabrics.

10.7.3 Dyeing

Dyes can affect the flammability of fabric in two ways, either by changing the flammability of the fibre itself or by changing the fabric structure (e.g. hairiness, density, weight). In one report[26] it was shown that the oxygen index value of cotton was raised from 19.1 to 25.8 by padding fluorescent brightening agents and to 20.0 by the application of a direct dye (Chlorantine Fast Green 5GLL), using conventional dyeing procedures. Acid Black 107 and Mordant Black 1 dyes with bichromate, for example, increase the flammability of nylon.

10.7.4 Washing process and cycle

Laundering or drycleaning can remove flame retardant material or other additives and can thereby affect burning characteristics. If, for example, flame retardant textile products are laundered in hard water with soaps, as opposed to synthetic detergents, deposits of calcium soap may increase flammability. This is the reason that care instructions on children's sleepwear urge users to avoid laundering with soaps and, preferably, to use phosphate-containing detergents.[27]

10.8 Effect of garment design

Garment design is one of the factors that also affects flammability. According to findings by the Shirley Institute, carelessly selected printed patterns, embroidered motifs, sewing threads, zip tapes and narrow fabric trimmings could all present flammability hazards in a garment.[14]

Garment fitting and style

Oxygen is necessary for combustion because any combustion, whether smouldering or burning, is an oxidation reaction. A critical point, however, is accessibility between the oxygen and the fuel. The more open and airy the fuel (textile), the more readily a vertical fabric will flame. Any style that increases the access or volume of air to the fibre or which increases air flow, especially the chimney effect of rising air, increases the burning rate. Thus, loose fitting or flowing garments and garments with open cuffs are more of a fire hazard. Close contact of fabric with a heat sink, such as a part of a person's body, will retard burning.[27,28] Therefore, more tightly fitting garments will generally be less of a fire hazard, although once they catch alight their closeness to the body, and possible difficulty in removing quickly, could pose a serious problem in terms of burn injury.

Garment length

The longer the garments are, the more vigorously they burn.[28] In 2002, Saudi girls in a private school were reported to have been burned to death since they were not allowed to leave because of not being properly covered. Full veils would have caught fire much faster.[11]

Accessories and garment details

Accessories and/or design details, such as belts, ties, cuffs and collars affect flammability.[28,29] A study by the Gillette group[29] showed that the presence of a belt in a dress design slowed down the rate of flame spread and reduced the burn area.

10.9 Test methods and standards for textiles and apparel

There are many national and international flammability test methods and standards for textiles and apparel. They have been developed to evaluate different products, such as protective clothing, children's sleepwear, upholstery, mattresses, bedding, and curtains. The principles of these test methods and standards are reviewed as follows.

10.9.1 Limiting Oxygen Index (LOI)

ASTM D 2863, Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-like Combustion of Plastics (Oxygen Index)

This test method measures the minimum concentration of oxygen (in O_2/N_2 mix) that supports combustion. The size of specimen can be varied. A small test specimen is supported vertically in a mixture of oxygen and nitrogen flowing upwards through a transparent chimney. The upper end of the specimen is ignited and the subsequent burning behaviour of the specimen is observed, to compare the period for which burning continues, or the length of specimen burnt, with specified limits for each burning. By testing a series of specimens in different oxygen concentrations, the LOI is determined. Three procedures are included in this test method. In Procedure A, a complete assessment of the oxygen index is conducted using top surface ignition. In Procedure B, a complete assessment of the oxygen index is conducted using propagating ignition. Procedure C provides a comparison with a specified minimum value of oxygen index and can be conducted using top surface ignition or propagating ignition.[30]

10.9.2 Burning rate tests

16 CFR 1610 (formerly CS 191-53) Standard for the Flammability of Clothing Textiles (General Wearing Apparel)

This test is used for testing clothing and textiles intended for clothing (except hats, gloves, footwear, and interlining). The test procedure used to determine compliance with the standard is the 45-degree angle test included in the original legislation. It specifies that a piece of fabric, placed in a holder at a 45-degree angle and in contact with a 5/8 inch flame for 1 second, should not be ignited and spread flame up the length of the sample in less than 3.5 seconds for smooth fabrics or 4.0 seconds for napped fabrics.[12,31–33]

16 CFR 1611 (formerly CS 192–53) Standard for the Flammability of Vinyl Plastic Film

This standard tests nonrigid, unsupported, vinyl plastic film of 10 mm or less in thickness, including translucent and opaque material, whether plain, embossed, moulded, or otherwise surface treated, and intended for or used in clothing. The test requires that vinyl plastic film for wearing apparel, placed in a holder at a 45-degree angle, should not burn at a rate exceeding 1.2 inches per second.[12,31–33]

16 CFR 1615 (FF3–71) Standard for the Flammability of Children's Sleepwear (Sizes 0–6)

This standard covers testing for any children's sleepware in sizes 0 to 6X, which includes nightgowns, pajamas, or similar or related items such as robes, intended to be worn primarily for sleeping or activities related to sleeping. Underwear and diapers are excluded from this definition. The standard measures the extent of the flame spread. Fabrics and yarns that are intended or promoted for use in children's sleepwear must also meet the standard. The test process requires that five samples, each 3.5 by 10 inches (8.9 by 25.4 cm), be tested. Each specimen is suspended vertically in a holder in a cabinet and is exposed to a 1½-inch gas flame along its bottom edge for 3 seconds. The specimens together may not have an average char length of more than 7 inches, and no single specimen may have a char length of more than 10 inches. This test must be passed both when the product is new and following 50 washings and dryings. Any item intended for children's sleepwear manufactured after July 1973 must meet the standard. Although a label indicating that the product meets the standard does not have to be provided, many manufacturers do provide such information as a service to customers.[12,31–33]

16 CFR 1616 (FF5-74) Standard for the Flammability of Children's Sleepwear (Sizes 7–14)

The product category in this standard is the same as 16 CEF 1615 except that the product size is from 7 to 14. This standard tests the extent of flame spread, examines if there is any afterglow and whether it extinguishes after 1 minute, and then the char length is measured. Basically, this standard extends the one established for sizes 0 to 6X, and the testing procedure is the same. All children's sleepwear, sizes 0 to 14, and fabric intended for such use must meet the standards. Products not meeting the provisions of the regulation may not be imported for sale or exported to other countries.[12,31–33]

16 CFR 1630 (FF1-70) Standard for the Surface Flammability of Large Carpets and Rugs

This standard tests all types of carpets and rugs (one dimension greater than 6 ft and surface area greater than 24 ft^2) used as floor covering materials, regardless of the method of fabrication or whether they are made of natural or synthetic fibres or films, or combinations of or substitutes for these. One-of-a-kind carpets or rugs, such as antique, oriental, or hide, are excluded. This standard measures the extent of flame spread and char spread. A 9 by 9 inch (23 by 23 cm) specimen is exposed to a burning tablet placed on its centre, and must not char more than 3 inches in any direction. The burning tablet is intended to simulate small ignition sources such as matches or cigarettes dropped on the carpet.[12,31–33]

16 CFR 1631 (FF2-70) Standard for the Surface Flammability of Small Carpets and Rugs

The textiles covered in this standard are same as those in 16 CFR 1630 except that the products' size is one dimension not greater than 6 ft and surface area not greater than 24 ft^2. The test principle of this standard is also the same as that of 16 CER 1630. If the product does not meet the standard, it may be labelled to indicate that the item failed to meet the standard.[12,31–33]

16 CFR 1632 (FF4-72) Standard for the Flammability of Mattresses (and Mattress Pads)

This standard covers the testing of mattresses including, but not limited to, mattress pads, adult, youth, crib, bunk-bed, convertible sofa-bed, daybed, roll-a-way bed, and trundle-bed mattresses. Sleeping bags, pillows, box springs, water beds, upholstered furniture lounges, and juvenile product pads are excluded. It tests ease of ignition from a smouldering ignition source. The test requires that a minimum of nine lighted cigarettes be allowed to burn on the smooth tape edge and quilted or tufted locations of a bare mattress. The char length on the mattress surface must not be more than 2 inches in any direction from any cigarette. Tests are also conducted with nine lighted cigarettes placed between two sheets on the mattress surfaces. Items that do not meet the standard must be labelled that they do not comply and may ignite. Mattresses that meet the standard do not need to be labelled, but many manufacturers provide labels to indicate that their product meets the standard for flame resistance.[12,31–33]

JIS L 1091 Testing Methods for Flammability of Textiles

This standard includes four testing methods:

(i) Burning test – this method is to measure the spread of burning, the afterflame time, the afterglow time and the smouldering time.
(ii) Surface burning test – to measure the spreading extent of the burning on the specimen surface.
(iii) Burning speed test – to measure the speed of burning of the specimen.
(iv) Flame touch test – to count the number of flame touches to the specimen required for heating to melt or to burn down the specimen.

The type to be selected should depend upon the purpose of the test and the nature of the textiles.[34]

ISO 6925 Textile Floor Coverings – Burning Behaviour – Tablet Test at Ambient Temperature

The method specified in this standard is applicable to all types of textile floor coverings, whatever their construction or their fibre composition. The method may also be extended to unfinished material. A specimen in a horizontal position is exposed to the action of a small ignition source (a methenamine tablet) under specified conditions, and the resulting damaged length is measured.[35]

10.9.3 Manikin tests

ASTM F 1930 Standard Test Method for Evaluation of Flame Resistant Clothing for Protection Against Flash Fire Simulations Using an Instrumented Manikin

This test method covers quantitative measurements and subjective observations that characterize the performance of single layer garments or protective clothing ensembles in a simulated flash fire environment having controlled heat flux, flame distribution, and duration. The method is extremely complex and requires a high degree of technical expertise in both the test setup and operation. The test specimen is placed on an adult-size manikin at ambient atmospheric conditions and exposed to a laboratory flash fire simulation with controlled heat flux, duration, and flame distribution. The test procedure, data acquisition, results calculations, and preparation of the test report are performed with computer hardware and software programs. Heat, which is transferred through the test specimen during and after the exposure, is measured by sensors. These measurements are used to calculate the second-degree, third-degree, and total burn injury areas resulting from the flash fire exposure. Identification of the test specimen, test conditions, comments and remarks about the test purpose, and response of the test specimen to the exposure are recorded and are included as part of the report. The performance of the test specimen is indicated by the calculated burn injury area and the way the specimen responds to the test exposure.[36]

ASTM F 1958/F 1958M Standard Test Method for Determining the Ignitability of Non-flame-resistant Materials for Clothing by Electric Arc Exposure Method Using Mannequins

This test is used to identify materials that are ignitable and that can continue to burn when exposed to an electric arc, and determines the incident exposure energy that causes ignition, and the probability of ignition. The apparatus consists of a supply bus, arc controller, recorder, arc electrodes, manikins, and incident energy monitoring sensors. The specimens tested in this test method are materials fabricated in the form of shirts. During the test procedure, a material is observed for ignitability during and after exposure to an electric arc. The material performance is determined from the ignitability of the specimen(s).[37]

10.9.4 Measurement of heat transmission factor

ASTM D 4108 Test Method for Thermal Protective Performance of Materials for Clothing by Open-flame Method

This test covers any fabric that is intended for use as clothing for protection against a short exposure to open flames, and it measures heat energy transmitted through the fabric to a thermocouple as related to the heat required to cause a second-degree burn.[33]

BS EN 336 ISO 6942 Protective Clothing – Protection Against Heat and Fire – Method of Test: Evaluation of Materials and Material Assemblies when Exposed to a Source of Radiant Heat

This test standard specifies two complementary methods for determining the behaviour of materials for heat protective clothing subjected to heat radiation. Method A serves for visual assessment of any changes in the material after the action of heat radiation. With Method B, the protective effect of the material is determined. The material may be tested either by both methods or by only one of them.[38]

10.9.5 Smoke tests

ASTM E 662 Test Method for Specific Optical Density of Smoke Generated by Solid Materials

This method tests carpeting, etc. by measuring the specific optical density of smoke generated from flaming and non-flaming combustion. Values determined by this test are specific to the specimen or assembly in the form and thickness tested, and are not to be considered inherent fundamental properties of the material tested. Therefore, it is likely that closely repeatable or reproducible experimental results will not be obtained from tests of a given material when specimen thickness, density, or other variables are involved.[39]

BS 6401 Measurement, in the Laboratory, of the Specific Optical Density of Smoke Generated by Materials

This test measures the specific optical densities of smoke generated by materials when a specimen of specified form and thickness is exposed vertically to a radiant heat source. The values of specific optical density measured by this method are specific to the form and thickness of the product tested.[40]

10.10 Concluding remarks

As mentioned in Section 10.4.1, all textile fibres are flammable to a greater or lesser extent, the burning degree and behaviour being dependent mainly upon the chemical nature of the fibre. In order to reduce the flammability and burning characteristics of fabrics and garments, the use of flame resistant fibres or flame retardant finishes are generally the most effective methods. Nevertheless, environmental protection organizations claim that flame retardant chemicals can cause a hazard to human beings and to our environment. Therefore, other than applying fire retardant finishing, textile manufacturers and researchers may also need to focus on other factors, such as fibre moisture regain, fabric/yarn construction and fabric weight/density, as possible means of reducing the flammability related hazards of fabrics and apparel.

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11
Waterproofing and breathability of fabrics and garments

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Abstract: This chapter discusses the different ways in which breathable waterproof fabrics and garments can be constructed and produced, including the use of microporous and hydrophilic membranes and coatings. The measurement of breathability and waterproofing is covered, as well as the specifications and standards applicable to such fabrics and garments.

Key words: breathable fabrics, breathability, waterproof fabrics, waterproofing, hydrophilic membranes and coatings, microporous membranes and coatings.

11.1 Introduction

Consumers, particularly those regularly involved in outdoor activities (e.g. sport or leisure) or subjected to extreme conditions such as snow, rain, heat, wind and cold, are increasingly seeking multifunctional clothing to maintain their comfort under such conditions (see also Chapter 8). This is illustrated, for example, by the fact that the global market for waterproof breathable textiles is growing by some 8% annually. Ideally, such clothing should keep the wearer dry and comfortable under hot, cold, windy or wet (rain) conditions, even under the extremes of such conditions, for example, driving rain and/or extreme temperatures and/or physical activity. In order to effectively do so, the fabric and garment need to be:

- Breathable (water vapour permeable)
- Waterproof.

In addition, they should also have good heat insulation properties, a good handle, and preferably be lightweight, the water vapour permeability of a fabric depending on both the water vapour diffusion and thermal resistance of the fabric.[1] The main driving force for moisture from the body to the outside is the difference in partial pressure of the water vapour between the two areas.[2]

Although waterproofing and breathability are entirely different concepts, today they are commonly combined, in that the term 'breathability' is used to imply both 'waterproofing and breathability'. For the purpose of this chapter, 'breathability' is taken to mean[3] 'the ability of a textile fabric to allow water vapour (molecules smaller than ≈ 0.0004 μm in diameter) to pass through it (i.e. from the body surface to the outside) while not allowing liquid water (molecules ≈ 100 μm in diameter) from the outside to pass through it'. Later in this chapter, the difference between waterproof, water repellent and water resistant will be defined. In recent years, the term 'moisture management' has been used to describe the ability of a garment to transport moisture vapour and liquid water (perspiration) away from the skin through the fabric to the outside in a controlled manner, and this has increasingly involved advanced technologies, such as 'body mapping'.

During physical and other activities, and under certain conditions, the body cools itself partly through insensible perspiration, which needs to evaporate, absorbing energy (heat) in the process, thereby causing cooling. For example, during intensive training, an athlete's clothing has to transport around 1.5 to 2.5 litres of moisture per hour.[4] The human body is a very inefficient converter of stored energy into work or physical motion, most of the energy being turned into heat.[5] For the body to maintain its 'core temperature' of 37°C, the heat produced needs to be removed by conduction, radiation and convection from the skin, and also by evaporation of water released from sweat glands. The first three are adequate for low levels of activity, whereas the fourth predominates at high levels of activity.[5] To accommodate the latter, the garment must allow moisture to be easily carried away from the point where it is generated, i.e. the skin, so as not to cause the moisture to remain on the skin or to condense on the inside of the garment. This is a critical requirement to maintain acceptable temperature and comfort (see also Chapter 8), particularly under either very hot or high activity conditions, or various levels and combinations of such conditions.

Historically, different garments, or layers of garments, each designed with a specific function in mind, were worn to provide the required functionality. Thus, for example, a heavy coat would be worn over clothing to offer protection against cold, and if waterproof, also against rain. If only protection against rain is required then a waterproof coat, a raincoat, sometimes also termed a Macintosh, was generally worn over outerwear. One of the first, if not the first, such raincoat was produced in 1823[6] by Charles Macintosh, who coated a fabric with crude rubber. Such garments did not 'breathe' and did not allow perspiration and water vapour to escape, therefore often resulting in the wearer becoming wet with perspiration and highly uncomfortable. In fact, the question of breathability only surfaces when the garment is expected to provide those protective functions mentioned above, mostly protection against rain, since by their very nature most conventional garments are breathable, but not waterproof.

Ideally, a fabric layer against the skin should remove (wick) liquid perspiration as quickly as possible away from the skin, without becoming or feeling wet, since a wet fabric is very effective in removing heat from the body and feels uncomfortably clammy.[7] The challenge, therefore, is to engineer the fabric (and entire garment) in such a way that the fabric or layers of fabric, and ultimately the garment, allow air, water vapour and perspiration to pass easily from the inside to the outside of the fabric or garment, while at the same time providing a barrier to liquid water (as opposed to water vapour) from the outside. In the extreme case, this is in essence a conflicting requirement, and there generally needs to be a compromise. Another important consideration is that the handle and overall comfort properties of the fabric not be adversely affected by any multifunctional finish or property added.

This chapter will discuss ways in which these requirements can be 'engineered' into a fabric or garment and can be measured.

11.2 Definitions

It is first of all important to define some of the terms relevant to this chapter:

- *Breathability* is defined as the ability of a fabric to allow perspiration, evaporated by the body, to escape (diffuse) to the outside (termed moisture vapour transmission), thereby allowing complete comfort. Breathability can therefore be defined as the ability of clothing (and fabric) to allow the transmission or diffusion of moisture vapour, and therefore facilitate evaporative cooling.[8,9]
- *Water repellency* generally refers to the ability of a fabric to resist wetting.[10] *Water repellent* (also referred to as 'shower resistant') fabrics (e.g. light fashion rainwear) will provide some protection against intermittent rain but are not suitable to be worn in a downpour, as they will then become wet through and dampen the wearer. Water will bead and run off the surface[11] of water repellent fabrics but under sufficient pressure it will come through. The amount of pressure required to do so is a measure of *water resistance*.
- *Water (or rain) resistant* fabrics will resist wetting by water and also not allow water to penetrate or pass through the fabric under most pressures, thereby keeping the wearer dry in moderate to heavy rain.[12]
- *Waterproof* is the extreme case of water resistance, implying complete resistance to water. The fabric will not allow water – even wind driven rain – through, since water cannot penetrate the fabric surface,[6,11] and

such fabrics and garments should keep the wearer dry in prolonged moderate to heavy rain.[12]

- *Windproof* means that air cannot pass through the fabric.

Water resistant fabrics therefore provide better protection than *water repellent* fabrics against rain, snow and sleet, particularly driving rain. Nevertheless, both will eventually become saturated with water and allow water to leak through.[13] Thus, if a fabric or garment needs to keep a person completely dry under virtually all, including prolonged, conditions of rain and weather, it has to be *waterproof*. In essence, this means that a person wearing a waterproof garment will not become wet even if exposed to driving rain or snow for extended periods. For a garment to offer such protection, the fabric, seams, zips, etc. all need to be waterproof and the garment must be so designed that there are no 'openings' through which water can penetrate (see Section 11.6). Therefore, a 'waterproof breathable' garment needs to satisfy the above waterproof requirements, as well as being able to 'breathe', i.e. allow water vapour to escape so as to maintain a comfortable 'micro-climate' between the skin of the wearer and the garment. The term *weatherproof* is used to stand for both 'waterproof' and/or 'windproof' technologies.[14]

11.3 Measurement of waterproofing and breathability

As the title of this chapter implies, two distinct concepts are involved, namely waterproofing and breathability, and both need to be measured if a fabric or garment is to be categorised as waterproof and breathable. Traditionally, and also still largely today, two different types of tests are carried out: one to measure the breathability (i.e. water vapour transmission) of the fabric and the other to measure the waterproofing of the fabric. In the case of garments, it is also essential to test the waterproofing of the seams, joins, etc. of the garment. It should be noted, however, that different test methods and testing conditions[15] can produce widely different values for the water vapour resistance of waterproof fabrics, for example those coated with hydrophilic coatings,[16] where the resistance to water vapour diffusion decreases with increasing relative humidity.[16] Furthermore, the different test methods can be differently affected by changing the conditions of testing. Holmes[15] and Overington and Croskell[17] have reviewed the various test methods and standards.

Testing for breathability (Water vapour permeability or moisture vapour transport rate – MVTR) is covered under Chapter 8 and will not be dealt with here. The various methods have also been reviewed and compared in other publications,[15,17–19] including the forces that drive MVTR, namely gradients of water vapour concentration, the temperature and, in the case of forced convection, pressure gradient.[20] Overington and Croskell[17] have presented an excellent table summarising the various test methods for water vapour permeability.

11.3.1 Air permeability (wind resistance)

For certain applications and conditions, a fabric/garment is required to be windproof (i.e. resistant to wind). This is normally assessed by measuring air permeability.

The air permeability of a fabric also has some bearing on its water vapour permeability, but the two are by no means identical. Air permeability can be measured using the following test methods:

- EN ISO 9237: Textiles: Determination of the Permeability of Fabrics to Air.
- ASTM D737-96: Standard Test Method for Air Permeability of Textile Fabrics.

Çay *et al.*[21] developed an artificial neural network model to predict the air permeability and water content after vacuum drying of woven fabrics, based upon the fabric structural parameters.

11.3.2 Testing for water repellency/resistance/proofing

Water repellency and resistance (shower and rain resistance)

Water repellency is essentially taken[22] to be the ability of a fibre, yarn or fabric to resist wetting, one of the oldest tests being the 'spray test' in which water is sprayed against the taut surface of the test specimen.[22] *Water resistance* (rain test) measures the resistance to the penetration of water by impact, providing a measure of the resistance to rain penetration of a fabric.[22] A blotter underneath the fabric is weighed before and after the test to provide a measure of water penetration. The Tumble Jar Dynamic Absorption Test, for example, measures water (rain) repellency and absorption of fabrics.[22] *Water resistance* (Hydrostatic Pressure Test) measures the resistance of a fabric to the penetration of water under hydrostatic pressure.[22]

The following test methods can be used to measure water/shower/rain repellency and resistance:[12,23]

- AATCC TM42: Water Repellency, rain test.
- AATCC TM22: Water Repellency, spray test.
- EN ISO 4920: Textiles – Determination of resistance to surface wetting (spray test) of fabrics.
- AATCC TM35: Water Repellency: Impact penetration test.

- EN ISO 9865: Textiles – Determination of Water Repellency of Fabrics by the Bundesmann Rain-shower Test (5 mm diameter water drops fall from a height of 150 cm onto the fabric, and water penetrations is measured after 60 mins).
- AATCC Test Method 42-2000: Water Resistance: Impact Penetration Test, where 500 ml of water is sprayed from a height of 2 feet (61 cm) onto the surface of the test specimen, at 45° angle to the flow, backed by a pre-weighed blotter.[23] The increase in the weight of the blotter provides a measure of water penetration through the fabric. Water repellency is measured in a similar manner, except that the fabric is clamped in a hoop and the water is sprayed from a distance of 6 inches (15.2 cm).
- BS 5066: Method of Test for the Resistance of Fabrics to an Artificial Shower (WIRA SHOWER).
- DIN 53886.
- J.I.S. Z – 0208.

Waterproofing and rainproofing[22]

The following test methods are used to test the water/rainproofing of fabrics:

- AATCC 127: Water Repellency: Hydrostatic pressure test.
- ISO 811: Textile fabrics – Determination of resistance to water penetration, hydrostatic pressure test.

General

EMPA has developed new test methods to assess the water and rain resistance of materials and garments,[24] concluding that water resistance should be measured dynamically to obtain a more realistic assessment,[24] the hydrostatic head test not always being a true reflection of what occurs in practice. Benltoufa *et al.*[25] have developed an experimental device for measuring the water permeability of fabrics, while Butz and Elzer[26] have described a test method that differentiates between nano-structured and conventional water repellent textiles.

11.3.3 Specifications

The Hohenstein Institute has developed a 'wear comfort quality label' grading system,[4] from 1 (excellent) to 6 (inadequate) for waterproof breathable garments. According to European standards,[27] for a fabric to be classified waterproof it must withstand a hydrostatic head pressure of 1500 mm, with most such outerwear fabrics exceeding 10 000 mm.

It has been stated that fabric for active sportswear should support at least a 450 mm water column,[28] and if a fabric can withstand a hydrostatic head (pressure) of 100 g/cm^2 (1.41 psi) or higher, then it will be impermeable to rain.[29] Most specifications require a hydrostatic head (pressure) of 2000 mm; above 1500 mm the fabric is impenetrable to raindrops. According to ISO 811, materials with a hydrostatic head of 1500 mm and more may be designated as rainproof.[24]

11.4 Engineering fabric and garment breathability

11.4.1 Introduction

As mentioned and defined previously, breathability encompasses two different requirements, namely, breathability and waterproofing. Therefore, when engineering breathability into a fabric or garment, both these characteristics need to be considered and designed into the fabric or garment. This generally involves some compromise between the two extreme cases of total waterproofing and complete breathability. Frequently, the precise balance of properties required for breathable fabrics depends upon the end-use of the fabric and the specific level and balance appropriate to that particular end-use. Moisture diffuses readily through air, whereas fibres present a barrier to such diffusion. Therefore, the resistance of a traditional textile fabric/garment to moisture vapour diffusion will *largely* depend upon the fabric construction, notably density (compactness or tightness) and thickness, and to a lesser extent on the fibre properties, notably hydrophilic and hygroscopic properties, such as moisture absorption. Nevertheless, fabrics mostly have a high ratio of air to fibre volume and only in extreme cases do differences in the fabric construction (i.e. density and thickness) *per se* play a major role in changing moisture vapour diffusion for conventional or traditional fabrics.

The subject of engineering breathable fabrics has been reviewed.[15,30,31] In broad terms, the main ways of achieving waterproof breathable fabrics, in practice, are (i) using tightly woven constructions (usually involving cotton or micro-fibres), (ii) using micro-porous or hydrophilic membranes (a thin polymer film laminated to the fabric) and (iii) using coatings (polymer, usually polyurethane, applied directly to the fabric).

There are various types of breathable fabrics and ways in which breathability can be engineered into a fabric, including the following categories:[30]

- Closely woven fabrics
- Micro-porous membranes and coatings
- Hydrophilic membranes and coatings

- Combination of both micro-porous and hydrophilic membranes and coatings
- Smart breathable fabrics
- Fabrics based on bio-mimetics.

11.4.2 Effect of fibre and yarn properties

Except in the case of very closely or tightly woven fabrics, fibre and yarn properties generally play only a secondary role in achieving the required standards for waterproof breathable fabrics. In view of this, only brief reference will be made to the effects of the fibre and yarn properties *per se* on breathability. Essentially, the most important fibre properties within the context of closely woven fabrics are fibre fineness (the finer the fibre the better) and the ability of the fibre to swell with increasing moisture content (the greater the swelling the better), with intrinsic fibre moisture absorption and water repellency characteristics of lesser importance. Similar considerations apply to the yarn, with yarn twist factor, compactness and smoothness having some effect.

11.4.3 Effect of fabric and laminate structure and properties

Tightly woven fabrics

Breathable waterproof fabrics can be achieved by appropriate selection of the fabric structure and tightness (e.g. dense Oxford structure), together with the appropriate fibre (e.g. cotton or micro-fibres/filaments), yarn composition and properties, and water repellent fabric finish (e.g. silicone or fluoro-chemical). The foremost requirement for tightly woven breathable fabrics is that the pore structure is such that water droplets cannot permeate into and through the fabric from the outside. The first showerproof (rather than waterproof) breathable fabric, called Ventile, which was developed by the Shirley Institute (UK) in the 1940s, was made from low twist mercerised (generally combed and plied) yarns containing fine Egyptian cotton, and woven in a very dense Oxford fabric construction. This construction was ideal for this purpose, providing good fabric abrasion resistance, packing density and flexibility. Although the fabric is not showerproof to start with, when it comes into contact with water, the cotton fibres swell, thereby reducing the size of the inter-yarn pores (from about 10 μm to 3–4 μm) and hence the ability of water to penetrate the fabric. A water repellent finish is essential, but must not restrict the ability of the cotton to absorb moisture and then swell.

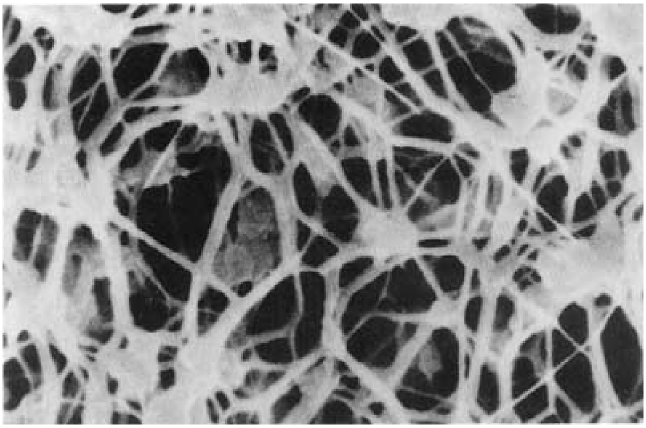
More recently, tightly woven fabrics have been woven from man-made micro-fibres/filaments, such as polyester, polyamide, viscose and acrylic fibres (conventional and bi-component), which produce sufficiently small pores, even when dry. Very fine filaments and micro-fibres (e.g. 1 dtex, 10 μm or less) can be woven into tight constructions (e.g. 4800 × 7680 filaments/cm) to produce pores small enough to prevent water molecules from penetrating, but large enough to allow water vapour to pass through. They can be laminated to a highly absorbent outer fabric (e.g. viscose or cotton), wicking perspiration to the outer fabric which absorbs it and allows it to evaporate to the outside.[28] Alternatively, they can be used on their own, but with a water repellent or other coating (finish), such as silicone or fluoro-carbon, which can increase water repellency and reduce water penetration. An example of a fabric in this category is Hoechst Trevira Finesse, which will support a 500 mm water column,[28] also after 5 washes. In the Bundesmann Water Repellency Test (DIN 5388), in which the fabric is exposed to artificial rain, it will remain dry for 5 hours, even after five washes. These fabrics are softer and more water repellent than the original Ventile fabric. They have a narrow pore size distribution, within the sub-micron range.[32]

Yoon and Buckley[33] showed that air permeability and water vapour transmission rate are mainly dependent on the fabric geometrical properties (thickness and porosity), whereas liquid water transport is strongly dependent on the fibre properties, although geometrical factors also play an important role here.

Micro-porous membranes and coatings

Micro-porous membranes are generally made from the polymers[27] PTFE, polyurethane (PU), polyolefins, polyamides, polyester, polyether and polyether based copolymers, with the first two mentioned (i.e. PTFE and PU) being the most popular. In most cases they can be cast directly onto the fabric (i.e. coated) or formed into a membrane and then laminated to the fabric.

A micro-porous membrane (or coating) can be defined[34] as a thin-walled structure having an open spongy morphology of precisely controlled pore size, typically ranging from 0.03 μm to 10 μm in diameter. Micro-porous coatings and membranes rely on an interconnected network of tiny holes (pores) introduced by various means into an otherwise impermeable polymeric structure.[35] Sheets of polymers can be produced with common salt incorporated which is washed out afterwards to leave voids/pores. Such holes (or pores) are too small to allow water droplets to pass through, but are large enough to allow water vapour to pass through. Micro-porous structures work, as do tightly woven structures, because of the large



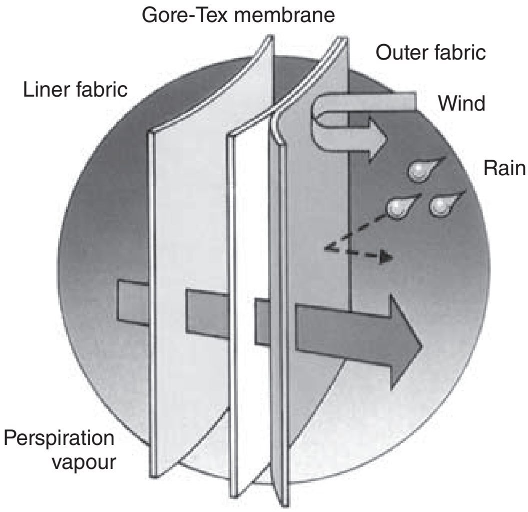
11.1 Gore-Tex® fabric membrane magnified by 40 000. Source: Ody, 1990[36]

difference in size between individual water molecules present in water vapour and water droplets of rain, each of the latter consisting of many millions of water molecules held tightly together by surface tension forces.[35] Micro-porous membranes typically weigh 10–20 g/m^2 and should be durable and resistant to laundering, chemicals and UV degradation.

Micro-porous based breathable fabrics usually have a layer of hydrophilic polyurethane or water repellent finish (fluorocarbon or silicone) so as to ensure consistent performance and to prevent the pores being contaminated.[30]

The first use of a micro-porous membrane to produce a breathable fabric in the 1970s, called Gore-Tex (W.L. Gore; *http://www.gorefabric.com*), represented a major step forward in the achievement of comfortable breathable fabrics and garments. The membrane (thin film) comprises an expanded polytetrafluoroethylene (or Teflon) (ePTFE), having over a billion pores per square centimetre (Fig. 11.1),[36] their size ($\approx$ 0.2 µm in diameter) being orders of magnitude smaller than the smallest water droplet (±100 µm) and several times larger than a water vapour molecule (40×10^{-6} µm),[15] and able to withstand a water pressure of up to 100 psi.[28] Pore size should preferably be below 3 µm[30] for optimum balance between waterproofness and breathability. The PTFE membrane is chemically inert, smooth, UV resistant, water repellent, durable and can withstand high temperatures.

Today, some of the most durable and high-quality breathable fabrics are produced by laminating (sandwiching) a micro-porous membrane between two fabrics: an inner, soft and flexible fabric (e.g. warp knitted) and an outer abrasion resistant fabric (e.g. woven nylon fabric). Such fabrics are popular



11.2 Gore-Tex®, three-component laminated fabric.
Source: Ody, 1990[36]

for military wear, foul weather garments and work-wear. Two-layer laminated fabrics are popularly used for sportswear and fashion leisurewear, often with a loose lining or other insulation material. Drop liners are also used, where the breathable laminate is inside, but separate from, the outer fabric, and therefore in no way affects the handle, drape and constructional characteristics of the outer fabric. The membrane can be laminated to a non-woven or tricot fabric. Generally, the membrane is 'dot' laminated (for example hot melt screen printing using polyurethane adhesive dots) to the outer fabric and frequently also to an inner, fairly open and flexible fabric which provides flexibility and facilitates the passage of perspiration to the outside, the membrane being sandwiched between the two (Fig. 11.2[36]).

Tetratec Corporation also produces a micro-porous PTFE fibre. Donaldson Membranes has a portfolio of Tetratex fabrics, involving expanded micro-porous PTFE (ePTFE) membranes, films and laminates, the membrane being stable from –270° to +260°C. Other such membranes are based on micro-porous polyurethane (e.g. Aquatex, produced by Porvair) or on micro-porous polyvinylidene fluoride (PVDF) cast directly onto the fabric. Honeycombed micro-porous polyurethane coatings (pore sizes 2 to 3 μm) provide waterproof breathable fabrics[28] with, for example, a water vapour transmission of 4000 g/m^2/24 hr and a resistance to 2000 mm of water column for the Entrant Fabric of Toray.

Problems that can arise with micro-porous membranes and coatings include contaminants and detergents blocking the pores, stretching the fabric, increasing the size of the pores, and reducing adhesion to the textile substrate.

Hydrophilic membranes and coatings

Hydrophilic membranes and coatings are very thin polymer films, generally of chemically modified polyester or polyurethane, containing essentially no holes (pores) as such and sometimes referred to as non-porometric.[15] They combine 'soft' segments (e.g. polyether chains) with 'hard' segments (e.g. polyurethane chains[37]). Hydrophilic coatings 'breathe' by passing water vapour molecules along their chains to the outside, while preventing water molecules from penetrating. Such hydrophilic (non-micro-porous) polymer films (membranes and coatings) can transmit water vapour efficiently by a complex molecular diffusion or chemical adsorption mechanism,[38] with the water vapour molecules reacting with the hydrophilic 'polar' groups (e.g. polyethylene oxide) incorporated into the polymer chain, these regions acting like 'inter-molecular pores' which allow water vapour molecules to pass through, by absorption, diffusion and desorption, but not liquid water. The vapour initially 'dissolves' in the polymer, with the concentration directly proportional to the vapour pressure, after which it migrates to the opposite surface under the concentration gradient.[15] Incorporation of hydrophilic functional groups into conventional coatings achieves the desired water vapour diffusion, the hydrophilic–hydrophobic balance required[30] in the coating being achieved, for example, by the use of segmented copolymers, incorporating polyethylene oxide into the hydrophobic polymer chain.[30] Commercial films are around 10 to 25 µm thick, have a vapour permeability above 2500 g/m^2/24 h, with 5% swelling, and can support a hydrostatic head of 1500 mm.

A membrane 0.01 mm thick can have over 584 billion hydrophilic cells/cm^2 which transport moisture.[30] It needs to be flexible, and have good strength and softness. One of the first such coatings developed by the Shirley Institute,[35] was polyurethane based. Coatings are generally less expensive and easier to handle than the membranes. They are up to 50 times more effective in water vapour transmission than conventional polyurethane coatings, and compare favourably with micro-porous structures.[35]

One example of a hydrophilic membrane is Sympatex,[39] by Akzo (Enka AG), which is about 10 µm thick. It consists of a copolymer of 70% polyester and 30% polyether. Polyester is hydrophobic (repels water) and polyether is hydrophilic (allows water vapour through). The direction of travel is influenced by the temperature gradient, always being from high to low.[39] It is claimed to be able to stretch up to 300% and still be impermeable to liquid (water); only water vapour (e.g. evaporated perspiration) can pass through the membrane. It can withstand a water pressure (column) of 10 metres (1 bar[39]). It is windproof and is always laminated to a textile substrate, also sandwiched between the outer fabric and an inner (lining) fabric. Sympatex-containing garments can be dry-cleaned or washed in a washing machine (delicate wash) at a temperature of 40°C, after which the outer fabric has to be reproofed to re-establish its water repellency properties. The outer fabric needs to hydrophobic. It transmits more than 2500 g/ m^2/24 hrs of water vapour.[28] Sympatex has recently developed[40] an eco-friendly (100% recyclable) laminate made from polyester–polyether copolymers, a combination of the Sympatex membrane and recycled polyester. Its latest Reflexion III membrane is lightweight, waterproof, windproof and recyclable.

Other examples in this category include Porelle from Porvair. An alternative technology uses a polyether co-block polyamide film (e.g. Peebax from Elf Atochem[37]).

Advantages of hydrophilic films and coatings include:[37]

- Water and solvent resistance
- Strength and toughness
- Windproofness
- Good handle
- High breathability without water leakage
- Pinhole free films.

Disadvantages include:[37]

- Vapour reservoir is required for breathing to commence
- The surface wets out in rain, giving a cold clammy handle
- The film swells when wet, leading to possible 'noise' effects in wet laminates.

Combination of micro-porous and hydrophilic membranes and coatings

Fabrics can also be coated with copolymers (coatings and membranes) combining a non-micro-porous hydrophilic layer with a micro-porous hydrophobic layer, which can offer the following advantages over a pure micro-porous film:[30,37,41]

- Hydrophilic layer seals the micro-porous base, reducing any tendency for water leakage
- Increased strength and toughness
- Reduced stretch
- Greater windproofness and resistance to penetration by some solvents and light mineral oils
- Film swelling is lower
- Lower friction during sewing when making 2-ply laminated fabrics.

Disadvantages include:[30]

- Increased stiffness
- Cost
- Reduced breathability
- Moisture vapour reservoir required to initiate water vapour transmission
- Tends to 'wet out', giving a cold clammy handle.

Smart breathable fabrics

Smart (or intelligent) breathable fabrics, as is the case with smart (intelligent) textiles in general, imply that the fabric can respond to different ambient conditions by changing its properties accordingly. Phase change materials (PCM) for example, are, being used which change the breathability properties of the fabric as the environment (micro-climate) changes. If the moisture-saturated outside air is as warm as the 'micro-climate' between the skin and the membrane, perspiration will no longer be able to be evaporated and transmitted to the outside, and the wearer will feel uncomfortable, as would be the case with no clothing. Products have therefore been developed[42] (for example by Schoeller Textil) which adapt to the climate, by, for example, the hydrophilic membrane opening up with increasing water vapour and body heat, and closing up when the converse occurs. Schoeller's c_change three-layer fabric's hydrophilic membrane changes as the activity and temperature change, allowing moisture to escape more rapidly when the body temperature and the moisture increase, by opening up (and by closing, when the body temperature drops),[43] thereby retaining body heat.

The use of temperature-sensitive polyurethanes (TS-PU) is also being explored,[30] their water vapour transmission increasing with increasing temperature.

Biomimetic-based fabrics

Biomimetic fabrics, which mimic biological mechanisms, have been developed. One example is improving the water vapour permeability of fabric coatings by incorporating an analogue of leaf stomata, which open and close according to water vapour transmission needs.[15] Akzo Nobel markets a product under the name of Stomatex, which is used in conjunction with its Sympatex waterproof breathable membrane.[30]

The Super-Microft fabric developed by Teijin Co., Japan, which emulates the high water repellency of the structure of the lotus leaf, is another example of a biomimetic fabric.[30] Ramaratnam *et al.*[44] reported on a method of mimicking the lotus effect on polyester fabric using silver nano-particles and a non-fluorinated hydrophobic polymer.

11.4.4 Production of coated and laminated breathable fabrics

As previously mentioned, several methods are available for producing waterproof breathable fabrics, including tightly woven fabrics (e.g. using cotton or micro-fibres), membranes (hydrophilic or micro-porous) and coatings (hydrophilic or micro-porous), the latter generally being thicker than the former.[45]

Essentially, the construction of breathable fabrics can be grouped into the following categories:

- Tightly woven fabrics (e.g. cotton, linen and micro-fibres)
- Laminated and coated fabrics, for example:
  - Micro-porous or hydrophilic membrane laminated to a fabric
  - Micro-porous or hydrophilic membrane sandwiched between a high performance outer fabric (e.g. woven) and an inner fabric (e.g. knitted fabric)
  - Micro-porous or hydrophilic polymer coating applied directly to a fabric.

Membranes and coatings need to be joined with at least one textile or other substrate to produce a material with the desired balance of functionality, aesthetics, handle, drape, durability, etc. (see also Section 11.4.3). There are various ways of combining membranes and textile fabrics.[30,37] If the outer fabric and the membrane are laminated it is referred to as an 'outer' laminate, while if the membrane is laminated to an 'inner' fabric (lining), it is referred to as a 'lining fabric' or liner.[46] A three-layer laminate involves three layers (outer fabric, membrane and inner fabric) being bonded. For coatings, a thin plastic film (generally polyurethane) is applied directly to the fabric[46] from a solution, dispersion, or hot-melt.

The lamination process must be such that it does not deleteriously affect breathability, and it must be durable and flexible. The membrane can be laminated to one or more of the following materials:

- Woven (most common for apparel and generally used as the outer fabric)
- Knitted (provides softness/flexibility, often used as the inner fabric)
- Non-wovens that are cost effective (e.g. wound dressings, roofing membranes)
- Foams (e.g. upholstery).

Behera and Singh[27] provided a table (Table 11.1) of commercial breathable fabrics.

Mid-layer fabrics, i.e. between those in contact with the skin and the outer fabric, need to offer good wicking and insulation. An example is the Polartex Power Dry polyester fabrics, with large capillaries on the inside to remove (wick) perspiration quickly, and to spread it on its outer surface by means of small capillaries for maximum evaporation.[7] Sarkar *et al.*[47] have compared the water transport behaviour of different multilayer fabric structures.

11.5 Fabric finishes

Generally, waterproof breathable fabrics require a water repellent finish to be applied to the outer layer which does not adversely affect breathability. Mechanical, chemical and coating treatments are the main methods[10] for imparting water repellency to textiles, the effect also depending upon the fibre type and the fabric structure and tightness (density). Ozcan[10] has compared various water repellent finishes.

Fabrics are generally given a water repellent finish by depositing hydrophobic substances such as fluoro-polymers, fluoro-chemicals, silicones and waxes on the fabrics[10] (applied, for example, by spraying, lick roller or padding). These are based mainly on the reduction of the critical surface tension of the fabric surface to below that of water, which results in a chemical barrier against water penetration.[48]

Initially, wax emulsions, with a maximum surface energy of 30–32 dynes/cm, were used, which was good enough for aqueous fluids but not for many oily substances.[49] Fluoro-chemicals (fluorocarbons) are now popularly used, providing effective repellency against both aqueous and oily based substances (polar and non-polar liquids[48]), generally being applied from an aqueous dispersion. They also provide easy cleanability. The fluoro-chemicals, which are mostly applied by padding, provide both 'repellent' and 'release' properties, preventing wetting and soiling (i.e. repellency) on the one hand, and easy removal (release) of dirt, soil, etc. during cleaning on the other hand. The fabric needs to be properly prepared prior to the application of the fluoro-chemical, it being particularly important that the fabric is free from residual substances, such as silicone de-foamers, residual alkaline, rewetting tensides (detergents, emulsifiers), preparations and sizing residues.[48] Wetting agents are included to enable even wetting and application of the fluoro-chemical. Such wetting agents should preferably volatilise during the subsequent drying or curing processes so as to prevent re-wetting.[48] Various 'supplementary' products can be applied with the fluoro-chemical so as to enhance the performance of the fluoro-chemical and extend the range of properties imparted to the fabric,[48] these including

Table 11.1 Commercially available breathable fabrics. Source: Behera and Singh, 2007[27]

Product brand name	Company	Features of the product
Permatex	DuPont	PU based film, offers 70% MVTR
Microtech	Aigle Inc.	Micro-porous coated fabric
Walotex	Deerfield Co. Ltd (Bayer Group of Cos.)	Monolithic hydrophilic membrane
Crosstech	Gore-Tex Associates Inc.	Bi-component membrane technology
Hydroseal, Vertex, HyVent	The North Face	Micro-porous laminated
Powertex	Salewa	Laminated breathable
Coopertex™	Cooper Fabrics, USA	Membrane based WPB fabrics
Formosa Raintex WPB	Formosa Raintex, Taiwan	Multilayer laminated fabric
Triple Point	Lowe Alpine	Micro-porous coating
Weathertight	Karrimor Inc.	Hydrophilic coating
Gore-Tex (3-Ply)	WL Gore Associates Inc.	Micro-porous PTFE membrane
Aquatex	Aquatex Co. Ltd, Malaysia	Micro-porous laminates
Sympatex	AKZO Nobel	Hydrophilic laminates
Entrant	Toray Coatex Co. Ltd Japan	Superior waterproof, breathable, pore size 2–3 mm
		Bi-component coating
Gore-Tex	WL Gore Associates Inc.	Bi-component laminates
Tetratex	Tetratec	PU bi-component film
Breathe-Tex Plus® and Stediar 2000®	Aldan Industries Inc.	Monolithic moisture barrier products using polyurethane
Proline	Lainiere de Picardie Inc.	Waterproof, breathable, windproof laminated fabric
Poldura	Modulo M	PU based multilayer fabric for dry suit
Sure-seal	Carlisle coating and WP	Membrane and coating waterproof system
Eclipse Barrier/Tech	BarrierTECH	Monolithic barrier membrane
Paclite	WL Gore Associates Inc.	Lightweight and soft membrane
Aquadry	Aquatex Co. Ltd	Hydrophilic coating
Conduit™	Conduit	Hydrophobic and hydrophilic membrane

'extenders' (e.g. blocked isocyanates), cellulose cross-linkers, softeners, antistatic agents, fungicides and flame-proofing. Care must be taken not to adversely affect other desirable properties of the fabric, notably handle and comfort. Fluoro-chemicals have good fastness to washing and dry-cleaning, although a heating process (ironing or tumble drying) is often necessary after the cleaning process.

Blackwood[50] has compared the different methods of applying silicone coatings to fabrics, silicone finishes generally protecting against water-based soils and liquids only.[51]

An ion-mask plasma treatment has recently been developed,[52] while nano-structured finishes, e.g. nanosols, with particle sizes of less than 100 nm (e.g. self-cleaning) have also been developed.

11.6 Construction of showerproof garments

The first requirement for producing a waterproof breathable garment[53,54] is to use fabric(s) with the required performance characteristics, as discussed in the previous sections of this chapter. Thereafter, the design, seaming and seams of waterproof breathable garments need to be carefully engineered to ensure that water (rain etc.) cannot enter from the outside, either through seams or openings in the garment, while still allowing water vapour to escape from the body to the outside. Seams are commonly sealed with special tapes (e.g. heat bonded to the laminate) which must be durable to both washing and dry cleaning. Cuffs, hems, zippers, hoods, pockets, etc. all have to be specially designed for water proofing. These are normally specified and compulsory when trademarks are to be applied to garments. Seam tapes are thermoplastic adhesive films applied to sewn seams to prevent water from leaking through.[49] Such tapes must be resistant to washing and dry cleaning.

Even the best water-repellent fabrics can be made up into a very disappointing garment unless certain rules are observed.

Lining

First, the lining of the garment has an important influence on its wettability. A wettable lining causes the water to wick through from the outer surface, and transmits it to the clothing underneath. Linings, therefore, as well as the top fabric, should be given a water-repellent finish to delay this happening. Linings are often made from nylon, viscose or acetate, or, for heavier garments, a cotton lining may be used.

Interlinings (i.e. the stiffening fabric inserted between the top and inner layers of the garment)

Without an effective finish, interlinings will also cause wicking of water, and where interlinings are fused to the top fabrics, at cuffs and collars for instance, this can accelerate the penetration of water and produce disastrous effects on the appearance of the garment.

Interfacing

Before fusing any interfacing, the fabric needs to be tested. Some of these fabrics do not respond well to the application of heat; in these cases, a sew-in interfacing will be necessary. Cotton muslin or batiste can be selected, washed to eliminate the possibility of further shrinkage, and cut using the same grainlines as the rainwear fabric. The interfacing can be attached to the rainwear fabric with adhesive dots of glue stick (the school variety glue stick works well). If a fabric will accept a low-heat iron, use the lightest weight fusible, such as So Sheer, and apply without using steam.

Seams, seam finishes, and hems

Seams are particularly vulnerable to penetration by water, and for this reason special attention must be directed to their construction and location when designing a garment. When stitching is visible on the outside of the garment, water is liable to pass through, and seams which lie horizontally are prone to the full impact of rain, for example on the crown of the shoulder, the top of an attached hood, and the top edge of a pocket. To minimise the risk, it is necessary to use proofed sewing threads and the finest needle possible. Resistance to water penetration is further assisted by ensuring that open and not closed seams are used. By opening out the seam of the top fabric on the inside of the garment, the stitching lies protected between two layers of the outer fabric; the initial penetration of water through the seam consequently is delayed from reaching the lining or wearer. Since such concealment of the sewing thread is desirable, it is obvious that stitching in seams should not be superimposed.

The most common method of making seams waterproof is by taping the inside, using an adhesive or a heat-sensitive tape, or welding the layers together.

Stitches should be lengthened slightly for rainwear/coated fabric, to approximately 3.0–3.5 length. Hems are attractive when sewn with a cover-stitch. Any auxiliary needles should be removed from the cover-stitch machine, as pinholes will leave a permanent mark in the fabric. If cover-stitch capabilities are not available, a double row of topstitching can be used for hems. The stitch should be lengthened to 3.5 for such hem-stitching. Seam finishes are not necessary to prevent fraying, as the fabric does not ravel. However, selecting a topstitch for seams may help them to remain flat. If so, the same 3.5 length stitching should be used as for the machine hem. It is advisable to finger press the seam open and stitch on each side of the seam line, or finger press the seam to one side, trim out the inner layer of the seam allowance, and run one row of topstitching to secure the seam in place.

For a creative topstitching, zigzag stitch should be used, set to 2.5 width and 2.5 length. Two strands of construction thread should be put through the machine needle.

Pockets

Patch pockets, with a horizontal edge, are greatly exposed to rain; if they are considered essential to the garment style, then fabric flaps must be used. However, pockets located at a slant are less likely to be a source of penetration. In any event, all linings for pockets should be proofed.

The design of pockets must be aimed at keeping out wind, wind-blown rain, and water that runs off the surface of the garment. Pockets need to be closable, say with a zip, with the opening preferably protected by a flap which itself can be secured in position.

Fastenings, buttons, and zips

Ideally, fastenings, buttons and zips should not be fully exposed to the rain. If the button thread and zip tape are absorbent it will assist penetration. Water-repellent sewing thread and tape should be used, with further protection given by a storm flap. Where buttons are used for decorative features, as with shoulder tabs, the stitching often provides an entry point for rain. Cuffs most of the time need to fit snugly, round the wrist, but they must also be capable of being 'opened' not only for the removal of the garment but to facilitate ventilation. Consequently, cuffs should be designed with adjustable openings. However, if an elasticated construction is used (differing in character from the top fabric), it is essential that it should not wet preferentially.

Design of fastenings, pockets, cuffs, and hoods must be directed to keeping out wind, wind-blown rain, and water which runs off the surface of the garment. A flap used to protect a zip is more effective if, in addition, a press stud, a touch-and-close fastener, e.g. 'Velcro', or other fastening is introduced to hold the flap close to the surface of the garment.

Magnetic closures, metal eyelets/grommets, long-prong snaps and separating zippers all work well with rainwear/coated fabric. Buttons and buttonholes will require additional reinforcement, such as a second layer of interfacing. It is important to avoid the use of heat on this fabric.

Needles and thread

Microtex needles represent a good choice for rainwear fabrics. Select the smallest needle that can be threaded easily, so as to avoid any needle and pin holes. If a Microtex needle is not available, a 75/11 sharp needle (packaged as a 'quilting' needle) should be used along with an all-polyester thread.

Style

Further scope for improvement hinges on the construction and location of seams. For instance, Magyar sleeves would ensure that seams will not occur along the shoulder or along the outer side of the arm. Such a style increases costs because it utilizes more material, and the choice possibly of a more complicated seam construction increases garment manufacturing cost.

Pattern suggestions

Some examples of waterproof garment constructions are given in Fig. 11.3.

Double overlap of zip

Underlay of zip

Overflap on pocket

Overlay of zip

11.3 Examples of Sympatex® (Akzo) waterproof breathable garment constructions.
Source: The Woolmark Company

11.7 Comparative fabric and garment properties

Several researchers[15,55,56] have compared the performance of different types of waterproof breathable fabrics, with Lomax[55] and Saltz[56] giving tables comparing the water vapour transport properties of different fabrics.

Often there has to be a compromise between high breathability and high waterproofing, with cost an important factor. Furthermore, the absolute and relative breathability of fabrics can often differ significantly under different test (and wear) conditions (e.g. steady state, rain, wind, etc.), with water (i.e. rain) generally decreasing breathability while wind increases it. Temperature (particularly sub-zero) and temperature gradient also play a role in the breathability of fabrics.

The following ranking was given[15,36] according to the time taken for breathability to cease under rainy and windy conditions:

- Micro-fibre (worst)
- Cotton Ventile
- Porometric polyurethane laminate
- PTFE laminate
- Polyurethane coated
- Hydrophilic laminate (best).

Based on a slightly modified BS7209 vapour permeability test, Holmes *et al.*[57] ranked the breathability of different types of breathable fabrics in the following order, from highest (best) to lowest:

- Tightly woven fabrics
  - Synthetic filament fabrics
  - Cotton
- Membranes
  - Micro-porous
  - Hydrophilic
- Coatings
  - Hydrophilic.

Various other authors[30,58,59] have compared the performance of different breathable fabrics.

Bartels[60] reported that hydrophilic lining material improved the transport of liquid perspiration through waterproof functional garments, and was superior to hydrophobic lining in this respect.

11.8 Sources of further information and advice

Various workers have reviewed the subject of waterproofing and breathability.[15,27,30,31,61–68]

11.9 Concluding remarks

Considerable research and development is taking place in the field of breathable waterproof fabrics and garments, with cost *vis-à-vis* performance and end-use being important factors. The trend is towards lighter-weight fabrics and garments[69] and towards smart (intelligent) fabrics. Smart fabrics (e.g. phase change materials), nano-technologies, as well as bio-mimetics, are areas which show promise in the development of the next generation of waterproof breathable fabrics. Venting and core comfort mapping represent new trends in making garments breathable and waterproof,[70] garments being engineered in such a way that they even provide for the different functional requirements of the various parts of the human body. There is also a strong move towards eco-friendly treatments (e.g. perfluoro-octanoic acid-free fluoro-chemical finishes) and environmentally friendly and recyclable fabrics and garments. In 2006, the breathable textile market was estimated[71] to comprise 63% PU coating, 20% PTFE laminates, 9% PE laminates, 6% PU laminates and 2% other.

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12

Ultraviolet protection of fabrics and garments

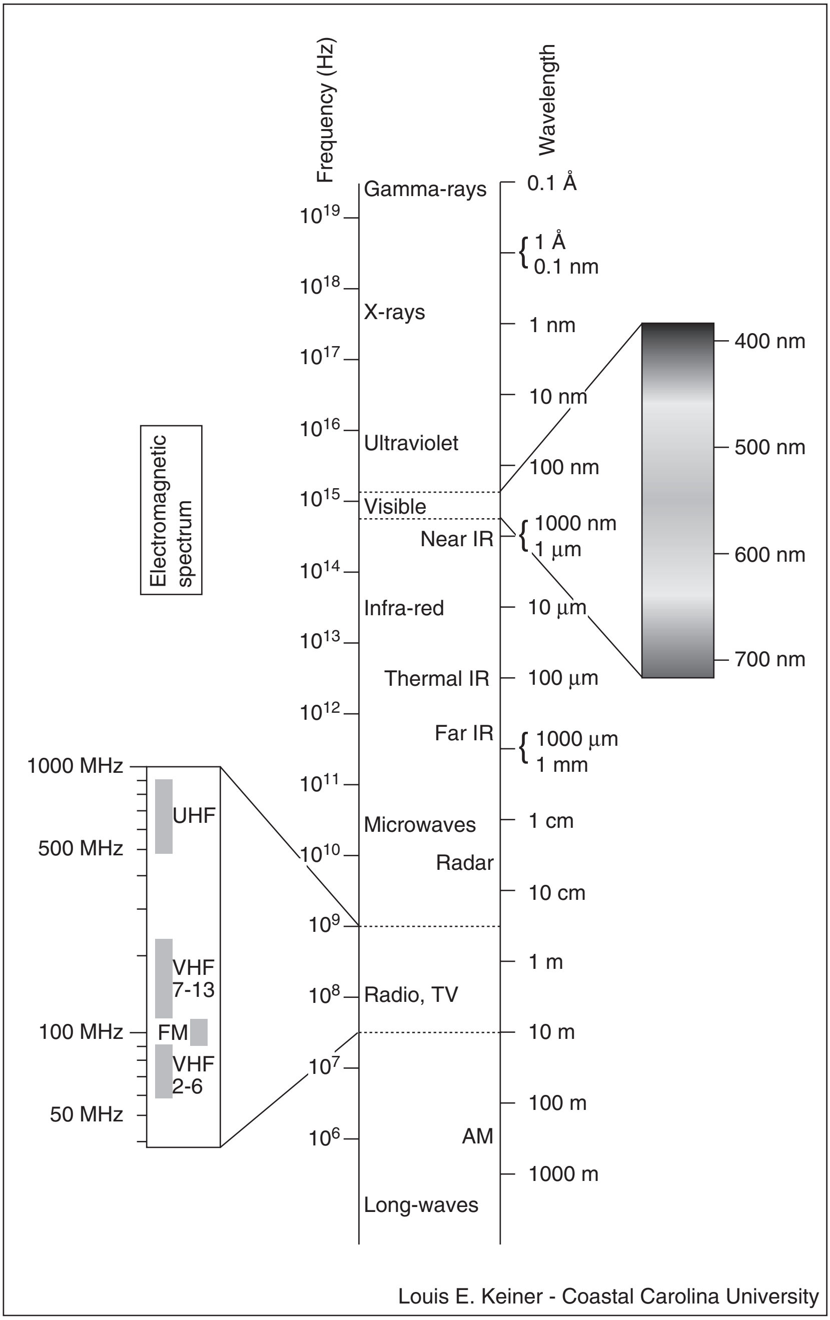
L. HUNTER

Abstract: The effect of ultraviolet radiation (UV) on the human body, notably on the formation of skin cancers, and the protective role of fabrics and garments are discussed in this chapter. The measurement of the protection offered by fabrics and garments to UV transmission and damage to humans is addressed. Ways in which fabric and garment protection against UV damage can be improved are covered, with particular reference to fibre type, fabric construction and UV protective finishing treatments.

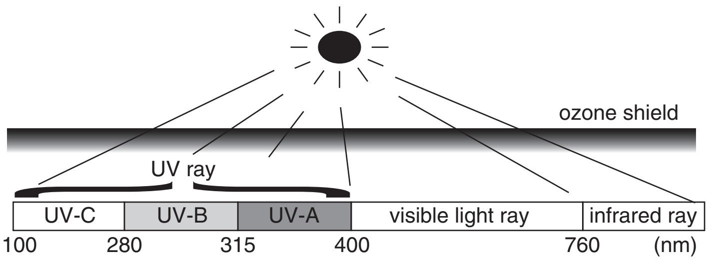
Key words: ultraviolet (UV) protection, ultraviolet protection factor (UPF), sun protection factor (SPF), clothing protection factor (CPF), skin cancer.

12.1 Introduction

Although sunlight is essential to all forms of life on earth, it can also be harmful, particularly exposure, or rather over-exposure, to certain components of its radiation, for example ultraviolet (UV) radiation, this being harmful to both humans and textiles. The spectrum of solar (electromagnetic) radiation reaching the earth's surface ranges in wavelength from about 280 to 3000 nm[1] (whereas it falls within the range of <0.03 nm to >5000 nm above the earth's atmosphere).[2] Ultraviolet (UV) light, ranging from about 150 to 400 nm, forms part of this radiation (Fig. 12.1[3]), with a wavelength shorter than the violet end of visible light but longer than soft X-rays (Fig. 12.2[4]), and accounts for about 6% of solar radiation (Table 12.1[5]). UV wavelengths are referred to as 'black light', since they are invisible to the human eye. Of the sunlight projected towards the earth, some 47% reaches the earth's surface, 34% being reflected by the atmosphere and 19% absorbed[6] (Fig. 12.3[3]). The amount of UV rays reaching the earth varies according to the season and time, weather conditions and geographical location. Radiation up to about 175 nm is absorbed by oxygen in the top half of the stratosphere (100 km),[7] infra-red (IR) radiation being absorbed by water vapour and carbon dioxide in the atmosphere.[7] Ozone (O_3) absorbs UV radiation between about 240 and 320 nm while oxygen (O_2) molecules absorb radiation with wavelengths below 242 nm.[6] The



12.1 Electromagnetic spectrum. Source: URL[3]



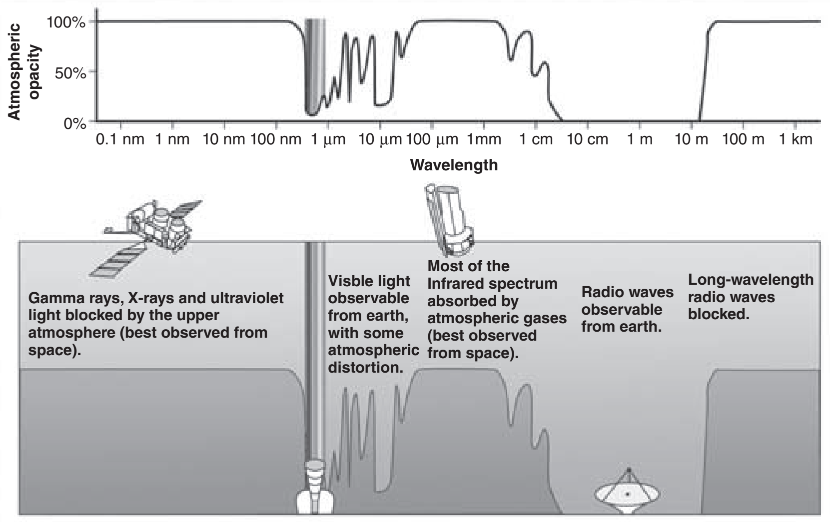
12.2 UV radiation spectrum. Source: Nakamura, 2005[4]

Table 12.1 Global radiation intensities at the earth's surface and their subdivisions (Summer, normal incidence). Source: *CIE Publication No. 20*, TC-2.27, 1972, given in Reference 5

Wavelength segment		Radiation intensity			
	[nm]	[W/m^2]	In [%]		
UVB radiation	280–320	5	0.45	6.05%	Increase of photon energy (↑)
UVA radiation	320–360	27	2.40		
	360–400	36	3.20		
Visible	400–600	325	29.00	51.8%	
	600–800	255	22.80		
IR radiation	800–1400	329	29.40	42.15%	
	1400–3000	143	12.75		

depletion of the ozone layer results in more of the sun's radiation, particularly harmful radiation, reaching the earth's surface, with countries such as South Africa, Australia and New Zealand having amongst the highest levels of UV radiation. This is becoming of increasing concern, partly because of the depletion of the ozone layer, and partly because of fair-skinned persons wishing to gain a 'brown' or 'tanned' appearance, through exposure to sunlight. Exposure to UV radiation can lead to three forms of skin cancer, namely basal-cell carcinoma and squamous-cell carcinoma (which are non-melanoma), and melanoma, which is more serious, with all three forms increasing virtually worldwide.

It has been estimated that two out of every three Australians will get non-melanoma skin cancer in their lifetime, one in ten of all skin tumours being a melanoma. In the UK there are about 46 000 new cases of skin cancer (40 000 non-melanoma and 6000 melanoma) each year, causing



12.3 Earth's atmospheric transmittance (or opacity) to various wavelengths of electromagnetic radiation. Source: URL[3]

some 2000 deaths.[8] In South Africa, the incidence of skin cancer has increased from one in 1000, 40 years ago, to more than one in 75 today. In the United States of America there were some one million new cases of skin cancer in 1998, and some 5000 persons die annually from melanoma, similar figures applying to Europe. In Germany alone, some 100 000 new cases of skin cancer are reported each year. Sun exposure is the main, and most preventable, risk factor with regard to malignant melanoma,[8] UV radiation having an immuno-suppressant effect.

It is the total UV radiation reaching the skin that is important in terms of skin reddening or skin cancers, especially melanoma, although for skin cancer, it is the total cumulative exposure over longer periods that is the prime determinant.[9]

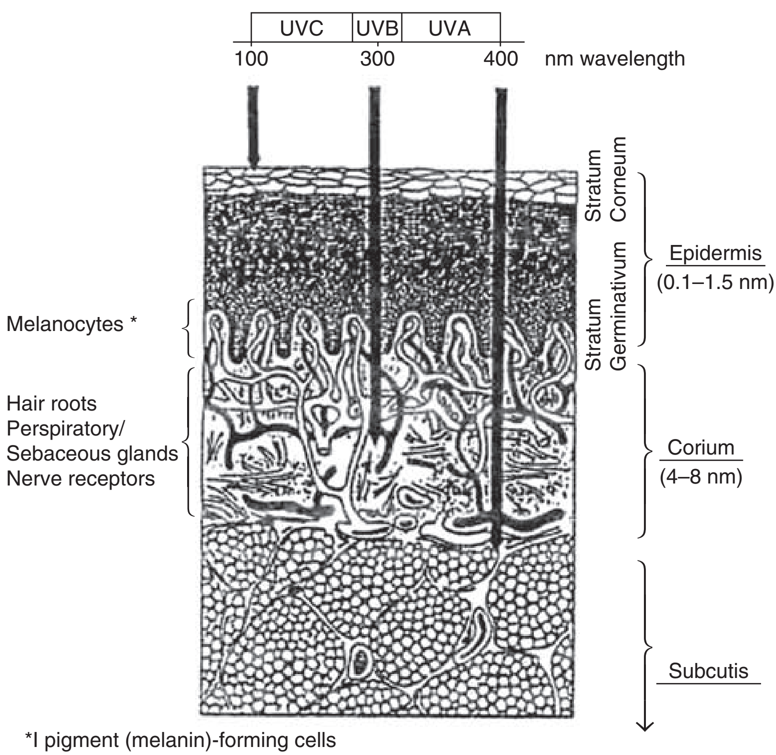
The major acute effects of UV irradiation on normal human skin comprise sunburn inflammation or reddening of the skin (erythema), tanning and local or systemic immuno-suppression,[10] with IR radiation possibly exacerbating UV induced photo-ageing. UV radiation represents a carcinogen, prolonged exposure causing acute chronic health effects to the human skin, eye and immune system, penetrating the skin up to 1 mm deep. The shorter the wavelength, the greater is the effect (harm) on the skin, the effect peaking between about 295 and 320 nm in practice.[11] To defend itself against UV radiation, the body tans when exposed to moderate UV levels, by releasing melanin (produced by melanocytes, pigment cells located in the epidermis) a brown pigment, which absorbs and blocks UV penetration and prevents damage to skin tissue deeper down. The pigmentable skin therefore protects itself by pigmentation and thickening of the horny layer.[1] The 320–340 nm (340–400 nm)[12] range of the spectrum is the only part that can cause excitation of pigmentation, which is tanning without reddening.[1] A by-product of tanning is beta-endorphin, the feel-good, pain-reducing neurotransmitter.[13]

UV radiation is highly energetic, converting into thermal and kinetic energy (which is absorbed by intracellular structures, notably DNA) and breaking chemical bonds, ionising molecules or making them unusually reactive, generally changing their behaviour. It triggers the production of highly reactive oxygen free-radicals in the skin. Sunburn is caused by the disruptive effects of UV radiation on skin cells, which can cause skin cancer if the complex DNA molecules and chromosomes in the skin cells are damaged.[3] UV radiation can damage DNA by either direct interaction with the nucleic acid or indirectly through intermediates. Children are particularly susceptible to skin cancer,[8] and their exposure to UV radiation is an influencing factor in the later development of melanoma.[8] The most common types of skin cancer are squamous cell and basal cell cancers[14] (non-melanoma), both of which are usually removed by excision or topical treatments. Malignant melanoma poses a more serious problem as a result of excessive sun exposure. Approximately 90% of non-melanoma and 65% of melanoma skin cancers have been attributed to UV exposure.

When considering the effect of UV radiation on human health and the environment, it is often subdivided into UVA (315/320–400 nm), called near UV, ‘long wave’ or ‘black light’; UVB (280/290–315/320 nm), also referred to as ‘medium wave’ or medium UV; UVC (200–280/290 nm), also called vacuum UV, ‘short wave’ or ‘germicidal’ UV[15]; and XUV or extreme UV (10–200 nm).[2,16] UVC rays represent the highest energy (shortest wavelength), most dangerous type of UV radiation, but are almost entirely filtered out by the upper atmosphere, together with about 50% of the UVB rays. Nevertheless, concern is now even growing about UVC because of the depletion of the ozone layer. A 1% decrease in the ozone layer can cause up to 2% increase in the amount of UVB reaching the earth and an increase of 0.5–5% in the number of skin cancer cases. UVA, UVB and UVC can all damage collagen fibre, thereby accelerating ageing of the skin, the wavelengths most effective at causing skin and cell damage being 305 (or 300) to 310 nm.[8] UVB causes long-term, more permanent tanning, but causes erythema (skin reddening), severe burns and an increase in the risk of malignant melanoma, while UVA transforms the melanin precursors in the skin, leading to rapid pigmentation of short duration (immediate tanning).

Because of absorption in the ozone layer, some 90% of the UV radiation that reaches the earth's surface is UVA, UVB accounting for only some 0.5%. Nevertheless, UVB is responsible for most of the acute and chronic sun related damage to normal skin,[17] it being between 1000 and 10 000 times more damaging to the skin than UVA. The increase in non-melanoma (basal and squamous cell) cancer is ascribed to cumulative exposure to UVB radiation, while the increase in the less common but more serious melanomas is ascribed to acute over-exposure.[18]

Although UVA is the least harmful, it contributes to skin ageing, flabbiness and wrinkles (destroying elastic fibrils deep inside and causing a deterioration in skin resilience), DNA damage and possibly even skin cancer,[15] penetrating more deeply into the skin than UVB, and reaching the lower layers of the dermis and causing sunburn, or reddening of the skin (Fig. 12.4).[5] UVA penetrates through clouds and through car windows. Ordinary



12.4 Schematic diagram showing the structure of the skin and the depth of penetration of UV radiation. Source: Reinert *et al.*, 1996[5]

Table 12.2 Effect of radiation on human skin. Source: Tronnier and Burg, given in Reference 5

UV radiation	Effect of overdose	Notes
UVA (320–400 nm) UVA_1 = 320–340 nm UVA_2 = 340–400 nm	Chronic reactions and damage, e.g. accelerated ageing; photodermatosis (acne); phototoxic reactions with medicaments	Skin protects itself by instant pigmentation and thickening of stratum corneum UVA_1: still carcinogenic potential UVA_2: only excitation of pigmentation (*) (tanning almost without reddening)
UVB (280–320 nm)	Acute and chronic damage, e.g. skin reddening (erythema); sunburn; accelerated ageing; eye damage (conjunctivitis, inflammation and opacification of the cornea)	Maximum erythemal effectiveness at 308 nm Stimulation of melanocytes to pigmentation (late tan)

* If capable of pigmentation

window glass is partially transparent to UVA, but is opaque to shorter wavelengths, passing about 90% of the light above 350 nm, but blocking over 90% of the light below 350 nm,[3] becoming opaque at about 290 nm. Maximum erythemal effectiveness (reddening) occurs at 308 nm.[12] Table 12.2 summarises the effects of UVA and UVB on the skin.[5] UVB has the beneficial effect of producing vitamin D (or calcitriol) in the skin, essential for the body's efficient utilisation of dietary calcium,[19] insufficient exposure to UVB causing a range of cancers due to vitamin D deficiency; however, only very short exposures (e.g. 10 minutes per day) are adequate for this purpose. Upon exposure to sun, the skin produces the inactive form of Vitamin D3, which is converted into its active form by dendritic cells in the skin,[20] which in turn helps to repair sun-induced damage. In addition to skin cancer, excessive exposure to UVB is hazardous to the eyes,[15] causing photo-keratitis (arc eye) and cataracts, pterygium and pinguecula formations,[15] it being considerably more harmful than UVA. Full-coverage eye protection is best in areas of high risk (e.g. high altitude mountaineering).

UVB radiation excites DNA molecules in skin cells, causing covalent bonds to form between adjacent thymine bases, producing thymidine dimers,[15] which can lead to a distorted DNA helix, stalled replication, gaps and misincorporations, resulting in mutations and ultimately cancerous growths. This connection between UVB and cancer is one of the reasons for the concern about ozone depletion and the ozone gap.[15]

Sun blockers or sunscreens were originally so designed to block, or more correctly partly block, UVB rays, but generally not UVA rays. Nevertheless, many sunscreens now also include compounds, such as titanium dioxide, zinc oxide and avobenzone, which offer some protection against UVA rays.[15] Naturally occurring products, such as the fern Polypodium leucotomes, are also known to protect the skin from UV radiation damage.[15] Exposure to relatively low doses of UVA and UVB can result in cumulative morphological changes in the skin, with that of UVA even exceeding that caused by UVB.[21] Overexposure to UVA produces similar effects to UVB, but the doses required are higher.[11]

Broadly speaking, the following factors affect the potential harm to humans due to the sun's rays, the UV component in particular:

- Intensity of the UV radiation from the sun, usually expressed as the UV index (see Table 12.3),[22] which represents the intensity of UV radiation and risk of overexposure. It ranges from 1 (very weak sun) to 11 (extremely strong sun), the numbers being directly related to the amount of UV reaching the earth's surface, measured in W/m^2 (see *http://www.epa.gov/sunwise/uvindex.html* and *http://ww.sunsmart.com.au/uvalert*), and relevant to the human skin. It has been standardised[11] to a scale from 0 (minimal risk) to 10+ (very high risk). It should be noted that the recommendations given in Table 12.3 are for adults with dark to moderately fair skin. Hence children, fair skinned and particularly sensitive persons need to take extra precautions. Several countries now forecast and publish UV index values on the internet.
- Duration of exposure. Damage from the sun's exposure is cumulative over one's lifetime.[22]
- Sensitivity of the person, or person's body parts, to UV.
- Amount, nature and effectiveness of UV screens/filters and clothing.
- Altitude; higher altitudes are generally worse.
- Latitude, closer proximity to the poles (ozone layer thinner) and equator (shorter distance through atmosphere) being worse.

UV damage to the human being can be avoided, or at least minimised, in the following ways:

- Avoid exposure, or at least extended exposure, to the sun, particularly during times when the intensity of the sun's rays (UV index) is high, for example between 10 am and 3 pm.
- Apply effective sunscreens and sunblockers to all parts of the body exposed to the rays of the sun.

Table 12.3 Recommendations for protection for different UV index values. Source: URL[22]

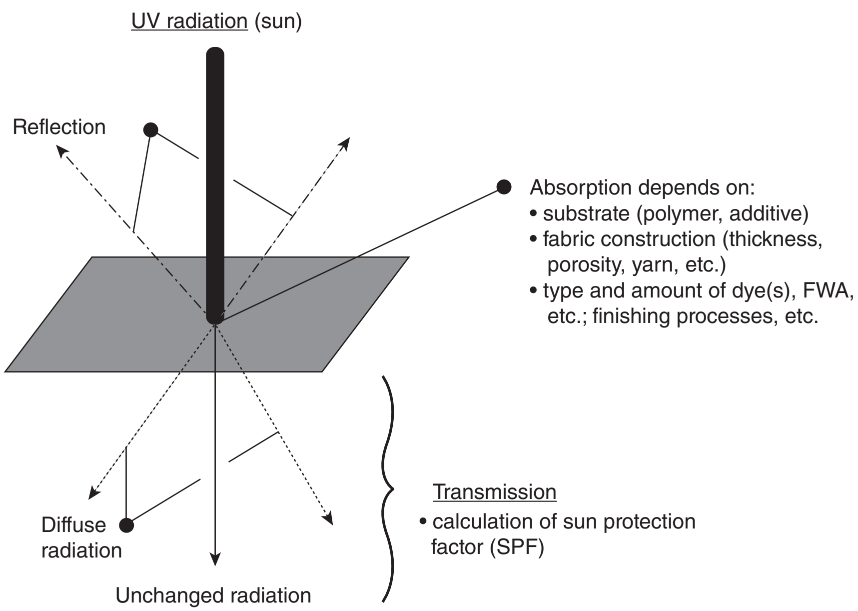
Recommendations for protection, when the day's predicted UV index is at various values:

UV index	Description	Media graphic colour	Recommended protection
0–2	Low danger to the average person	Green	Wear sunglasses; use sunscreen if there is snow on the ground, which reflects UV radiation, or if you have particularly fair skin.
3–5	Moderate risk of harm from unprotected sun exposure	Yellow	Wear sunglasses and use sunscreen; cover the body with clothing and a hat; and seek shade around midday when the sun is most intense.
6–7	High risk of harm from unprotected sun exposure	Orange	Wear sunglasses and use sunscreen having SPF 15 or higher; cover the body with sun protective clothing and a wide-brim hat; and reduce time in the sun from two hours before to three hours after solar noon (roughly 11:00 to 16:00 during summer in zones that observe daylight saving time).
8–10	Very high risk of harm from unprotected sun exposure	Reddish-purple	Same precautions as above, but take extra care – unprotected skin can burn quickly.
11+	Extreme risk of harm from unprotected sun exposure	Violet	Take all precautions, including: wear sunglasses and use sunscreen; cover the body with a long-sleeve shirt and pants; wear a broad hat; and avoid the sun from two hours before to three hours after solar noon.

- Wear effective UV protective clothing, including a hat and gloves; they are generally more effective than sunscreens.
- Wear UV protective sunglasses.
- Be aware, and careful, of UV reflected from surfaces, such as water.
- Be aware of the fact that clouds do not filter (screen) out all harmful UV rays.
- High dosages of vitamins E and C reduce the risks of skin cancer somewhat, the risk being further reduced if vitamin A is added, all being anti-oxidants.
- Vitamin C can be topically applied.

12.2 Measurement of UV protection

When UV radiation falls on a fabric, part of it is reflected, part is absorbed by the fibres, part is transmitted through the fibres and fabric pores (apertures) and part is scattered within the material (Fig. 12.5[5]). The last, if it reaches the skin, is also harmful. Hence it is important to measure the diffuse transmittance of textiles[8] when assessing their UV protective properties. UV transmission through textile fabrics is therefore influenced



12.5 Schematic representation of UV absorption by textile substrates. Source: Reinert *et al.*, 1996[5] by both absorption and scattering,[23] with a modified Kubelka theory being proposed for determining both the absorption and scattering coefficients. The fabric's ability to protect against UV radiation is generally measured by means of a spectrophotometer with an integrating sphere, which measures the amount of diffuse radiation passing through the fabric. The reduction of UV permeability by a fabric is referred to as 'UV cutting'.[12]

Clothing manufacturers are increasingly having their products tested for UV protection and indicating the measured values on swing tags attached to the garments, etc. The UV absorbance effectiveness of sunscreen products is measured and expressed in terms of a 'sun protection factor' (SPF), while the UV protection of fabrics is more commonly measured and expressed in terms of the 'UV Protection Factor' (UPF), sometimes also referred to as the Clothing Protection Factor (CPF), tested, for example, according to BS 7914: 1998 Part 2. A rating of 'very high' must have a UPF value greater than 30%. UPF and SPF differ essentially only in the manner in which they are measured. UPF can be defined as the amount (proportion) of radiation that is prevented from reaching the skin.[8] For example, a UPF rating of 20 means that the fabric allows only $^{1}/_{20}{}^{th}$ of the harmful UV radiation to pass through it.[8] It is also the factor by which the time of exposure to the sun can be extended before skin reddening takes place.[24] The SPF can be calculated as follows: SPF = MED protected skin/MED unprotected skin, where MED is the minimal erethymal (sunburn) dose or the minimum quantity of radiant energy needed to produce the first detectable reddening of the skin[25] (22 ± 2 hours after exposure[26]). MED ranges from about 300 Jm^2 for 'burner' (fair) types of skins, to about 1000 Jm^2 for naturally black skins.

Both UPF and SPF provide a measure of a fabric's sun screening power, and indicate how much longer a person covered in the fabric can stay in the sun without skin reddening compared to an unprotected person. If the UPF and SPF have the same value, it indicates similar protection.[25] By definition, the UPF value represents the ratio of the minimum dose of UV radiation which leads to reddening of the protected skin to the minimum dose of radiation of the unprotected skin.[27] The SPF or UPF is simply stated as the ratio between the time a protected skin takes to redden to that taken by the unprotected skin to redden. For example, if a person who is exposed for only 9 minutes to strong solar radiation before reddening takes place, wears clothing with a UPF of 40, then the person can be exposed to the same intensity of sun for 40 × 9 minutes (i.e. six hours) before reddening of the skin will occur. UPF provides a scale for assessing the sun's (UV) protection of fabrics, and was first introduced in Australia for textiles. The above provide inverse measures of the transmission of UV rays by the various products calculated as follows:[28]

$$\text{SPF or UPF} = \frac{100}{\%UV\,Transmission} = \frac{100}{100 - \%UV\,Shade} \quad [12.1]$$

Thus, for example, a 75% shade-rated fabric would have an SPF of 4,[28] and, by definition, a person who would normally burn in say 30 minutes of exposure to the sun would burn only in two hours (4 × 30 min) if covered by such a fabric.

Two methods, namely *in vivo* (essentially involving human beings) and *in vitro* (essentially involving instrument assessment), are generally used to measure SPF and UPF, the *in vitro* method generally producing slightly higher values than the *in vivo*[29,30] when measured on the same fabric. The best agreement is when the *in vivo* method measurements are made with the fabric 2 mm from the skin.[29] The *in vivo* method, in principle, involves subjecting a number of human subjects whose skin is covered by the test fabric (e.g. 2 mm away from the skin[30]) to light having a spectrum similar (identical) to that of the sun. It is highly time-consuming and not very suitable for routine measurement of fabrics. The *in vitro* method, in principle, involves the measurement of the diffuse and direct spectral transmittance of the fabric when exposed to UV radiation using spectrophotometers equipped with an integrating sphere,[8,14,28,31] this being the preferred method (wavelength from 290 to 400 nm generally being covered). In both cases the critical amount of 'irradiation' to cause skin reddening (erythema) ultimately forms the basis of the values generated.[8] From these results, the erythemal effectiveness, the reciprocal of the critical dose of a given wavelength, is determined. The *in vitro* values are regarded as more reliable than the *in vivo* values, since an artificial light source never perfectly matches the sunlight spectrum, and small discrepancies can have a significant effect. The UPF is generally calculated from the ratio of the average UV radiation transmitted through air to the average transmitted through the fabric,[32] using a spectrophotometer equipped with an integrating sphere for measurement, and weighted according to skin sensitivity to the different wavelengths. The SPF (or UPF) can be calculated as follows:[32]

$$\text{UPF} = \frac{ED}{EDm} = \frac{\sum_{280/290nm}^{400nm} E_\lambda S_\lambda \Delta\lambda}{\sum_{280/290nm}^{400nm} E_\lambda S_\lambda T_\lambda \Delta\lambda} \quad [12.2]$$

where: S_λ = Spectral irradiation ($Wm^2.nm^{-1}$) of the skin in UV region or solar spectral irradiation (to be obtained from AS/NZ Standard 26 or solar spectra, such as IE 85)

ED = Erythemal dose
EDm = Minimum erythemal dose
E_λ = Relative erythemal spectral effectiveness or erythema action spectrum (CIE)
T_λ = Spectral transmittance of the fabric
$\Delta\lambda$ = Increment relating to wavelength (wavelength step = 1 nm)
λ = Wavelength intervals in nm (e.g. 5 nm)

The following statistical correction is applied to arrive at the UPF of the fabric.[32]

$$\text{UPF} = \overline{UPF} - t_{\alpha/2}, N - 1\frac{\sigma}{\sqrt{\text{N}}} \quad [12.3]$$

where:

$\overline{UPF}$ = the mean measured UPF
$t_{\alpha/2}, N - 1$ = the t variate

where:

$\alpha = 0.005$
σ = the standard deviation of the mean UPF

Therefore, factors such as the related intensity and erythemal dose/damage of the different UV wavelengths reaching the earth and solar spectral irradiance, are taken into consideration in calculating the UPF, the UPF varying from 5 to 500+ for summer weight textiles. The UPF values are generally rounded down to the nearest multiple of 5 (e.g. a UPF of 39 becomes 35).[33]

To obtain reliable results, it is necessary to measure each colour in turn of a multi-coloured fabric, and also representative samples, particularly where the fabric structure (thickness, porosity, etc.) varies along and/or across the fabric, including fabrics containing fancy effects. UPF measurement of textiles can produce erroneous results if the textile fluoresces.

The UPF values may be classified according to Table 12.4[32] or Table 12.5.[8] Measured UPF values[30] for 'summer weight' textiles ranged between 5+ and 500+, although values higher than 50+ are normally not mentioned, simply being indicated as 50+.

12.2.1 Test methods and standards

The following test methods and standards[8] are available for evaluating the protection to UV (UPF and SPF) offered by fabrics[8] (see also a detailed discussion by Hatch[34,35]):

Table 12.4 UPF Classification System: AS/NZ 4399: 1996 and ASTM D6603-2000. Source: Originally published in Algaba, I. and Riva, A., 'Influence of fiber type and fabric porosity on the UPF of summer fabrics', *AATCC Review*, Vol. 4, No. 2, 2004, pp. 26–31; reprinted with permission from AATCC, *www.aatcc.org*, copyright holder[32]

UPF Classification System			
UPF Range	UVR Protection Category	Effective UVR transmission (%)	UPF Ratings
15–24	Good	6.7 to 4.2	15, 20
25–39	Very good	4.1 to 2.6	25, 30, 35
40–50, 50+	Excellent	≤2.5	40, 45, 50, 50+

Table 12.5 Fabric labelling requirements of ASTM D6603: Standard Guide for Labelling. Source: Pearson and Mullen, 2003[8]

UPF Rating	Category	Allowable UPF rating for label	UV Blocked* (approx. %)
15–24	Good protection	15 and 20	93.3–95.8
25–39	Very good protection	25, 30 and 35	96.0–97.4
40 or higher	Excellent protection	40, 45, and 50+	97.5–98.0

*For labelling purposes, the actual percentage for the product should be used

- AS/NZS 4399:1996 Sun Protective Clothing: Evaluation and Classification. Measures UPF ratings on dry untensioned fabrics with a spectrophotometer to determine UV transmission levels between 290 and 400 nm, using a solar spectrum measured in Melbourne.[36] Garments made from fabrics with a rating higher than 50 are labelled UPF 50+. At least 4 specimens must be tested, more if the fabric is not uniform, and from the most open areas if the openness of the fabric varies.
- BS 7914:1998 Method of Test for Penetration of Erythemally Weighted Solar UV Radiation Through Clothing Fabrics. Also measures the penetration of UV radiation on dry, untensioned clothing fabric by means of a spectrophotometer.
- BS 7949:1999 Children's Clothing: Requirements for Protection Against Erythemally Weighted Solar Ultraviolet Radiation. This specifies garments as well as fabrics; a maximum penetration of 2.5% is allowed. BS 7949 covers the requirements for children's sun protective clothing,

specifying the area to be covered by the clothing and maximum penetration of solar UV allowed, which is 2.5%, equivalent to a UPF of 40,[19] tested in the dry and relaxed state. A UPF value of more than 35 is stated[37] to be safe, although 50 would probably be necessary for persons with a fair skin. An SPF greater than 40 was required for clothing worn by persons officiating at the 2000 Sydney Olympic Games. As UV protection can be reduced when the fabric is wet or stretched, these factors need to be considered during testing and use.

- UV Standard 801:1999 General and Special Conditions. This is issued by the International Testing Association for Applied UV Protection, and this is said[8] to employ a more rigorous procedure than the above tests. Measurement of UV protection is determined using the erythemal effectiveness and irradiance spectrum as in AS/NZS 4399:1996. Fabrics are tested new and again after abrasion and after washing and dry cleaning in stretched and stretched and moistened states. Certified manufacturers must guarantee that all products conform to the standard.
- BS EN 13758-1:2002 Textiles, Solar UV Protective Properties, Part 1. Methods of Test for Apparel Fabrics. The standard describes a method for determining the erythemally weighted UV radiation transmittance of apparel fabrics to assess their solar UV protective properties, also recognising the effects of wear and usage, particularly stretching and wetting, on UV protection (also DIN ENISO 13758).
- BS EN 13758-2:2003 Textiles Solar UV Protective Properties. Part 2: Classification and Marketing of Apparel. This provides guidelines and proposes minimum requirements for the UV-permeability and skin coverage of clothing (e.g. T-shirts, swim-wear and ski-wear), to give reasonable protection for an average person exposed to the sun in Europe. To comply with the standard, a UFP of 30+ (40+) is necessary, the effect of wetting and stretching being recognised.
- AATCC Test Method 183–2002 Transmittance or Blocking of Erythemally Weighted Ultraviolet Radiation Through Fabrics. This describes a test to determine the UV radiation blocked or transmitted by textile fabrics to be used for UV protection, the UPF ratings of the tested fabrics being determined. It uses the solar spectrum measured in Albuquerque.[36] The fabrics are given domestic washings and dryings, exposed to simulated sunlight for a specified time and, in the case of swimwear, exposed to chlorine water for a specified time before being tested. The tested fabric should be labelled according to ASTM D6603 Standard Guide for Labelling of UV-Protective Textiles (see Table 12.5[8]). The UPF rating and classification are similar to those contained in AS/NZS 4399. See also ASTM D6544 for preparing the samples for UPF measurement.
- Bohringer *et al.*[24] gave a classification scheme for summer clothes.

Table 12.6 Some typical UPF values. Source: Beringer, 2007[38]

Ultraviolet Protection Factor	
UV Protection	UV or SPF Protection Factor
UV protective clothing (acc. to UV Standard 801)	20–80
Tightly woven cotton clothing (acc. to UV Standard 801)	Approx. 20
Sunscreen when applied correctly (SPF)	0–30
Lightly woven cotton clothing (acc. to UV Standard 801)	Approx. 10
Shade under a tree	Approx. 5–15
Shade under a sunshade (without special UV protection)	Approx. 5

It has been recommended[8] that, ideally, the test method is such that the UPF rating is determined with a wet, stretched, abraded fabric that has been washed and exposed for a significant amount of time to light, and that the UPF rating so obtained appears on the garment label. Measuring a fabric in a stretched state (e.g. 10% stretch) is particularly appropriate for tight fitting stretch garments.

Table 12.6 gives 'typical' UPF values.[38] To achieve an SPF of 40+, a fabric with a porosity of 1 to 2% is generally required.

It should be noted that the different test methods can produce different UPF values for the same fabric, it being stated[36] that a UV-801 rating of 20 may provide better protection than one of 40+ of AS/NZS4399. The Hohenstein Institute (Germany) has introduced a new label which informs consumers and retailers of the UPF of awnings and sunshades. It is based on UV Standard 801.

12.3 Effects of fibre properties

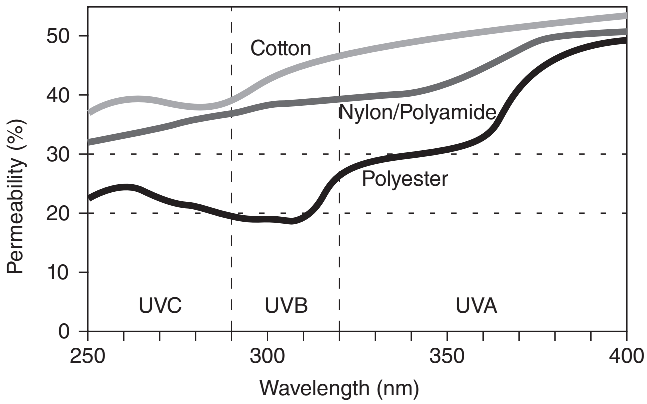
The role of fibre properties in the degree of UV protection offered by the fabric to the body can be understood by referring to Fig. 12.5. Essentially, the degree of protection provided by the fibre is determined by the 'transparency' of the fibre to the harmful components of the UV spectrum, largely UVB, but also UVA. This, in turn, would be dependent upon the following factors:

- Fibre chemical structure and type.
- Fibre colour (natural and/or created pigment or dye).
- Chemical treatment and presence of chemical compounds in or on the fibre, for example:

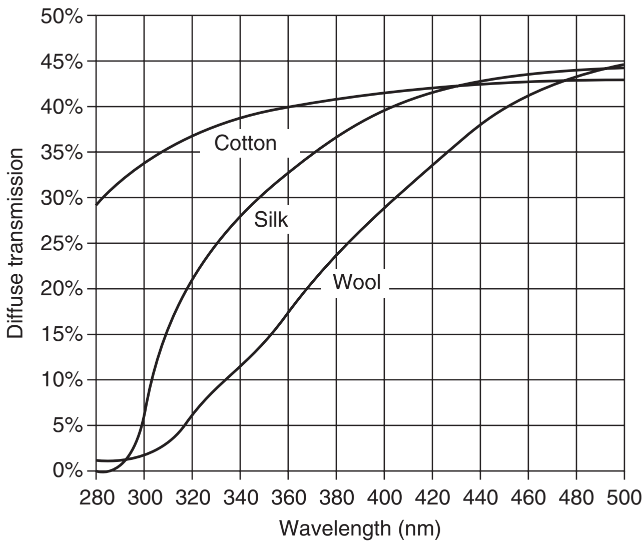
  - Delustrant (e.g. titanium dioxide)
  - Dye or pigment (type and depth)
  - Resin
  - UV absorbers and blockers
- Fibre cross-sectional size and shape, e.g. octagonal shape better than round.
- Natural waxes, pectins, lignins and pigments on and/or in natural fibres, particularly unscoured and (unbleached) such as cotton, hemp, jute and flax, generally also provide improved UV protection. Applying lignins to linen fabrics also improves their UV protection.[6]
- Fibre moisture content, as it relates to swelling and possibly any changes in fibre structure which could affect UV absorption. Therefore, for fibres which absorb moisture readily and swell, such as cotton, wool and viscose, the swelling effect will be much greater than for fibres, such as polyester, which neither absorb moisture, nor swell.

12.3.1 UV protection of various fibres

- Undyed cotton, silk and nylon are fairly transparent to UV,[12] with silk more absorbent than cotton but less than wool,[14,39] cellulose polymer transmitting most UVA and UVB radiation.[32] Nevertheless, the UV protection of cotton and other cellulosic fibres can be improved by various chemical treatments, including pigments, dyes and optical brightening agents. Cotton has a UPF rating significantly lower (particularly around 300 nm) than that of wool, polyester, and modal fibres,[40] with scouring and bleaching in particular, reducing it considerably[41] due to the removal of natural waxes, pectins and pigments which absorb UV. Naturally pigmented cotton has a higher UPF rating than bleached cotton. Wool has fairly high UV absorption capacity[5] over the full range of wavelengths,[1] due to several UV-absorbing chromophores present in the form of aromatic amino acid residues.[16] Wool absorbs strongly in the 280 to 400 nm range, and even far beyond 400 nm.[14,39] It has been estimated[16] that a single wool fibre could absorb up to 60–90% of UVB and 25–40% UVA. Polyester absorbs more UV than cotton, acrylic and polyamide fibres,[14,27] with aliphatic polyamides relatively more permeable and less effective (over the whole wavelength range)[1] than aromatic polyamides.[14] The presence of aromatic groups enhances UV absorption, as is the case with polyester. Polyester fibres have a relatively high absorption of UVB, not transmitting any wavelengths shorter than 310 nm,[42] and also of UVA if it contains a delustrant (e.g. titanium dioxide). The UV absorption properties of various fibres have been compared (Figures 12.6 and 12.7[12,27,28,43] and Table 12.7[44]).



12.6 Ultraviolet permeability of cotton, polyester and nylon. Source: Anon., 1995[27]



12.7 Diffuse transmission spectra of cotton (poplin III), wool (test fabric) and silk (crepe) fabrics measured. Source: Reinert *et al.*, 1996[5]

- The relatively low SPF of acrylic fibres may be attributed to the di-polarisation of the nitrile groups.[14]
- Micro-fibres (i.e. very fine fibres) have some advantage, all other factors being constant.
- Certain man-made fibre manufacturers have developed UV-shielding/blocking/absorbent and resistant fibres,[8] including viscose and modal, incorporating, for example, pigments such as TiO_2.

Table 12.7 UV transmittance of various materials. Source: Anon., 1992[44]

UV Transmittance of Various Materials[44]		
Fibre	UV Transmittance (%)	
	UVA	UVB
Regular polyester	22.3	4.5
Nylon	43.2	36.3
Cotton	35.7	31.5
Rayon	38.7	35.0

12.4 Effects of yarn properties

The main role which the yarn plays in determining the UV protection of fabrics, ignoring the effect of the fibre *per se* or of any chemical treatments, relates to its physical (dimensional) parameters, notably diameter/cross-section, bulk and hairiness. In essence, the greater the ratio of the surface area covered by the yarn, including the yarn surface fibres (hairs), to the total area covered by the fabric, and the greater the yarn thickness (bulk or cross-section) particularly in the direction of the incident light, the greater the protection. Therefore, the greater the yarn bulk and surface hairs, the greater will be the UV protection. From this it follows that textured yarns provide better UV cover than flat filament yarns, with staple fibre yarns being better still. Therefore, any fibre, spinning or yarn parameter which increases yarn bulk (diameter) and/or hairiness will increase the UPF. Thus, for example, bulking (or texturing) and/or brushing the yarn, either before or after fabric formation, should have a beneficial effect on UV protection. It follows that spinning systems or conditions which produce clean, smooth or compact yarns will generally not be ideal from the point of view of UV protection, unless some mechanical or other treatment is applied to the yarn, preferably when in fabric form, to increase its hairiness and/or bulk. The ability of the yarn to flatten along or parallel to the plane of the fabric, thereby covering a greater surface area, will also beneficially affect UV protection, although there could be some trade-off in terms of a reduced amount of material (e.g. number of fibres) through which the light travels.

12.5 Effects of fabric structure and properties

The extent to which a textile fabric absorbs or transmits UV depends upon the fibre properties (Section 12.3), fabric construction and finish. Figure

12.5[5] illustrates the key factors that determine a textile substrate's permeability to, and absorption of, UV radiation. The radiation that passes through a textile fabric consists of two components, the first component being that which passes partially or totally through the fibres and the other component that which passes through the pores (holes or openings) in the fabric; both components can suffer reflection and refraction within the fabric structure. The most significant effect of the fabric on UV protection is that related to the fabric openness (porosity) to UV (i.e. the amount of 'cover' offered by the fabric against UV). This in turn would depend upon:

- Fabric 'optical' cover factor or tightness (i.e. ratio covered by fibre/yarn to total fabric area) or porosity. Gorenšek *et al.*[41] calculated the optical cover factor (CF) on the basis of the total void area as follows: CF (%) = 100 – total void area (%); a maximum figure of 1.5 to 2% is recommended for the void area.
- Fabric thickness, this being based upon the assumption that the fibres only partly absorb UV radiation, and therefore the thicker (or more numerous) the layers of fibres (i.e. fabric), the greater the absorption and therefore protection. Furthermore, the thicker the fabric, the greater the probability that incident UV will encounter one or more fibres along its path. For maximum protection, the 'fabric material/substance' (i.e. fibres, together with any chemicals on or in them) must be totally opaque to UV, and the fabric cover (measured, for example, by image analysis) should be such that no UV can pass directly, unhindered by fibres, through the fabric (i.e. the fabric porosity to UV should be zero). For a fabric in which the fibres/yarns are totally opaque to UV, the UPF can be calculated as follows:

$$\mathrm{UFP} = \frac{100}{100 - \mathit{FabricCoverFactor}} \qquad [12.4]$$

Care must be taken not to adversely affect the fabric comfort properties by fabric (or fibre) coating or chemical treatment. A key factor would be to create a fabric porous structure which allows movement of air and perspiration, but protects against UV radiation, i.e. the fabric should ideally not have apertures or pores which allow sunlight to pass through unhindered (i.e. without encountering one or more fibres along the way). This could be achieved, for example, by sanding[45] the fabric surface to loosen or sever fibres which can then cover the pores, but without affecting breathability and associated comfort. Although abrasion and wear generally cause a decrease in UPF, they can also cause an increase in those cases where they produce a pile, i.e. increase surface fibres or hairiness.[45]

A balance must be maintained between UV protection and comfort, since the lower the fabric porosity (i.e. the greater the fabric cover factor) and the thicker the fabric, the lower the comfort under hot summer conditions, generally. The ultimate or ideal fabric would be one where there are no apertures or voids in the fabric which allow UV rays to pass directly (unhindered) through the fabric to the skin (i.e. without encountering any fibres along its path) and where the number of 'fibre layers' at any point in the fabric are so arranged and are sufficient to absorb all the incident, as well as internally reflected, UV rays. For comfort, such a fabric should allow air and moisture to pass (meander) easily through the fabric structure to the outside, thereby ensuring both comfort to the wearer (i.e. fabric breathability) and good UV protection. Such a fabric would most probably be a non-woven or a brushed/sanded/hairy woven or knitted fabric.

Algaba and Riva[32] found that the following type of reciprocal relationship between UPF (Y) and fabric cover factor (X) best fitted their results for woven fabrics containing modal and treated modal fibres:

$$1/Y = a + bX \quad [12.5]$$

$$\text{i.e. } Y = \frac{1}{a + bX}$$

Nevertheless, no single expression fitted all fabric types, since there was a highly significant effect of the type of fibre (i.e. cotton, modal or treated modal).

It is generally accepted[5] that for fabrics to provide good UV protection (i.e. high SPF or UPF), they must have a very low porosity (<1 to 1.5%[5,12]), porosity being calculated from the directed transmission and SPF from diffuse transmission measurements.[5] A maximum figure of 2.5% UV transmission is specified (BS 7949)[10] for children's sun protection clothing, this being equivalent to a UPF of 40, and 3% fabric open area is given as a general guideline for fabrics for adults. A fabric cover factor of greater than 93% is required to produce a UPF rating of 15. Above 93%, small increases in cover factor produce relatively large increases in UPF[46,47].

The UV protection of a wet fabric tends to be lower than that of a dry fabric, since water in the interstices of the fabric reduces the scattering effect, ultimately increasing UV transmission,[1] water being less effective than air in scattering UV. It has been reported[8] that most fabrics lose about a third of their sun protective ability when wet. Nevertheless, in some cases water may cause fibre swelling and an increase in fabric cover factor which could offset this effect to some extent. A typical light cotton shirt transmits about 15 to 20% of UV, increasing to 50% when the shirt is wet.[48] Hilfiker *et al.*[39] reported that thin, untreated dry fabrics produced from cotton, silk, polyamide and polyacrylonitrile will exhibit SPFs of between about 3 and 5.

All other factors being constant, a plain weave structure is best. Stretching a fabric will generally decrease its cover factor (i.e. increase its porosity) and its thickness, causing a decrease in its UPF. Any factor or treatment, such as milling, sanding, sueding, etc. which consolidates the fabric structure, increases cover factor, or improves UV absorption of fibre and fabric will improve the UPF. For example, washing can increase the UPF of a cotton T-shirt from 15 to 35.[24]

Special fabric structures, screens and finishes (e.g. sanding, washing) have been developed, specifically with UV protection in mind. Algaba *et al.*[49] have modelled the effect of cellulosic woven fabric parameters on the ultraviolet protection factor.

The effects of dyeing and finishing, and chemical treatments in general, on fabric UPF are covered in the next section (i.e. Section 12.6).

12.6 Effects of dyeing, finishing and other chemical treatments

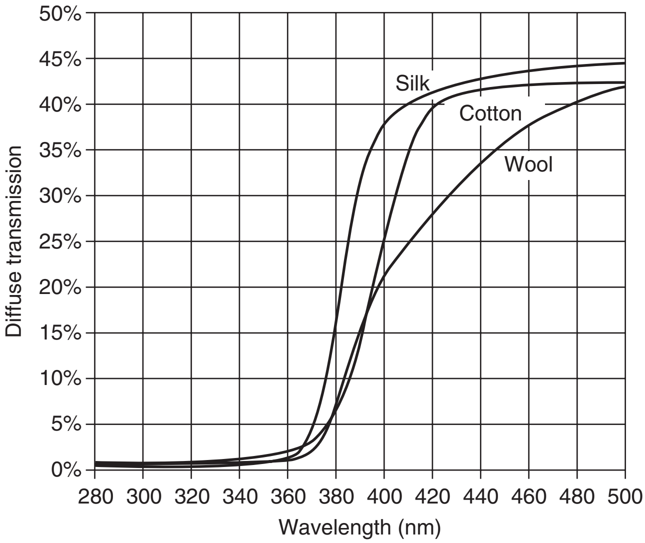
Broadly speaking, dyeing, finishing and other chemical treatments (e.g. fluorescent whitening) can affect the UV protection (UPF) of textiles in the following ways, with the treatment often protecting the textile against UV as well:

- Changing the amount of UV absorbed by the fibre *vis-à-vis* that transmitted by the fibre.
- Changing the amount of UV reflected by the fibre.
- Changing the fabric porosity or compactness (cover factor).
- Coating the fabric (or fibre) with a UV-absorbing compound.

UV blocking agents normally involve particles which block the UV (e.g. pigments etc.) or absorb the UV (mainly aromatic compounds).

Various studies have shown that the following treatments improve the protection against UV offered by a fibre and/or fabric:

- Fabric consolidation (for example felting, shrinking, milling and compaction), by reducing the fabric porosity and also increasing the fabric thickness.
- Dyeing and printing (including pigment dyeing and natural dyes[48,50] and pigments) – particularly to deep depths of shade, with certain dyestuffs having high absorption capacity in the UV region, which depends upon their structure rather than their class.[51–53] Depending upon their chemical structure, the absorption band of virtually all dyes extends into the UV region. The extinction coefficients of these dyes determine their UV absorption capabilities. Dyeing can reduce or even totally block the fibre permeability to UV, colour depth being more important than



12.8 Diffuse transmission spectra of cotton, wool and silk after treatment with UV absorbers. Source: Reinert *et al.*, 1996[5]

colour *per se*.[54] The UV spectra of dye solutions cannot, however, be used to predict the UPF of the dyed fabric.[48]

- Optical or fluorescent brightening agents (OBAs), also those applied in laundering, reduce the UV transparency of textiles by converting part of the UV spectrum into visible light[7,8] and also by absorbing UV. Nevertheless, their effect can be reduced, or even eliminated, when they are applied together with a UV absorber.
- Applying UV (photon) blocking or absorbing agents: UV absorbers, applied either by exhaustion or pad-batch techniques, can improve UV protection[30] (Fig. 12.8[5], compare with Fig. 12.7), such products having chromophore systems[5] that absorb well in the UV region (but minimal in the visible region) and maximise UV absorption of the textile. (Care must, however, be taken when they are applied with fluorescent whitening agents.) They convert the UV energy into heat or some other form of energy. Specific UV absorbers for different fibre types have been developed. It has been concluded[8] that UV-absorbing finishes are effective in reducing UV transmission of fabrics, particularly at wavelengths likely to cause skin damage. UV protective agents (absorbers or blockers) are inorganic substances (usually UV screening or reflecting agents, such as TiO_2 and ZnO) or organic substances (usually absorbents) capable of selectively absorbing UV (280–400 nm), and need to be UV stable and

must dissipate the absorbed energy (e.g. in the form of heat), so that it has no adverse effect on fibre or dye.[8] To be permanent, UV absorbers should preferably be bonded to the fibre by covalent bonding.[24] The most important chemical classes of UV absorbers include: O-hydroxybenzophenone, O-hydroxyphenyl-benzotriazole and O-hydroxyphenyl-triazine. Inorganic UV blockers (scattering agents), also sometimes referred to as 'ceramics', such as TiO_2, ZnO, SiO_2 and Al_2O_3, also nanosilver, are often preferred to organic ones because they are non-toxic and chemically stable to high temperatures and UV.[56] Applied as a delustrant (e.g. during synthetic fibre polymerisation), TiO_2 (Reference 12) reduces transmitted UV due to it reflecting and scattering UV radiation.[57] UV blockers, such as titanium oxide and zinc oxide, absorb and scatter both UVA and UVB. The optimum particle size for UV radiation between 200 and 400 nm is predicted to be between 20 and 40 nm,[58] thus nano-sized particles are considered more effective[56–59] – for example, nano finishing treatments involving sol-gel (nanosol) processes[60–64] have been found to be effective. Certain UV absorbers lose their effectiveness on prolonged exposure to light.[8] Some can also inhibit fabric shrinkage, thereby counteracting the beneficial effect which such shrinkage has on porosity (cover factor).[8] UV absorbers must be stable, durable, wash-fast, non-toxic, non-irritant and should absorb both UVA and UVB.
- Bleaching of plant fibres removes their natural pigments, pectins, waxes etc. which act as UV absorbers, thereby reducing UPF values.[65]
- Coating fabrics with resins and other polymers can absorb UV.[8,30]
- Certain natural dyes exhibit good UV absorption when applied to cotton, this being enhanced when mordants are used.[48]
- UV-absorbing ceramics can be blended with polymer to produce UV protective fibres.[37] UV protective treatments need to be wash-fast and not have a reaction with the skin.
- Applying nano-scale wool powder to cotton fabric[66] can be effective, possibly due to fibre swelling, blocking of the fibre surface pores, or interaction of the UV with the nano-wool (or a combination of these).
- Applying to wool a compound that consists of a large amount of tiny pores that hold and trap photochromic dye, which changes colour when exposed to UV light,[67] is another method put forward.

Holme[31,68] has reviewed UV protective agents in terms of their effects, uses, characteristics, chemical bases, finishes available and application. It should be emphasised, however, that the UPF ratings of high porosity fabrics is hardly improved by finishes or dyeing. Furthermore, any UV protective treatments applied to textiles must not deleteriously affect their desirable properties, for example handle and comfort, and must also not be harmful to human beings.

It should be noted[69] that other finishing treatments, as well as the order of their application, could affect the efficiency of UV protective agents. Various manufacturers of dyes and other textile chemicals (e.g. BASF, Ciba®, etc.) have developed treatments to improve the UV protection of various textile fibres.

12.7 Sources of further information and advice

A number of references are recommended for further reading: 1, 6, 8, 9, 11, 13, 14, 20, 24, 26, 30, 31, 40, 43, 55, 65, 70–97.

12.8 Concluding remarks

There can be little doubt that excessive exposure to sunlight, the UV part of the spectrum in particular, represents a serious and increasing health hazard, particularly as the ozone layer in the upper atmosphere is depleted. Three courses are open to humankind to minimise this health hazard: firstly to reduce the time spent outdoors, particularly when and where the sunlight is intense, secondly to wear effective protective sunscreens on all parts of the body exposed to the sun, and thirdly to wear protective clothing, hats, sunglasses, etc. With respect to UV protective clothing, the most important factor is the ratio of the area covered by the fibre/yarn to the total area of the fabric (i.e. the porosity of the fabric). This is followed in importance by the UV absorption effectiveness of the fibres and the presence of effective UV absorbers. When a fabric (or garment) has a high porosity, it is virtually impossible to provide it with adequate UV protective properties, even if UV absorbers and fibres are used with excellent UV absorbency properties, since UV radiation will still be able to pass directly through the pores (apertures) in the fabric without encountering any fibres along its path. The only solution in such a case would be to coat the entire fabric with a UV-absorbing coating, but this could compromise the comfort (breathability) of the fabric. In the final analysis, any part of the body directly exposed to sunlight (UV radiated), also that reflected from surfaces such as water, and not covered by a textile, sunscreen, glasses, hat, etc., will suffer UV damage even if the rest of the body is covered. This has to be taken into consideration, particularly in the case of so-called 'UV protective swimwear' which only covers part, and sometimes only a small part, of the body.

It has been suggested[13] that UVA protection rating should be based on measurement of melanin radical formation in the skin. Biological UV-detector films, which simulate the skin sensitivity to UV (e.g. Biochip) have been used to measure UPF values.[76] A new biological test procedure[96] assesses skin stress and DNA damage following UV exposure, using cultivated human skin cells in which UV-induced DNA damage can be measured directly, in accordance with European directives. In addition, the free radicals generated in the skin by the UV are also measured.

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13

Laundry performance of fabrics and garments

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Abstract: In order to minimise the damage caused by laundering, the proper engineering design of fabrics and garments as well as proper care labels are essential. In this chapter, the effects of the properties and processing parameters of fibre, yarn and fabric, as well as the effects of garment design, on laundry performance are discussed. Test methods and standards for care labelling and evaluating laundry performance of textiles and clothing are also reviewed.

Key words: laundry performance, serviceability of garments, care labelling, colourfastness, appearance retention.

13.1 Introduction

Dust, atmospheric pollution, human soiling matter (e.g. perspiration and natural fats and oils), food stains, accidental soiling, deposits of poor washing techniques, old starch, mildew and static electricity can produce dirty garments. For hygienic and aesthetic reasons, garments need to be washed or cleaned in some manner. In textile terms, 30 to 40 washes or cleaning cycles are considered to constitute the reasonable life expectancy of a laundered garment before wear and tear, or the dictates of fashion, necessitates its replacement. Garments should therefore be able to withstand washing or other methods of cleaning, such as dry-cleaning. However, physical and chemical effects occur during the washing process, especially during the first few washes. The damage caused by washing may be greater than that caused by wear and use. The adverse effects during washing and drying include fabric shrinkage, distortion, changes in handle, and colour fading. For this reason, garments should be able to withstand repeated laundering and maintain their fabric properties and appearance.[1,2] If good laundry performance is therefore to be achieved, then it is important that the garments, including fabric, seams, trimmings, fasteners, etc. are dimensionally stable (i.e. do not distort, shrink, stretch or change in appearance); the dyes and finishes are fast to laundering; the garment does not pill, fuzz, abrade or change in appearance during laundering; and the fabrics, or more specifically the fibres, do not excessively deteriorate in terms of their durability and performance characteristics, such as strength.

To minimise the adverse effects of laundering, proper care labels and strict adherence to care instructions are essential. Together, good laundry performance and adequate labelling go a long way towards ensuring the maintenance of the serviceability of garments during repeated use. In this chapter, the effects of the properties and processing parameters of fibre, yarn and fabric, as well as the effects of garment design, on laundry performance are discussed. Test methods and standards for care labelling and evaluating laundry performance of textiles and clothing are also reviewed.

13.2 Laundering

Laundering uses a solvent (generally water), a detergent, and mechanical action to remove soil. The basic process commonly involves pre-spotting to remove stains, washing to remove soil, extraction to remove water, and drying to remove excess moisture. Some garments require pressing or ironing to remove wrinkles and provide a crisp finish to the garment. Laundering is performed at home, in self-service commercial or coin-operated laundries and in professional service laundries. The equipment and procedures for home laundering and coin-operated laundering are very similar. The process and chemicals used in professional service laundering are somewhat different, but the principles of the cleaning process remain the same.[3] Most countries dry clothes mainly by hanging them in the open air and in sunlight, but in the developed countries, drying is increasingly being done in tumble dryers, where softeners are often applied.[1] Therefore, in essence, if a garment is to have acceptable laundering performance, it should be able to withstand the mechanical, chemical and heat actions which occur during the number and type of laundering processes (i.e. washing, drying, ironing/pressing, etc.) typical and specified for such a garment.

13.3 Care labels

The care label is defined as a label or other affixed instructions that indicate how a product should be treated. A care label shows a number of pictorial symbols that give directions for restoring or 'renewing' the consumer textile product. The symbols portray care instructions which are directions that describe practices which should treat a product without adverse effects, and warn against any action which may be used and which could harm the item.[4,5]

13.4 Effects of fibre composition, structure and properties

13.4.1 Fibre composition

Plant/cellulosic fibres

Cellulose fibres, such as cotton or rayon, are highly resistant to heat, hence they can withstand hot water washing, a hot clothes dryer setting, and even ironing at high temperatures.[6]

Cotton

Normally, most cotton fabrics can be safely washed, but finishes and dyes can alter their laundry performance so it is wise to study care labels carefully before laundering. Most cotton and cotton-blend fabrics are machine washable and may be dried in a dryer. Easy-care fabrics require some special attention if ironing is to be avoided. The usual precautions are to avoid overloading the washing machine. Cotton can withstand high (hot) wash temperatures, but many cotton fabrics retain their colour better if washed at cooler temperatures. It is therefore advisable to use warm rather than hot water, and a cool rinse, and to promptly remove fabrics from the machine. Pre-treatment of stains and soils will greatly help in their removal, especially oily stains on collars and cuffs and any oily spots. It is advisable to avoid over-drying cotton fabrics and remove them from the dryer promptly to prevent wrinkles and shrinkage. Cotton fabrics can be bleached safely with chlorine bleaches without seriously damaging the cotton fibre. Nevertheless, undiluted bleach poured directly onto the fabric will cause degradation of the garment; therefore it is better to follow the manufacturer's directions on the use of bleaching agents to ensure the best results.[3,6–9]

Linen

Linen items may be laundered, but following the care instructions is essential because dyes and finishes can alter fibre properties. Hot water, alkali detergent, and properly diluted chlorine bleaches do not damage the fibres. Linen fabric may, however, be difficult to iron. It is usually recommended that it be ironed while still damp or using a steam iron to achieve the maximum crispness and hand that are preferred for the garment/fabric. Linen calls for a hot (top setting), dry iron, and must be ironed until completely dry, or else wrinkles may form. To avoid shine, as with dark linens, for example, iron on the technical back, while if lustre (shine) is desired, iron on the technical face. Table linens and other linen items stored for long periods should be stored flat or rolled to prevent cracking and breaking of the fibre. Linen is a fairly brittle fibre, and older linen fabrics that have been folded repeatedly in the same place may break along the fold or crease line. Breakage of yarns along crease lines in garments has been noted as well.[3,6,7]

Animal/protein fibres

Heat frequently has a harshening and drying effect on wool, silk, leather, and fur.

Wool

One of wool's negative properties relates to the difficulties often encountered during its laundering. Care must be taken in washing wool, even those labelled as washable. Wool's scale structure, and associated directional frictional effect experienced when subjected to mechanical action in a suitable medium (solvent) during laundering, can produce felting shrinkage, which is irreversible.[10] Furthermore, similar to our hair, wool is weaker when wet (about 25% weaker), but the loss is temporary. Therefore, it needs careful handling in washing, even if it has had an anti-felt treatment. It should never be pulled (extended) or wrung while wet, but should rather be lifted and squeezed. Carefully followed label instructions ensure the best results in laundering wool and wool blends. In general, warm or cold water is preferred, and agitation should be kept to a minimum for preventing felting. It is advisable to hand-wash unless it has had a very effective shrink-resist treatment. To dry a wool fabric or garment, roll it in a towel, squeeze gently to remove as much moisture as possible, then spread it out to its original shape on a towel or heavy cardboard. Alkali can yellow wool; hence, a mild, neutral detergent or soap is recommended. Some detergents and pre-spotting agents for stain removal contain enzymes to remove blood and other protein-based stains. Such enzymes will degrade wool; hence the labels of detergents and stain removal agents should be studied carefully. Hydrogen peroxide and other commercial non-chlorine bleaches are usually safe, but chlorine bleaches degrade the fibre.[3,6,7]

Silk

Because of the smooth surface of silk, it does not attract or retain dirt readily. However, in order to avoid the tendering action of perspiration, a silk garment should be cleaned soon after it is worn. Silk also loses strength when wet, but it is much stronger than wool. Dry-cleaning is usually specified on labels as the preferred method of care for silk garments. Dry-cleaning is preferable for weighted silks, but wild-silk and spun-silk fabrics may be washed. Therefore, reading the care label is important before washing a silk fabric/garment. To ensure that silk garments receive the optimum professional care, the dry-cleaner or launderer should be informed that they are made of silk. Contrary to popular belief, silk may be washed, although care should be taken in handling the fabric. The fibre does not have scales, so it is not susceptible to felting like wool. Following the manufacturer's recommendations on care labels is advisable because some dyes may not be stable to washing. Use warm or cold water and a mild detergent. Pre-treat stains before laundering, but avoid the use of pre-treatments that may contain protein reactive enzymes. If bleach is required, use a non-chlorine bleach. Avoid wringing the garment, and rinse it thoroughly to remove all detergents. The best method of extracting water from silk garments is to wrap them in an absorbent towel and then squeeze gently. Silk should not be dried in the sun, nor should it be tumble dried unless the label specifically states that such treatment is acceptable. Iron or press silk with medium to low temperatures; steam pressing with a press cloth is recommended to avoid producing shiny spots on the fabric. Silk and many of the dyes used on silk are sensitive to perspiration as well as to the aluminium chloride present in many deodorants and antiperspirants. Do not allow wet antiperspirants to come in contact with silk garments. If perspiration is a serious problem, protective dress shields can be worn.[3,7]

Suede and leather

Unlike fabric, leather has natural oils that protect and preserve the appearance and life of a garment. Removing these oils reduces the hide's suppleness. The chemicals used to clean leather frequently remove the natural oils as well as the undesired dirt. These oils must be restored by a professional leather cleaner. Since stains that are old and set cannot always be removed safely, any stains need to be pointed out to a professional cleaner. Dust and dirt should be wiped away with a soft, water dampened sponge or cloth. If suede or leather gets wet, let it dry naturally and away from heat or direct sunlight, hanging the garment so that it does not touch other clothing. Press, using heavy paper as a 'press cloth', at low heat without steam, and press lightly on the outside. Make sure the garment is dry before ironing and that the iron is continually moved across the surface of the garment when pressing. In order to prevent severe soiling, water and stain repellents should be sprayed onto suede or leather when new, although they will likely be less effective on suede. If the garment has been pre-treated, consult the manufacturer's recommended care instructions.[6,11–13]

Synthetic fibres

Nylon and polyester, being thermoplastic, are likely to melt under a hot iron, but will withstand hot water or a hot (cotton setting) home dryer. Ironing or pressing any thermoplastic fibre must be done with care (this includes all major synthetic fibres except those of reconstituted cellulose, such as rayon). Reading the care instructions for synthetic fabrics is especially important.[3,6]

Polyester

Polyester is usually advertised as 'the easy-care fibre'. Because the fibres generally are smooth and have a very low absorbency, many stains lie on the surface and can easily be removed by machine washing and drying, and also without shrinkage as a result of washing. Oily stains may present a problem, but pre-treating with one of the prewash sprays that contain solvents or with concentrated liquid detergent helps to remove oily stains. Adequate detergent and hot water help remove body soils. Fabrics of spun polyester yarn that have a tendency to pill should be washed gently and brushed with a soft brush while drying in order to disentangle the fibre ends and straighten them out. Follow care instructions for the best results. As with most thermoplastic fibres, better performance is obtained if care is taken to avoid wrinkling the fabric when it is hot. When ironing polyester, it is best to use low to medium heat. When polyester fibres became popular, the manufacturers of washers and dryers developed special machine cycles that would improve the performance of permanent-press fabrics containing polyester fibres. In most machines, the permanent-press cycle includes a cool-down rinse which reduces the temperature of the fabric before it goes into a deep-spin cycle to remove excess water. Dryers also have a cool-down cycle to reduce the heat of the fabrics before the dryer stops and the fabrics fall to the bottom of the machine. For the best performance, it is sensible to remove fabrics from the machine as soon as the cycle is completed. Less energy, meaning a shorter drying time, is needed to remove water from polyester fibres, because the fibres absorb very little moisture.[3,7]

Acetate

The smoothness of acetate fibres helps to produce hygienic fabrics that shed dirt and wash easily. However, acetate loses strength temporarily when wet, so it must be handled gently during washing. Avoid wringing or twisting acetate fabrics when they are wet, because the resulting wrinkles and creases are difficult to remove. Acetate is thermoplastic, and therefore the water temperature and ironing temperature should be carefully controlled.

Some problems still exist with colourfastness of disperse-dyed acetates. Some dyes are sensitive to gas-fume fading; hue changes occur in fabrics exposed to atmospheric contaminants, such as oxides of nitrogen and ozone. The problems are more prevalent in areas with high concentrations of atmospheric contaminants. In homes with gas heating, it is advisable to make sure that acetate decorative fabrics have been treated with inhibitors to prevent fume fading.[3,7]

Rayon

Rayon is similar to cotton in its care requirements. Requirements for washing or dry-cleaning garments will depend on the dyes and finishes used on the fabric and the construction of the garment. Detergents and bleaches that are safe for use on cotton are also safe for rayon. However, rayon loses strength temporarily when wet, so it must be handled with care during washing. White rayon remains white after washing and therefore bleaching can be avoided. Fabrics that have not been treated with crease-resistant or easy-care finishes require careful ironing to remove wrinkles.[3,7]

Nylon

Nylon is quick and easy to wash, dries rapidly and requires very little ironing.[10] Because of the smooth surface of nylon fibre, dirt and stains are often removed merely by using a damp cloth.[7] The first drip-dry, non-iron clothing was made of nylon. Hot water does not harm the fibre, but wrinkles and untidiness are minimised by the use of warm or cold water. Spun nylon has a tendency to pill, or form balls, on the surface of the fabric. To minimise this, the fabric/garment should not be rubbed during washing but should be washed gently, preferably by hand. Brushing with a soft brush will reduce pilling. Tumble drying produces a smoother and softer fabric than drip-drying. As with all thermoplastic fibres, prompt removal of garments from the dryer reduces the number of wrinkles that must be removed by pressing. An iron that is too hot will melt the fibre, glaze (scorch) the surface of the fabric, or actually make a hole in the fabric. Press the fabric carefully to avoid ironing wrinkles into it. Once heat-set wrinkles are put into a fabric, it is difficult to remove them, so care should also be taken to avoid squeezing or compressing the fabric during laundering at high temperatures. A major problem in laundering and dry-cleaning nylon fabrics is their tendency to scavenge stains from other fabrics. Pre-spotting fabrics and laundering similar colours together minimise the problem. Most bleaches will not remove the grey colouration that builds up on white nylon lingerie after repeated laundering, but there are special reducing bleaches on the market that are designed to whiten nylon. Hot water, adequate detergent, and thorough rinsing are helpful in controlling the buildup. Special fluorescent whitening agents have been added to many white nylons to help them maintain their pristine appearance. It is sensible to follow the care labels on such fabrics carefully.[3,7]

Acrylic and modacrylic

Fabrics made from acrylic fibres may be laundered or dry-cleaned. Tumble-drying acrylic knits improves their handle, and most of the high-bulk fibres are labelled to indicate that the fabrics are made fluffier by machine drying. If ironing is necessary, it is advisable to use a low iron setting.[3,7,9]

Aramid

The care of aramid fibres is the same as that of nylons; they may be machine washed and dried. In some cases, functional finishes have been used, and there may be special care instructions for some protective clothing.[3]

Olefin (e.g. polypropylene)

Olefin fibres are easy to maintain if careful attention is paid to lower heat settings in washing, drying and ironing. Very hot water and high-temperature drying may shrink improperly processed fibres. Prompt attention to oily stains is necessary. It is advisable to follow care label instructions carefully for the best performance.[3]

Spandex

Spandex is always blended with other fibres. Read care labels carefully before washing. When handling Spandex garments, wash with a detergent in warm water. Avoid using chlorine bleach as it can lead to discolouration and eventual breakage of Spandex fibre.[9]

Fibre blends

Ideally, blend-fabrics with a small percentage of one fibre should be laundered at the recommended temperature and cycle for the dominant fibre in the blend. According to a study of the Clothes Care Research Center (CCRC), when comparing 100% cotton knit and comfort stretch knit fabrics (92% cotton, 8% Spandex), the dimensional change, smoothness, colour change and stretch are not significantly different, and hence it is recommended that washing and drying instructions be based on the dominant fibre in the blend.[14] An exception to this rule could be when unshrink-proofed wool is present, even at levels below 50%.

Table 13.1 Principal dry and wet glass transition temperatures for common fibres and their recommended wash temperature. Source: Bishop, 1995[1]

	Tg (°C) in dry air	Tg (°C) in water	Recommended wash temperature range
Cotton	None before thermal decomposition at ~200°C	<0	All temperatures
Viscose rayon	None before thermal decomposition at ~200°C	<0	Up to 60°C
Cellulose triacetate	~180	~90	Up to 40°C
Cellulose diacetate	~180	~60	Up to 40°C
Polyester	~100	~85	Up to 60°C
Nylon 6	~56	Close to 0	Up to 60°C
Nylon 6.6	~62	Close to 0	Up to 60°C
Acrylics	70–90	50–70	Up to 40°C
Wool	None before thermal degradation	<0	Up to 40°C

13.4.2 Glass transition temperature of fibres

Garments should preferably be washed at a temperature below the glass transition temperature of their constituent fibres so as to avoid excessive fibre swelling and associated shrinkage and creasing. Table 13.1 lists the glass transition temperature (Tg) values of some common fibres in the dry and wet states, and their recommended washing temperatures.[1] For cellulosic (e.g. cotton, viscose) and proteinaceous fibres (e.g. wool, silk), in which the secondary forces between molecules result largely from polar or semipolar interactions such as salt linkages and hydrogen bonds, Tg may be lowered by 200°C or more when the accessible polar sites are hydrated by imbibed water, resulting in the wet Tg being below 0°C. For typical polyamide fibres (e.g. the nylons), a 50–60°C reduction in Tg occurs when wet, attributed to disruption of hydrogen bonding between the amide hydrogen and carbonyl oxygen atoms in adjacent polymer chains, and resulting in the wet Tg being close to 0°C. For these fibres, the recommended wash temperature ranges are above their wet Tg as these fibres are in the rubbery state at all possible wash temperatures. For other types of fibres (e.g. cellulose triacetate, cellulose diacetate and polyester) with wet Tg well above 0°C, the recommended wash temperatures are below the wet Tg.

13.4.3 Fibre properties

Fibre fineness

The finer the fibre is, the greater is the care needed.

Swelling properties

Fibre swelling causes many cellulosic textiles to become 'jammed' in the wet state. This may limit the relaxation that can occur in a single wet treatment, even when considerable mechanical agitation is applied. In woven fabrics in which the wet swollen yarns cannot move readily, fabric buckling or wrinkling may develop as a means of relaxing the 'swelling stresses' in the yarns.[1]

13.5 Effects of sewing thread linear density

After laundering, the strength and efficiency of the seams sewn with coarser sewing threads decreases more than seams sewn with finer threads. This can be explained because relatively coarse threads, due to their greater surface, are susceptible to greater damage than finer threads. However, even after laundering, the strength of seams stitched with coarser threads is higher than that of seams stitched with finer threads.[15]

13.6 Effects of fabric structure and properties

13.6.1 Fabric structure

Fabrics can be manufactured by weaving, knitting or the non-woven process, with many variations in terms of manufacturing methods and processing procedures that will affect the properties of the fabric in different ways. Different fabric constructions will have different properties, even when produced by the same manufacturing method. Woven fabrics normally have better dimensional stability than knitted fabrics. In most cases, tighter fabric constructions lead to better dimensional stability during laundering than looser constructions. The main exception to this rule is if such tighter fabrics are produced in a more distorted shape, on the machine knitting machine in particular. This means that the fabric is further away from its 'minimum energy' or 'fully relaxed state' and will change in dimension during laundering until it reaches that state.

Flat drying of knitted items, such as wool sweaters, is usually recommended to retain the shape of the garment. Removing excess water from wool garments by blotting them with an absorbent towel reduces drying time. In cases where machine drying of a wool fabric is indicated on a label, it is preferable to set dryers at a low temperature.[3]

The looped yarn configuration of knitted fabrics produces a structure that reacts quite differently from woven structures of the same fibre content and yarn dimension. In general, warp knitted fabrics are more stable than weft knitted ones and are less prone to snagging and dimensional instability.

Weft knitted fabrics tend to undergo large changes in dimensions and are often prone to distortion upon repeated laundering. A large number of factors are responsible for causing these undesirable effects in knitted structures; these are all associated with the yarn, knitting, finishing and making-up of the fabrics.[16] Most general care precautions for knitted fabrics and garments are more applicable to weft knitted fabrics than to warp knitted fabrics. Instructions on the care label of any knitted item should be closely followed to ensure maximum performance.

The knitted structure is usually less prone to wrinkling than the woven structure. Knitted garments are often referred to as 'the original easy-care apparel'. Ironing is seldom required, but when 'touch-up' pressing is required, care should be taken not to distort the fabric by pulling on it.

Tumble drying may cause excess shrinkage in some knitted garments. The loops in a weft knitted structure may become distorted during tumble drying: the top of the loop rises above the normal plane of the fabric, and the fabric becomes shorter. According to the research of Anand,[16] and many other workers in the past, dimensional change and distortion occurring after laundering are largely due to alterations in the loop shape of the knitted fabric, rather than to yarn or loop length shrinkage. If the yarn itself has not shrunk, which is generally the case, it is possible to shake and stretch the fabric to reorient the loops and restore the original dimensions of a knitted product. Most consumers have removed a knitted garment from a dryer and noted that it appears to have shrunk, but once the garment is stretched, and put on, it can be worn with no problem. Most of the shrinkage is reversible and the stretchy structure of a knitted fabric probably makes any permanent shrinkage that occurs less noticeable than it would be in a woven fabric. The exception to this is the felting shrinkage which occurs in knitted garments containing unshrinkproofed wool, this shrinkage being largely irreversible.

Spirality, or skewing or twisting, is another form of dimensional change or distortion that can occur in knitted fabrics and garments. The spirality of a weft knitted structure often produces skew in garments. To determine whether a product is skewed, it is advisable to place the leg of a T or L square along a wale in the fabric. If the fabric is not skewed, the other leg of the square will be parallel to a course in the fabric (perpendicular to the wale). It is possible for a knitted garment to maintain its original dimensions in length and width but become unserviceable because of excess skew, which causes the garment to twist on the body.

Many knitted items are labelled with precautions against hanging the product, particularly when wet. As it hangs, the weight of the fabric elongates and distorts the loops to pull the fabric out of shape. Again, weft knitted fabrics are more prone to such distortion than warp knitted fabrics. Laying knitted items flat to dry after laundering, and storing them on a flat surface, avoid the problem. Loosely knitted items made from soft, coarse yarns are more likely to exhibit such distortion.

Knitted fabrics tend to snag when pulled across a rough surface. The snag is produced when the yarn in a loop is pulled out of the surface of the fabric. In many warp knitted fabrics, the surface of the fabric may become distorted and puckered from snags, but it is seldom that long loops of yarn are pulled to the surface. In weft knitted fabrics, long loops may be pulled out, and if the yarn is broken the fabric will ladder, or run. Where fabrics are not unduly distorted, it is possible to repair the fabric to avoid further damage by pulling the snagged loop to the back of the fabric with a needle, a crochet hook, or a latch hook sold for that purpose.[3] Snagging is worse for fabrics that contain filament yarns, have a raised surface or have long floats on the surface.

The yarns used in lace are fairly tightly twisted to withstand the manipulations required to produce the material, so modern machine-made lace is less delicate than it appears. Lace requires some care in handling to prevent snagging and pattern distortion. The material is quite open; thus, dimensional stability may be a problem in laundering and dry cleaning. Properly heat-set nylon and polyester lace can, however, be handled with minimal difficulty.[3]

13.6.2 Fabric properties

Fabric weight and density

Fabric weight is one of the criteria for determining the washing parameters. For instance, silk responds well to hand laundering. However, heavier (suiting) fabrics of silk may shrink out of shape, unless they have been preshrunk. In any case, dry cleaning may be preferable for these heavier fabrics, as they may pill less and keep their shape better if not softened by washing.[6] As a general rule, tightly knitted fabrics, or more correctly, fabrics knitted with a low loop length relative to the machine gauge, are stretched in their width on the machine and therefore contract, i.e. shrink, in their width direction during laundering. Relatively loosely knitted fabrics tend to be stretched in their length direction by the fabric take-down tension and therefore relax (shrink) in their length direction during laundering. Herath and Kang,[17] for example, showed that tight fabrics have lower length shrinkage and higher width shrinkage for both 1x1 rib 100% cotton and 1x1 rib cotton and core spun cotton/Spandex fabric (93% cotton and 7% Spandex). Tightness factor and relaxation treatment significantly affect the length, width, area and spirality changes of 1x1 rib 100% cotton, and 1x1 rib cotton and core spun cotton/Spandex fabric (93% cotton and 7% Spandex).

Lamination

'Laminated fabrics' means one fabric is laminated with a membrane or another fabric. To avoid the problem of delamination or peeling off, the heat setting and washing properties of the different layers should be similar.

Fabric strength

Fibre strength and tensile properties in general, e.g. elastic modulus, especially when wet, are important considerations in home care. Fibres that are weak or stretch (extend) easily when wet need support and special care when they are washed. For example, a bulky article made of wool can absorb a lot of water. As a result, the wet garment is heavy and hence requires careful handling during washing, even if it has had an antifelt treatment, because, like our own hair, wool is weak and stretches easily when wet. Silk also loses strength when wet, but is much stronger than wool to begin with, and fabrics made of it are often light. Standard rayon and acetate both lose a great deal of their strength when wet and have only fair or poor strength to start with, so care is needed. Cotton and flax are two natural fibres that have good wet strength; they can therefore withstand mechanical action in laundering.[6]

13.7 Effects of colouration and finishing

13.7.1 Colouration

Different dyes can affect the laundry performance in terms of colour fading and bleeding. Certain colours that have relatively poor colourfastness, e.g. red and black, need to be washed separately or sorted into similar colours. To avoid garment shine, it is generally recommended to iron on the reverse side, whereas if lustre is desirable, ironing on the right (face) side is recommended. Dark leather combined with light fabrics can give problems in terms of colour loss from the leather.[6]

Azoic dyes are used on natural and regenerated cellulosic fibres, nylon, polyester, and silk. They produce brilliant shades, particularly red, yellow, orange, violet, and burgundy. They offer good fastness to washing, light, chlorine and peroxide bleaches, but they have poor resistance to crocking, or transferring colour under rubbing. Many azoic dyes are finished to reduce crocking problems. They are low in cost and can be applied in the same quantities.[3]

Direct dyes are anionic dyes that are substantive to cellulose when applied from an aqueous bath containing an electrolyte. Their colourfastness to washing may be poor and, since they are soluble in water, the laundering process tends to dissolve some dye and remove it from the fabric. The problem of poor washfastness can be solved to some degree by the application of selected finishing compounds, such as the substances used to provide easy-care.[3]

Pigment colour is economical to use and simple to apply but may not be colourfast to laundering and dry cleaning. The abrasion produced by a fabric rubbing against itself or against the sides of machines may cause crocking and loss of pigments. The solvents used in dry cleaning may also dissolve or soften some of the binders used in pigment colouring.[3]

The colourfastness to dry cleaning of reactive dyes is from very good to excellent, depending on the particular dye structure.[3]

Sulphur-dyed fabrics have good colourfastness to washing but are sensitive to chlorine bleaching.[3]

Vat dyes have excellent colourfastness to washing.[3]

13.7.2 Durable press/wrinkle-free finishes

The terms durable press and permanent press are often used synonymously to describe the ability of a fabric to retain its original surface appearance and shape following laundering, with little or no ironing required.[3] The effect of laundering on the performance of the garment in terms of breaking strength and appearance characteristics of durable press and liquid ammonia treated cotton broadcloth has been investigated by Raheel and Lien,[18–22] who found that durable press finished fabrics retained a higher proportion of their initial tensile strength compared to non-resin treated broadcloth in repeated laundering. According to the findings of Lau *et al.*,[23] wrinkle-free treatment can reduce the adverse effect of washing on many low-stress mechanical properties. Washing has only a small effect on the wrinkle-free treated fabrics in terms of water absorption rate, air penetration, fabric density and resilience. Wrinkle-free treated fabrics can achieve better shrinkage control and resilience than fabrics without wrinkle-free treatment, even after repeated laundering.

13.7.3 Water-repellent and waterproof finishes

Waterproof finishes are those that resist wetting and the penetration of water. Such fabrics are often non-permeable to air and water vapour and thus are not as comfortable as wearing apparel. Water-repellent finishes produce a fabric that resists wetting but allows both water and air to penetrate it.

It is important to follow any care instructions provided for textile products treated with water repellents. Some finishes are removed by dry cleaning but are not adversely affected by laundering; others can be removed by any method of care. Proper rinsing of fabrics is a necessity because surfactants left on fabric surfaces reduce the efficiency of finishes. Most dry-cleaning establishments can reapply a water-repellent finish to fabrics.[3]

13.7.4 Dimensional stabilising finishes

A fabric is considered dimensionally stable if it retains its original shape or dimensions after use and cleaning. Products that become smaller are said to shrink; those that become larger are said to exhibit fabric growth. Dimensional stabilising finishing includes heat setting of thermoplastic fibres, resin treatment of cotton fabrics, shrinkproofing of wool, fabric relaxation, and compaction (compressive shrinkage).

13.7.5 Chloride salts

Chloride salts of any type will weaken silk yarns over a period of time. Chloride salts are present in many foods, beverages, medicines, table salt and salt water, as well as in perspiration and some deodorants. Unfortunately, there is no practical way to predict or prevent this type of damage from occurring during acceptable cleaning. Contact with any salt substances, e.g. from food and beverages, can also cause leather staining and damage. Such damage is caused by accidental contact with moisture-containing salt that has remained on the leather for a period of time. Salt will continually absorb moisture from the atmosphere, thus keeping the stained area of the leather damp. Salt staining may be invisible prior to cleaning, and generally is not removed by regular leather cleaning procedures. When the jacket undergoes normal drying and finishing after cleaning, the salt-stained areas can shrink, stiffen, and sometimes the leather may even crack. Usually this damage cannot be prevented unless the garment owner knows when the contact occurs and immediately rinses the substance off the leather with some cold water and lets it air dry. If the stain is still fresh and is visible, the leather cleaner can attempt to remove the remaining residue prior to cleaning in order to minimise the damage.[11]

13.8 Effect of garment design

13.8.1 Garment nature/type

Different garment types need different washing care. Luxury garments, such as wedding gowns, usually need to be dry cleaned. When washing luxury garments in a home washing machine, study the care label carefully and avoid labels that say ‘Spot clean’ or ‘Dry clean exclusive of ornamentation’.[24] Swimsuits are usually made of nylon and Spandex, and should not be bleached but subjected to gentle washing. Lingerie is fancy and fine, which suggests hand washing or placing it into a net-bag for machine washing.

Daily wear garments, e.g. underwear or T-shirts, need to be washed after being worn. Therefore, this kind of garment is usually made from comparatively durable and easy-care fibres, such as cotton and polyester, which allow machine washing. Some garments, such as those containing down (used during cold weather), usually require washing only about twice a year. The cleaning procedure for this kind of garment is more complicated than that for daily wear garments. For baby clothes, choice of a detergent which will not produce an allergic reaction in the baby is very important. To preserve the fire-retardant qualities of baby clothes, they should be laundered in a detergent, not a soap, following the manufacturer's instructions. It is probably not a good idea to use fabric softener in the washer or dryer. It tends to be highly perfumed and may cause a rash on the baby.[25]

13.8.2 Fastenings

All fastenings, including buttons, buckles, Velcro and zippers, must be closed before washing.

Zippers

Polyester Coil and Moulded Plastic (Vislon®) zippers are, by and large, non-reactive to the chemicals used in the treatments during garment manufacturing. In such cases, however, care must be taken to avoid any adverse effects on the slider enamel from the chemicals and equipment used during the treatment. In the case of metal zippers, special care needs to be taken when subjecting them to any type of chemical treatment, other than washing with standard formulated household detergent.

Normal home laundering, with a standard formulated detergent, will not affect the zipper provided the zipper is kept closed. If there is a hook or button above the zipper, it should be fixed. However, when laundry is done on an industrial scale, it must be ensured that the inner surfaces of the equipment used are soft and smooth so as to avoid chipping and scraping of the slider enamel or plating. If necessary, the garments may be kept inside a protective net-bag while being laundered.

For dry cleaning, to reduce the friction caused by metal-to-metal contact when opening and closing a metal zipper, a touch of non-staining paraffin-wax is given to the elements during the production process. This ensures that the movement of the slider remains smooth and silent, and also extends

Table 13.2 Optimum ironing temperatures for various types of zippers. Source: Anon[26]

Zipper type	Optimum ironing temperature
Coil zipper	150°C
Conceal zipper	160°C
Vislon zipper	130°C

the life of the zippers. The process of dry cleaning involves use of a strong solvent, such as perchloroethylene, which is effective in removing greasy stains adhering close to the fibre surface. Naturally, during this process the paraffin-wax on the elements is also removed, which causes the movement of the slider to become noticeably more difficult. However, the original smoothness can be instantly restored by using a special zipper lubrication spray. Alternatively, light re-application of non-staining paraffin-wax on the metal elements will also be effective.

Ironing should be done only at temperatures within the recommended range for each type of zipper (Table 13.2). During ironing, the zipper should be closed and preferably be under a cloth; direct heating should be avoided.

13.8.3 Garment details

Beads, sequins or fancy trims

Beads, sequins, crystals, or other decorative and fancy trims may bleed or dissolve in dry-cleaning solvent or may be heat sensitive. There are also mirror-look plastic trims with solvent-soluble backing. Since such trims are usually applied to garments for special occasions, they are normally dry cleaned.[6] Reading care labels is recommended. If washed in a washing machine, the garments should be placed, inside out, into net-bags. Reading care instructions and care labels before washing is always highly recommended.

Surface designs

Fabrics having surface designs, including shag, pile, nap or other three-dimensional surfaces and floating yarns, can snag, as in satins. Some surface designs are simply attached by glue, the adhesive being easily dissolved during washing. Therefore, they require light and careful treatment on the reverse side.

13.9 Test methods and standards related to laundering and care labelling

13.9.1 Care instructions/care labelling

ASTM D3136 Standard terminology relating to care labeling for apparel, textile, home furnishing, and leather products

This standard is a compilation of all terminology developed by Subcommittee D13.62 on Labelling, and is related to cleaning and labelling for apparel, textile, home furnishing, and leather products other than upholstered furniture and floor coverings. The terminology provides a uniform language for the disclosure of care instructions on labels that are to be attached to apparel, textile, home furnishing, and leather products in a logical restoration sequence (wash, bleach, dry, iron, dry clean, wet-clean), in order to disclose maximum information in a small label space and to help the consumer understand recommended practices.[4]

ASTM D3938 Standard guide for determining or confirming care instructions for apparel and other textile products

This guide is intended for general use by those who wish to determine whether apparel or other textile products (piece goods and upholstery) will perform in an acceptable manner when the care instructions on the label are followed. Restored products are evaluated against previously selected product performance specifications to determine whether the products can be cleaned successfully by following the instructions on the care label.[27]

ASTM D6322 Standard guide to international test methods associated with textile care procedures

This guide lists test procedures used in evaluating care label instructions appropriate for colourfastness, susceptibility to damage due to retained bleaching agents, dimensional stability, safe ironing temperature, and appearance retention.[28]

BS 5742 Specification for textile labels requiring to be washed and/or dry-cleaned

This standard specifies the materials, design and method of application of labels and name tapes for garments and other made-up textile articles. It also specifies the colourfastness requirements of the markings on garment labels and name tapes when subjected to methods for washing, rubbing, dry cleaning, and washing in the presence of sodium hypochlorite, and to perspiration. Requirements are given for both general purpose and heavy duty products.[29]

ASTM D3962 Standard practice for selection of zippers for care-labeled apparel and household furnishings

This practice provides guidelines to the manufacturer for the selection of zippers to be used in garments and household furnishings that have care labels. The use of this practice will facilitate the selection of a zipper compatible with the end-item requirements. In the absence of a complete knowledge of end-item characteristics, it is not possible to stipulate specific universal characteristics for a care label. Therefore, following initial selection, the chosen zipper should be tested on a prototype item to confirm its suitability. Zipper properties to be considered are those that may, following cleaning, be the ones likely to adversely affect the continued use and enjoyment of the item in which the zipper is installed. The product characteristics evaluated by this practice are shrinkage, colourfastness, and ironing deformation.[30]

13.9.2 Tests for determining laundry performance

AATCC 143 Test method for appearance of apparel and other textile end products after repeated home laundering

This test method is designed for evaluating the smoothness appearance of any washable constructions (such as woven, knitted and non-woven) and flat fabric and seams, and the retention of pressed-in creases in garments and other textile products after repeated home laundering (hand or machine washing, alternative machine washing cycles and temperature, and alternative drying procedures). Evaluation is performed using a standard lighting and viewing area by rating the appearance of specimens in comparison with appropriate reference standards.[31]

AATCC 99 Test method for dimensional changes of woven or knitted wool textiles: relaxation, consolidation and felting

This method is an accelerated test for the determination of relaxation, consolidation and felting shrinkage of woven and knitted textiles containing 50% or more wool. The overall dimensional change in a fabric during home laundering is a significant performance factor to the ultimate consumer of a garment. However, further analysis of the components of dimensional change is invaluable to a fabric manufacturer, since it allows the fabric manufacturer to make appropriate changes in the design and processing of fabrics to reduce their tendency to change dimensionally when washed.[32]

AATCC 61 test method for colorfastness to laundering, home and commercial: accelerated

These tests are to evaluate the colourfastness to laundering of textiles which are expected to withstand frequent laundering. The fabric colour loss and surface changes resulting from detergent solution and abrasive action of five typical hand, home or commercial launderings, with or without chlorine, are roughly approximated by one 45 min test. However, the staining effect cannot always be predicted by the 45 min test. Staining is a function of the ratio of coloured to undyed fabrics, fibre content of fabrics in the wash load, and other end-use conditions which are not always predictable.[33]

AATCC 172 Test method for colorfastness to non-chlorine bleach in home laundering

The test is designed to evaluate the colourfastness to non-chlorine bleach in home laundering of textiles which are expected to withstand frequent laundering. The fabric colour changes resulting from the non-chlorine bleach, detergent solution and abrasive action of five home launderings are evaluated. Results of the test can be used for establishing care instructions.[34]

13.10 Concluding remarks

Laundering is a process for removing the soil on a garment and keeping it hygienic and aesthetically acceptable. However, at the same time, laundering may cause a deterioration in the appearance, dimensions and other desirable and performance-related properties of a garment. In order to minimise the damage caused by laundering, the proper engineering design of fabrics and garments, as well as proper care labels, is essential. The factors outlined in this chapter serve as a basis of reference for the engineering of the laundry performance of fabrics and garments, and include the influence of fibre type and properties, fabric construction, fabric finishing, dyestuff, garment design, fastenings, trimmings and garment care.

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14

Applications of artificial intelligence in fabric and garment engineering

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Abstract: This chapter reviews the application of artificial intelligence (AI) in establishing the approximate relationships (sometimes 'rule of thumb' and sometimes a more definite relationship but with a narrow scope) between the performance of the fabrics or garments and their constituent components (e.g. fibres), construction (e.g. yarn structure, weave, and garment design), and manufacturing parameters (e.g. weaving conditions, dyeing methods, finishing routes and sewing conditions). This chapter also reviews the application of AI in building these relationships into computer systems to assist in the engineering design of fabrics and garments.

Key words: artificial intelligence (AI), expert systems, artificial neural network (ANN), engineering design of fabrics.

14.1 Introduction

If fabrics and garments are to be engineered at the design stage so that their end products will have the anticipated performance, the relationship between the performance of the fabrics or garments and their constituent components (e.g. fibres), construction (e.g. yarn structure, weave, and garment design), and manufacturing parameters (e.g. weaving conditions, dyeing methods, finishing routes and sewing conditions) must be first quantitatively established. There are traditionally two approaches to the establishment of the relationship: theoretical modelling and empirical regression.

Theoretical models are based on physical principles. They are very useful in understanding the mechanisms involved, but they generally fall short of predicting the resulting performance of fabric and garments with practically acceptable accuracy, because simplifying assumptions are normally employed in theoretical models to make the mathematics tractable, and the uncertainties, complexities and dynamics associated with real-world processes cannot be accurately modelled.

Empirical models may also be regressed statistically by techniques such as curve fitting or multiple regression analysis, using a large experimental database. Such models, however, can have only limited applications. This is firstly because the sizes of the experiments are generally limited due to cost and time factors; as a result, only a selection of material and process variables can be considered within a narrow range. Secondly, there is a lack of precise control of material, constructional and process variables in textile and clothing manufacture. Thirdly, conventional statistical techniques generally cannot model the complex non-linear processes of fabric and garment formation.

The lack of defined relationships between the performance of apparel products and their material, construction and processing variables makes it impossible to engineer fabrics and garments in the same way as many other engineering products, such as roads, building, electrical and electronic devices, where much of the engineering work is based on proven calculations. Although it may not be possible, at least for the time being, to 'engineer' fabrics and garments in the traditional sense, it is possible and practically beneficial to build the approximate relationships (sometimes 'rule of thumb' and sometimes a more definite relationship but with a narrow scope) into artificial intelligence (AI) systems to assist in the engineering design of fabrics and garments.

Artificial intelligence (AI) is the science of making machines do things that would require intelligence if done by humans. AI includes the following areas:

- Expert systems
- Artificial neural networks (ANNs)
- Knowledge representation
- Machine learning
- Machine planning
- Genetic programming
- Genetic algorithms
- Computational linguistics
- Computer vision.

Among these, expert systems and artificial neural networks (ANNs) have been applied in the engineering design of fabrics and garments.

14.2 Expert systems

14.2.1 Fundamentals of expert systems

An expert system (sometimes referred to as a knowledge-based system) is a computer program that represents and reasons with knowledge of some specialist subject with a view to solving problems or giving advice.[1]

Typically, the problems to be solved are difficult enough to require significant human expertise for their solution.

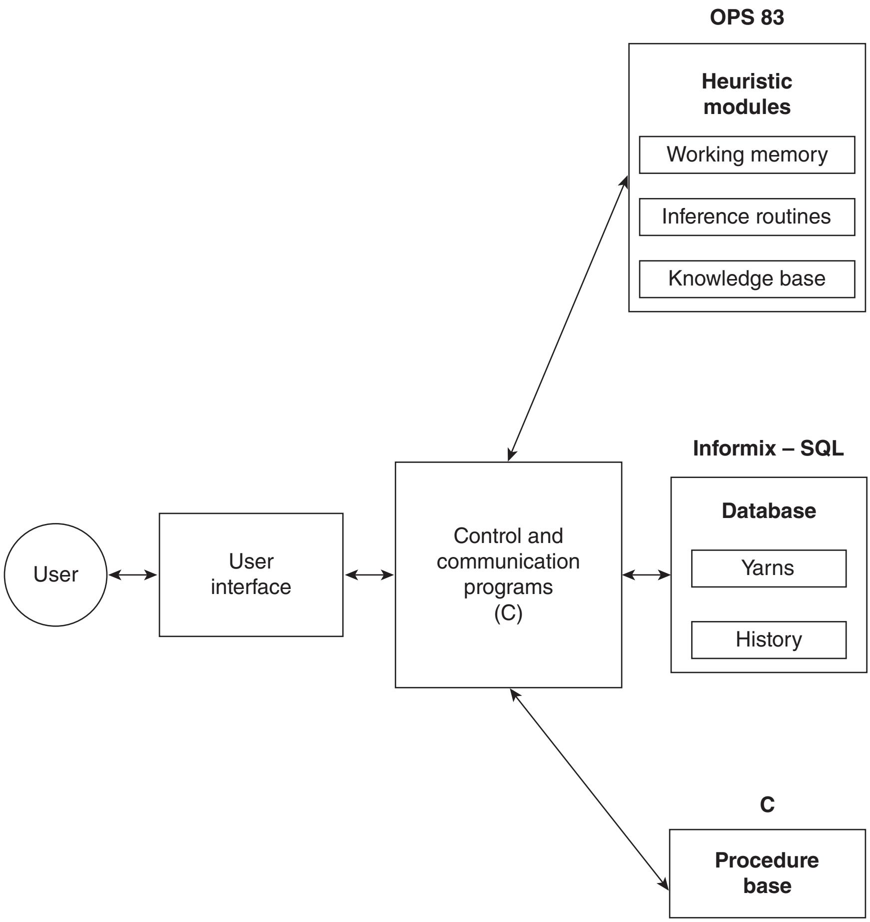
An expert system can be distinguished from a more conventional applications programs in that:[1] (i) it simulates human reasoning instead of mathematical modelling or computer animation; (ii) it performs reasoning over representations of human knowledge in addition to doing numerical calculations or data retrieval; the knowledge in the program is normally expressed in some special-purpose language (usually referred to as the knowledge base) and is kept separate from the code that performs reasoning (normally referred to as the inference engine); (iii) it solves problems by heuristic or approximate methods which, unlike algorithmic solutions, are not guaranteed to succeed. A heuristic is essentially a rule of thumb in some domain. Such methods are approximate in the sense that they do not require perfect data, and the solutions derived by the system may vary in their degrees of certainty.

Expert systems generally cannot surpass human experts in the experts' domain, but they can surpass a human expert in areas where he or she is not an expert. As an integrated system, an expert system can provide support to even highly specialised experts. Furthermore, unlike human experts, who can be lost to an organisation, the expertise of expert systems is permanently available and can be incrementally improved. Expert systems have therefore found applications in many different fields, including business, manufacturing, medicine, engineering, applied sciences, military, space, transportation and education.[2]

14.2.2 Expert systems for the engineering of fabrics and garments

An expert system is beneficial in terms of fabric engineering as it provides knowledgeable advice during the process based on an expert system's strength, *viz*. its knowledge base, but leaves the final decision to the expert, who can take into account both those knowledge aspects that have not been built into the system and other special and unpredictable factors.

The possibility of using an expert system that incorporates a structured dynamic database for the engineering design of fabrics was first proposed by Postle *et al.*[3] They envisaged that the system should consist of a natural language interface, a knowledge acquisition model to acquire newly available knowledge or data, and a knowledge base that encompasses both the subjective knowledge or the rule of thumb employed by the 'expert' fabric designers/engineers and the objective knowledge, namely the various processing models and structure and property models.



14.1 The structural organisation of 'FABCAD'.
Source: Dastorr, *et al.*, 1994[4]

Dastorr *et al.*[4–6] developed a prototype knowledge-based CAD system, called 'FABCAD', for assisting the engineering design process of industrial fabrics. The system consists of a *user interface*, *control and communication programs*, *heuristic modules*, *database* and *procedure base*. The structural organisation of FABCAD is shown in Fig. 14.1. The *heuristic modules* are encoded representations of fabric design rules, principles and methods, which are specific to the various subtasks of the fabric design process, including *fibre selection*, *yarn linear density and density determination*, *weave selection* and *cover factor modification*. The *database* contains historical information on previously fabricated structures and their measured property values. The *procedure base* contains stand-alone algorithms (e.g.

the calculation of fabric weight per unit area given yarn linear density, fibre specific gravity and yarn densities in the fabric) and models dedicated to predictive estimation of a particular fabric behaviour characteristic (e.g. prediction of the tensile deformation of the fabric). The function of *control & communication programs* is to supervise the overall working of different components of FABCAD. These programs should be such that the system's operation matches the designer's concept of the design process flow without forcing him or her in directions contrary to practice.

Frei and Walliser[7] reported an expert system, called 'Wooly', for the wool dyer, which helps the user to find the dyes with the most favourable dyeing behaviour based on the type of wool article to be dyed, the care level required (i.e. dry clean, hand wash or machine wash), and care fastness requirements.

Kienbaum[8] described a software called 'opTex'. This is perhaps not an expert system in the strict sense, but contains computer programs for the calculation of weaving parameters (e.g. the sett of cloth, reed counts, fabric weight) and cost estimation (e.g. cost of materials, production and overheads).

In 1992, an expert system for assisting the engineering design of worsted fabrics (called 'WOFAX') was developed at the CSIR Division of Textile Technology, South Africa, by Fan and Hunter.[9,10] WOFAX was developed to provide advice or guidelines during the fabric design process, and to predict the properties and performance of the designed fabric. The system has eight 'advisers', which may be regarded as small (or sub) expert systems, for providing advice or guidelines in determining fabric composition, weave, yarn linear density and sett, weaving details, yarn type, twist, fibre specification and finishing procedure. After a fabric is designed, the properties of the designed fabric are predicted using a neural network model incorporating a fabric databank. Based on these predicted fabric properties, the performance of the designed fabric is then evaluated by the 'Fabric Performance Interpreter'.

14.3 Artificial neural networks (ANNs)

14.3.1 Fundamentals of ANNs

An artificial neural network (ANN) is an information-processing system that has certain performance characteristics in common with the biological neural networks of the brain.[11] Although the theories of ANNs have been developed based on the inspiration from the current understanding of the brain's neural processes, they are applied to the solution of problems in areas which may or may not have neurological relevance,[12] for example, signal processing, control, pattern recognition, performing general mapping from input data to output data.

An ANN is typically composed of a number of interconnected units (or artificial neurons). Each unit has an input/output (I/O) characteristic and implements a local computation or function. The output of any unit is determined by its I/O characteristic, its interconnection to other units, and possibly external inputs. Although 'hand crafting' of the network is possible, the network usually develops an overall functionality through training.[13]

Patterson[14] developed a single ANN neuron (or unit) with three inputs and a single output. Each input link i ($i = 1, 2, 3$) receives an input signal or stimulus x_i and has a corresponding weight w_i (a sort of filter in between the input and the neuron). The neuron behaves as an activation function $f(x)$ producing an output $y = f(net)$, where *net* is the cumulative input stimuli to the neuron, *net* is often taken as the weighted sum of the inputs, *viz.*:

$$net = x_1w_1 + x_2w_2 + x_3w_3 = \sum x_iw_i \tag{14.1}$$

The activation function $f(x)$ may be a matter of choice, but should have several important characteristics. It should ideally be continuous, differentiable, monotonically non-decreasing, and approaching finite maximum and minimum values asymptotically. Furthermore, for computational efficiency, it is desirable that its derivative is easy to compute and can be expressed in terms of the values of the function. The most often used activation function is the binary sigmoid function or its variations. The binary sigmoid function with a range of (0, 1) is defined as follows:

$$f(net) = \frac{1}{1+\exp(-net)} \tag{14.2}$$

The derivative of the activation function is

$$f'(net) = f(net)[1 - f(net)] \tag{14.3}$$

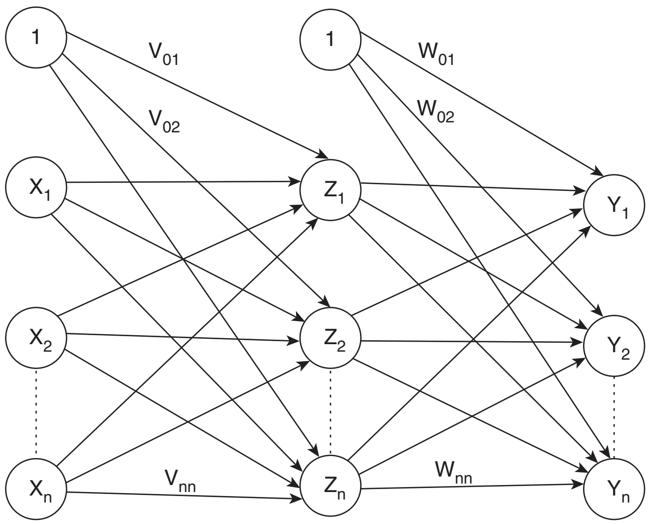
The radial basis function (RBF) is another widely used activation function, which is found to be advantageous in some applications.[15–17] In RBF networks, the response of the neuron is localized and decreases as a function of the distance of the inputs from the neurons' receptive field centre. A common form of the RBF activation function[14] is:

$$f(net) = \alpha \cdot \mathrm{e}^{-net}, \tag{14.4}$$

where:

$$net = \sum [(x_i - c_i)/\sigma_i]^2, \tag{14.5}$$

α and σ_i are constants, and c_i is the centroid of the ith input.



14.2 Architecture of the backpropagation neural network.

The principle of ANN is to train the model (i.e. adjusting the weights or constants between the nodes in each layer) using experimental datasets so that the output from the ANN is equal, or as close as possible, to the target pattern.[11]

A simple ANN, as developed by Patterson,[14] is of little practical use. A widely used ANN is the backpropagation neural network with one hidden layer, as shown in Fig. 14.2, since it performs as a universal function approximator. In Fig. 14.2, X, Y and Z are input, output and hidden layer, respectively. The output units and hidden units may have biases. In the hidden layer and output layer, each neuron summarizes the weighted inputs and produces an output through an activation function.

Training a network by backpropagation involves three stages: the feedforward of the input training pattern, the backpropagation of the associated error, and the adjustment of the weights.

The training process may involve the following steps:[11]

Step 0. Initialise weights (set the weights, *viz.* Vs and Ws in Fig. 14.2, to small random values).
Step 1. While stopping condition is false, do Steps 2–9.
Step 2. For each training pair, do Steps 3–8.

Feedforward:

Step 3. Each input unit (X_i, $i = 1, \ldots, n$) receives input signal x_i and broadcasts this signal to all units in the layer above (the hidden units).

Step 4. Each hidden unit ($Z_j, j = 1, \ldots, p$) sums its weighted input signals,

$$z\_in_j = v_{oj} + \sum_{i=1}^{n} x_i v_{ij},$$

applies its activation function to compute its output signal,
$z_j = f(z\_in_j)$,
and sends this signal to all units in the layer above the output units.

Step 5. Each output unit (Y_k, $k = 1, \ldots, m$) sums its weighted input signals,

$$y\_in_k = w_{ok} + \sum_{j=1}^{p} z_j w_{jk}$$

and applies its activation function to compute its output signal,
$y_k = f(y\_in_k)$

Backpropagation of error:

Step 6. Each output unit ($Y_k, k - 1, \ldots, m$) receives a target pattern corresponding to the input training pattern, computes its error information term,
$\delta_k = (t_k - y_k)f'(y\_in_k)$,
calculates its weight correction term (used to update w_{jk} later),
$\Delta w_{jk} = \alpha\delta_k z_j$,
calculates its bias correction term (used to update w_{ok} later),
$\Delta w_{ok} = \alpha\delta_k$,
and sends δ_k to units in the layer below.

Step 7. Each hidden unit (Z_j, $j - 1, \ldots, p$) sums its delta inputs (from units in the layer above),

$$\delta\_in_j = \sum_{k=1}^{m} \delta_k w_{jk},$$

multiplies by the derivative of its activation function to calculate its error information term,
$\delta_j = \delta\_in_j \, f'(z\_in_j)$,
calculates its weight correction term (used to update v_{ij} later),
$\Delta v_{ij} = \alpha\delta_j x_i$,
and calculates its bias correction term (used to update v_{oj} later),
$\Delta v_{oj} = \alpha\delta_j$

Update weights and biases:

Step 8. Each output unit ($Y_k, k - 1, \ldots, m$) updates its bias and weights ($j = 0, \ldots, p$):
$w_{jk}(new) = w_{jk}(old) + \Delta w_{jk}$

Each hidden unit (Z_j, $j = 1, \ldots, p$) updates its bias and weights ($i = 0, \ldots, n$):

$v_{ij}(new) = v_{ij}(old) + \Delta v_{ij}$

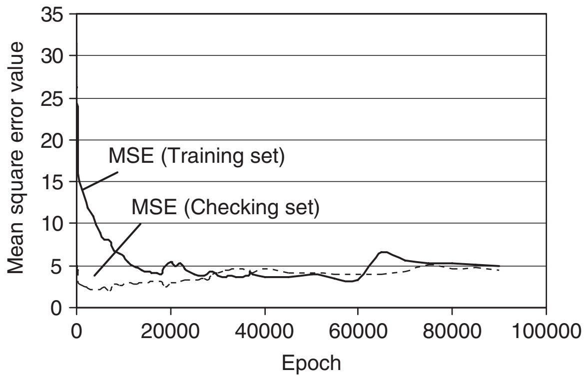
Step 9. Test stopping condition.

An epoch is one cycle through the entire set of training vectors. Typically, many epochs are required for training a backpropagation neural net. The foregoing algorithm updates the weights after each training pattern is presented. A common variation is batch updating, in which weight updates are accumulated over an entire epoch.

During training, two sets of data pairs are normally required: a set of training pairs and a set of training–testing pairs. Weight adjustments are based on the training patterns; however, at intervals during training, the error is computed using the training–testing patterns. As long as the error for the training–testing pairs decreases, training continues. When the error for the training–testing pairs begins to increase, the net is starting to memorise the training patterns. At this point, training should be terminated to avoid losing generalisation of the model. Figure 14.3 plots typical changes of error with epoch.

14.3.2 Overview of applications of ANNs in textiles and clothing

ANNs have been extensively applied in the field of textiles and clothing for their strength in modelling complex non-linear processes. A rather comprehensive review was given by Guha *et al.*,[18] in 2001, after which a number of applications of ANNs in clothing appeared.



14.3 Typical changes of error with epoch.
Source: Chan, 2005[61]

In general, ANNs have been found to be most advantageous in providing solutions to the following types of problems in textiles and clothing:

- Pattern recognition problems
- Process control
- Prediction of the properties of semi-processed or end products.

Pattern recognition problems

In the area of fibre identification and classification, ANNs have been trained to identify fibre composition from the near-infrared (NIR) absorbance spectrum,[19,20] to identify the type of animal fibres from the image of the fibres,[21,22] to classify cotton colour grades from the measurements of high-volume instruments (HVI),[23,24] to classify the various kinds of trash in the raw cotton from the colour and image taken by a CCD camera,[25,26] and to differentiate trash and neps in fibres from the image of fibre webs.[27]

An ANN has also been applied to classify the types of yarn appearance faults from four yarn fault factors obtained from the image analysis of the yarn images.[28]

In the area of fabric defect classification, many researchers[29–41] have applied ANNs to classify different types of fabric defects from fabric images.

An ANN has also been used to classify the weave patterns of woven fabrics from the ratios of the vertical lengths to the horizontal lengths between the crossover points, which can be obtained by analysing the digital image captured by a CCD camera.[42]

Process control

ANNs have been applied in yarn manufacture to predict the degree of spinnability of a fibre from fibre properties and process conditions,[43] to improve sliver evenness in a drawframe by using a neural-network-controlled autoleveller in which the linear density of the feed sliver and the desired linear density of the output sliver are inputs while the ratio of front- and back-roller speeds is the output,[44] and to predict the efficiency of a spinning unit from the capacity of the plant and the type of job it is undertaking.[45]

In fabric manufacture, Ara and Imamura[46] developed a neural network based control device to provide a warning signal or adjust the weaving conditions according to the state of the loom, particularly weft insertion. Ucar and Ertugrul[47] applied an ANN to predict knitting machine parameters to produce a fabric with desired properties.

In garment manufacture, a neural network based online classifier of fabric type and number of plies was developed by Barrett *et al.*[48] for use on a sewing machine to improve the quality of stitch formation. Stylios and

Sotomi[49] developed a neural network and fuzzy logic based control system to predict fabric sewability and to optimize the setting of presser foot pressure and thread tension. ANNs have also been trained to predict the possibility of a fabric to have seam pucker from fabric properties[50] and to provide a severity rating to the puckered seam based on the surface profile obtained by a laser triangulation sensor.[51]

In colouration, ANNs have been trained to predict colour recipes,[52] the concentrations of commercial dyes from the absorbance spectra of targeted mixture dye solutions,[53] and the concentration of fluorescent dyes from the total spectral radiance factor.[54] Conversely, ANNs have also been trained to predict dye absorbance from wavelength and concentration.[55]

Prediction of the properties of semi or end products

Many workers have applied ANNs to predict the properties of yarns from the fibre properties and process parameters. For example, by applying an ANN, Ramesh *et al.*[56] predicted the strength and elongation of air-jet-spun yarns from yarn count, percentage of polyester fibre in a polyester–cotton blend, and front and back nozzle pressure; Cheng and Adams[57] predicted the tenacity of ring-spun yarns from the eight fibre properties determined on an HVI system; Zhu and Ethridge predicted the hairiness[58] and evenness[59] of ring- and rotor-spun yarns from fibre properties measured by HVI, AFIS and traditional instruments; Beltran *et al.*[60] predicted the quality of worsted yarns, including the average number of fibres in the yarn cross-section, evenness, tenacity, elongation and hairiness from fibre properties, yarn count, twist and processing conditions.

Considerable work has also been carried out to predict the properties/performance of fabrics and garments from the constituent material and constructional and processing variables. As this is a key area relevant to the main topic of the book, *viz*. engineering design of fabrics and garments, it will be extensively reviewed and discussed in the following section.

14.3.3 Advances of ANNs for engineering of fabrics and garments

ANNs offer great advantage in mapping the complex non-linear relationship between the properties/performance of fabrics and garments and the constituent material and constructional and processing variables.

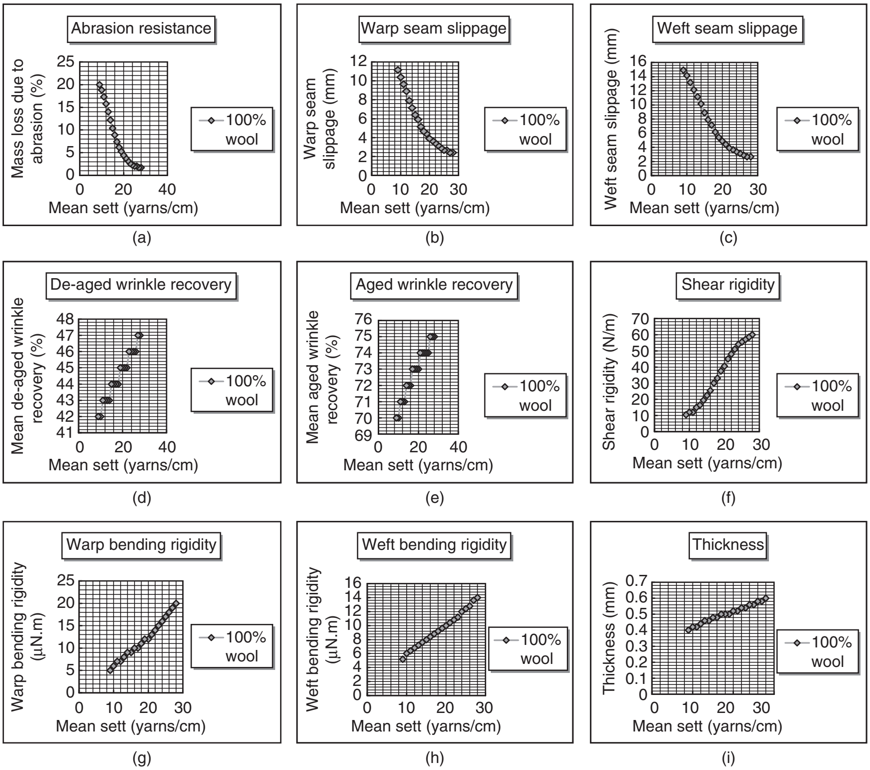
Fan and Hunter[9,10] reported an ANN model (WOFAX) for predicting the properties of worsted fabrics from 30 input variables, including fibre composition, fibre properties, yarn properties and weave constructional

Table 14.1 Input parameters of WOFAX

Finished fabric details	– Fabric type – Weave – Ends/cm	– Composition – Mass – Picks/cm
Yarn details	– Warp yarn count (linear density) – Weft yarn count (linear density) – Warp yarn type – Weft yarn type – Warp single yarn twist (Z) – Weft single yarn twist (Z) – Warp yarn folding twist (S) – Weft yarn folding twist (S) – Warp yarn uptwist (S) – Weft yarn uptwist (S)	
Fibre details	– Warp yarn wool	– Weft yarn wool
Weaving instruction	– Ends/dent – Picks/cm on loom – Reed width/grd – Ends/grd	– Ends/cm on loom – Reed fineness/10 cm – Reed dents/grd
Finishing routine	– Inspect, burl, and mend – Press – Lustre or finish decatise – Conticrab: water at 60–80°C, drum at 110–120°C, speed at 10–12 m/min – Dye in bagged form in the winch – Smooth on the crab or conticrab – Tenter with 8% overfeed to 158 cm, and dry – Shear once at the back, twice at the face	– Open-width scour – Pressure decatise – Final inspection

parameters. The output of the ANN model included abrasion resistance, seam slippage, wrinkle recovery, shear rigidity, bending rigidity and thickness. Typical input and output parameters are listed in Table 14.1. As can been seen, they include continuous and discrete variables. The model was trained with data pairs of 417 fabrics, of which 379 were used as the training set and 38 were used as cross-validation pairs. Figures 14.4 to 14.7 plot the prediction of the model on the effects of sett, yarn tex, weave type and fibre diameter on fabric properties.

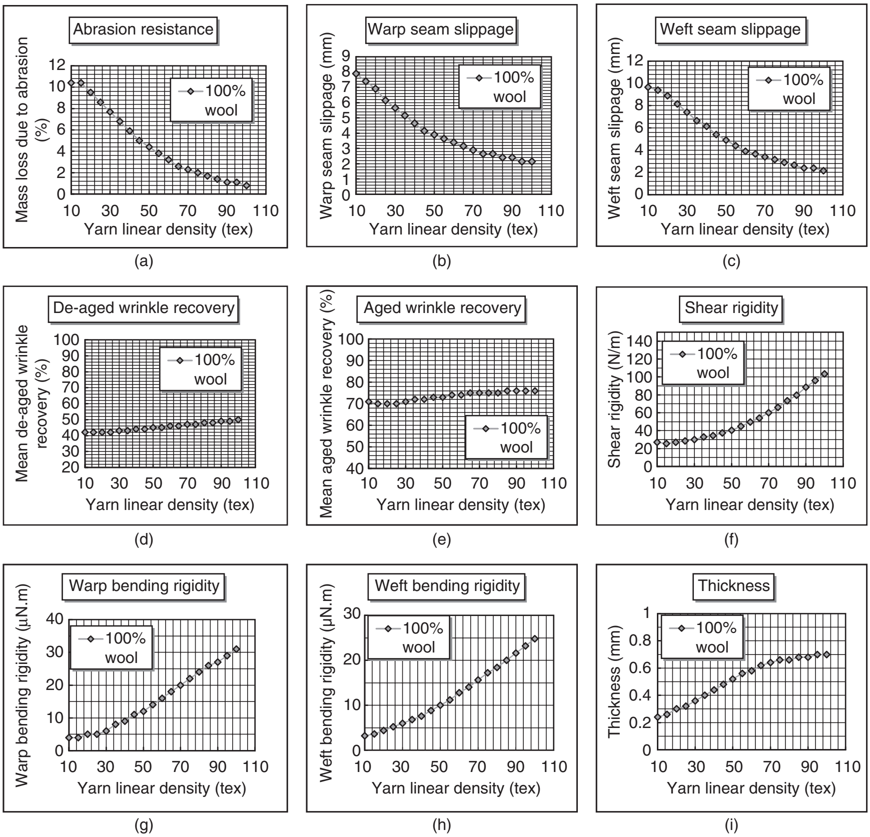
By comparing the model's predicted values with the actual measurement values, it can be concluded that the ANN model has successfully mapped the general trends of the effects of various fibre, yarn, and fabric constructional parameters on fabric properties, but large predictive errors may still result in practice because fabric manufacturing parameters, particularly dyeing and finishing processes, can still not be quantified. Therefore, the



14.4 The effect of sett on fabric properties as determined by the neural network model. Note: Assuming a constant yarn linear density of 50 tex, and a constant weave crimp of 8%; assuming changing fabric sett from 29 × 27 to 10 × 8; assuming plain weave fabric.

model can be used in the fabric design stage to check the changes in fabric properties due to any changes in fibre type, composition, yarn type or fabric construction, but care must be taken in interpreting the absolute values of the properties predicted by the model. The model was implemented in a worsted fabric expert system using the following two approaches:

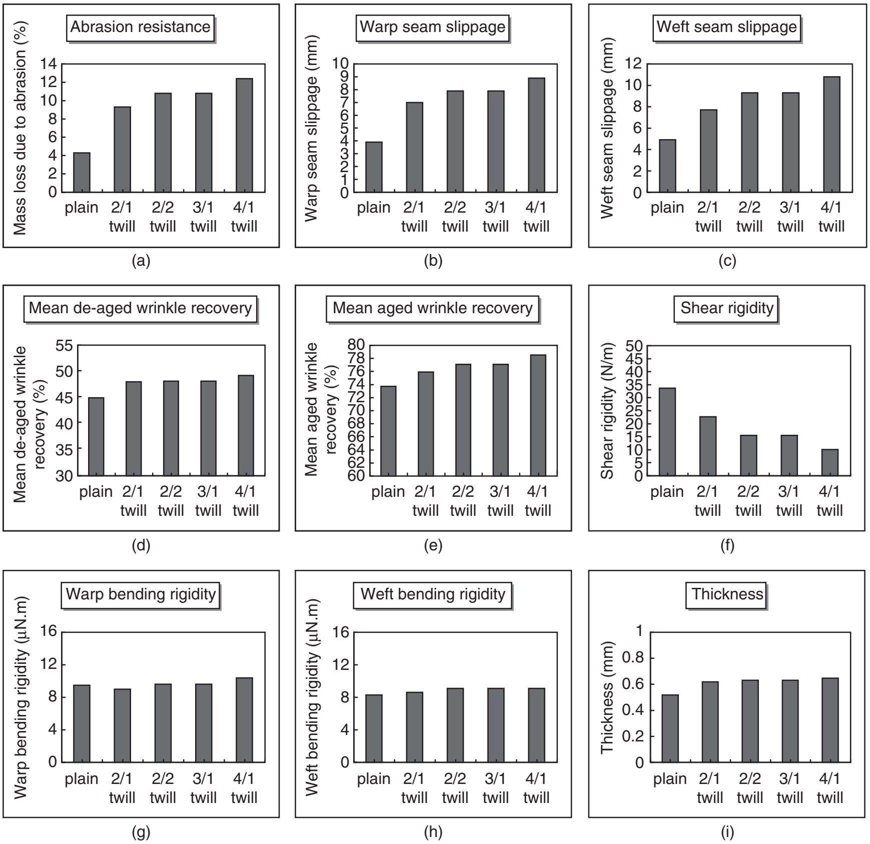
(i) The expert system searches a databank to find a fabric which is similar to the one being designed and has been manufactured in the same way (e.g. same dyeing and finishing methods, etc.) and in the same environment (e.g. factory). The properties of the similar fabric are then recorded. The artificial neural network model is then used to predict the differences between the properties of the similar fabric and the newly designed fabric. The predicted differences and the



14.5 The effect of yarn linear density on fabric properties as determined by the neural network model. Note: Assuming a constant tex twist factor a constant ends and picks (21 × 19), and a constant weave crimp of 8%; assuming changing yarn linear density from 100 tex to 5 tex; assuming plain weave.

previously recorded properties of the similar fabric in the databank are then used to derive (or predict) the properties of the newly designed fabric. This approach is more suitable when designing a new fabric.

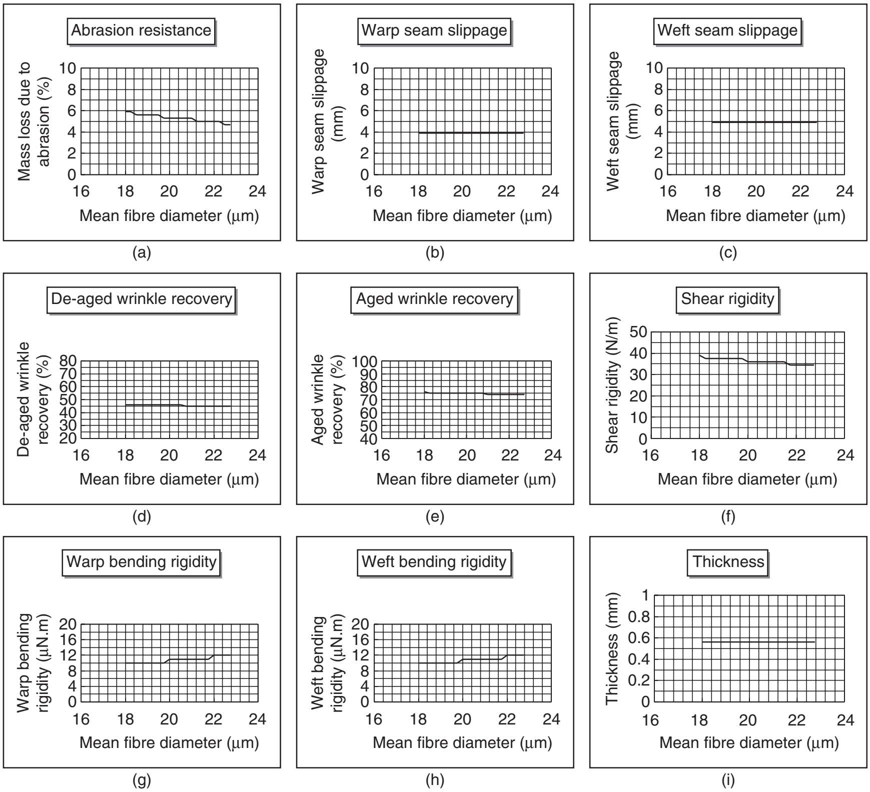
(ii) In the case where a fabric designer wants to make slight material and constructional changes to an existing fabric (manufacturing methods remaining the same), which is a very common practice in the industry, the following approach is more appropriate. The expert system requests the user to enter the properties of the existing fabric which has been manufactured and tested. The artificial neural network model is then used to predict the differences between the properties



14.6 The effect of weave structure on fabric properties as determined by the neural network model. Note: Assuming that the warp and weft yarn linear density is 50 tex, the sett is 21 × 19, the composition 22 μm wool, yarn twist 590Z/540S and piece dyed.

of the existing fabric and the newly designed fabric. The predicted differences and the properties of the existing fabric in the databank are then used to derive (or predict) the properties of the newly designed fabric.

Behera and Muttagi[15,16] later compared a radial basis function neural network (RBFN) and an error backpropagation neural network (EBPN) in predicting the low-stress mechanical, dimensional and tensile properties of woven suiting fabrics from the fibre/yarn properties and fabric constructional parameters, or *vice versa*, and showed that RBFN had better predictability and that the prediction is in good agreement with the generally accepted trends.



14.7 The effect of mean fibre diameter on worsted fabric properties as determined by the neural network model. Note: Assuming plain weave, piece dyed, constant twist (590Z/540S), constant yarn linear density (50 tex), constant sett (21 × 19) and constant weave crimp; assuming changing wool fibre diameter from 19 μm to 24 μm.

Gong and Chen[62] developed an ANN to predict the making-up performance of fabrics during garment manufacture, based on 19 fabric properties measured by the KESF system. The predicted making-up performances included laying-up, cutting, overall handling, inter-ply shifting, structural jamming, seam slippage, needle damage, seam pucker, ease of pressing, dimensional stability and appearance retention.

Hui and Ng[17] also predicted the sewing performance of fabrics from fabric composition, weave structure, yarn count, sewing thread properties and fabric low-stress mechanical properties, using an extended normalized radial basis function (ENRBF) neural network model. The sewing performance included severity of seam pucker, severity of needle damage, distortion and overfeeding. The model prediction was found to be in good agreement with results of sewing tests carried out by sewing experts.

Ceven *et al.*[63] used radial basis function neural network models (or generalised regression type (GRNNs)) to predict the abrasion resistance of chenille yarns and fabrics from the constituent chenille yarn parameters, such as yarn count, pile length, twist level and pile yarn material type. The GRNN was also applied to predict the air permeability of 100% cotton plain weave fabrics from warp density, weft density and fabric mass per unit area.[64] The prediction error was shown to be five times lower than the corresponding error produced by multiple linear regression.

Beltran *et al.*[65] developed an artificial neural network model to predict the pilling propensity of pure wool knitted fabrics from the fibre, yarn and fabric parameters. On that basis, they further applied[66,67] three input feature selection techniques, *viz*. sensitivity analysis, forward/backward search and genetic algorithms to rank the relative importance of various fibre/yarn/fabric input parameters in the pilling of wool fabrics. They showed that fabric cover factor has the greatest effect on pilling, followed by yarn count and number of thin places, fibre length, yarn twist, etc.

ANNs were also trained to predict fabric handle. In one study,[68] hand values were predicted from the image of a circular piece of fabric hung on a small round column. In another study,[69] hand values were predicted from KESF measurements, *viz*. tensile recovery, maximum tensile elongation, compressional recovery, bending rigidity, shear hysteresis, surface roughness and weight of the fabric.

Recently, ANNs were also applied to predict garment drape, garment pattern design and body image of the wearer. Fan *et al.*[70] proposed to use a fuzzy-neural network system to predict and display the drape image of garments made from different fabrics and styles. The basic logic is to find and display a drape image from a database that is closest to the drape of the newly designed garment of the same style. The advantages of the approach include very fast computation, avoiding the difficulty of taking into account the effects of accessories, seams and styles on drape in conventional drape simulation and, if sufficient drape images are stored in the database, the predicted drape image can be very close to the actual one. A disadvantage is that only limited styles and changeable feature dimensions can be allowed in the approach.

Designing optimum fit garment patterns for diverse individual consumers is a challenge to be tackled before mass customisation can be realised in the fashion industry. Chan *et al.*[71] proposed the prediction of garment patterns from 3D body measurements using ANNs. They developed an ANN model to predict men's shirt pattern parameters, based on which a pattern could be drafted from the 3D body measurements obtained by

3D laser scanning. They demonstrated that the ANN model had significant advantage over traditional tailoring and could be built into apparel CAD software for practical application.

Garments should not only fit the wearer well, but should also enhance the image of the wearer. From the point of view of beautifying the body image, there may be different optimum garment fits for people who have different body shapes. Liu *et al.*[72] demonstrated that an ANN model can be trained to identify the optimum garment ease for wearers of different sizes. For a thin person, garment ease should be larger, in order to be perceived to have a close to average body size. On the other hand, the optimum garment ease for an obese person can be about 2 cm, in order to create the illusion of being thinner.

14.4 Concluding remarks

Artificial Intelligence (AI) offers great potential for the engineering design of fabrics and garments for the following reasons:

(i) The engineering design of fabrics and garments involves a great deal of expertise and experience. Nevertheless, even a highly experienced expert cannot avoid a certain amount of trial and error. AI is able to significantly reduce the product development process and time to delivery.
(ii) The design process involves numerous rules of thumb and is heuristic in the sense that it should meet several targets simultaneously. Such expertise resides in only a very few specialists, and could be lost due to the retirement of such individuals and the fact that fewer young people are entering the industry. AI is ideal in providing a solution to this acute problem and can be used to acquire such specialists' knowledge and build it into a knowledge base.
(iii) The relationship between the properties/performance of fabrics and garments and their constituent material properties, constructional parameters and processing variables are very complex and are generally nonlinear. Traditional mechanistic models and statistical techniques fall short of mapping such complex relationships, whereas the ANN is an ideal tool to do so.

Currently, the main obstacle for AI in realising its full potential in the engineering design of fabrics and garments is that the effects of changes in many processing variables, particularly those in dyeing and finishing, have not been fully quantified. This is an important task for the textile and clothing industry to accomplish in the future.

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