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Fabric composition testing

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Abstract: This chapter discusses fabric composition testing which is necessary for organizations such as textile manufacturers, import and export houses and R&D institutes, for carrying out applied research and investigation. Much of the information presented in this chapter focuses on some new testing methods such as quantitative fibre mixture analysis for fabrics by scanning electron microscopy (SEM), using the environmental scanning electron microscope (ESEM) method to characterize the surface, interface and dynamic properties of fabrics, computer image processing technology and so on. The traditional tests such as burning, chemical, optical, staining and density tests are systematically considered. The exposition in the chapter indicates general procedures and only suggests interpretation.

Key words: fabric composition testing, environmental scanning electron microscope (ESEM) technology, near infrared spectral image measurement system, thermogravimetry (TG) analysis, computer image processing technology.

3.1 Introduction: the importance of testing fabric composition

The testing of composition of fabric is necessary for various organizations such as textile manufacturers, import and export houses, government agencies, R&D institutes and academic institutions, for carrying out applied research, investigation such as archaeological studies for identification of ancient textile fibres from various archaeological tracts, case analyses by legal medical experts, and so on. In response to ever-changing governmental regulations and the ever-increasing consumer demand for high quality, regulatory testing of fabric composition is essential to minimize risk and protect the interests of both manufacturers and consumers.

Most countries importing apparel and soft home furnishing products require testing the fabric composition mainly for fibre identification labels that indicate the fibre type and percentage of fibre components. Some countries even use fibre composition to classify quota categories. All fabrics contain textile fibres. The exact fibre composition of a specific fabric is important because different fibre types have different characteristics, which can significantly affect the properties and value of the item in question. This

is a particularly important consideration for clothing. A consumer paying a high price for a silk garment would be most unhappy to discover it was made of polyester, for example. There are also implications for duty on imported goods in some countries, such as the United States, while in others regulations may exist to protect consumers. These regulations may require fibre content to be stated, and impose legal penalties for infringement. For fabric manufacturers testing the fabric composition will play an important role in developing and/or revising quality assurance programmes and product specifications. In addition, it also helps to develop, monitor and/or improve manufacturing processes and assists fault-finding and problem-solving processes.

The trend of green consumerism has been extended to textile and apparel products. Major textile product buyers throughout the world, especially in Europe and the USA, have responded to this public awareness by viewing their textile products from an ecological viewpoint and are establishing relevant requirements. All finished fabrics contain different chemicals which may be hazardous or poisonous to both environment and consumer health. So current testing methods on fabric composition also include eco-testing such as chemical analysis for banned azo colourants, formaldehyde content, heavy metal residues, ozone-depleting chemicals, pesticide residues and so on.

The very survival of early humans was greatly aided by fabrics. In modern times, fabrics still perform many essential protective, decorative and social functions, as well as being the basis of a range of advanced structural and functional products. An important factor which is driving the changes in the fabric industry at the present time is the expanding markets created through increase in population and increase in disposable income. Competition between a wide range of similar fabrics, especially in the mass markets, demands a constant pressure for cost reduction in processing methods. On the other hand, new technologies create opportunities for new fabrics, particularly in niche markets. Demand for environmental friendliness will also be important in the future. Environmental concerns have already led to changes in processing methods to conserve energy, water and chemicals. Biodegradable products and recycling technologies are being demanded by consumers.

The fabric industry is becoming an increasingly competitive environment and new types of fabrics have been developed with the help of new technologies. Differentiating fabrics is therefore important and this can be facilitated through optimizing fibre composition, rationalizing fabric structure for more suitable end use, and improving the quality. Testing fabric composition can be done to legal standards, industry standards or custom standards to test whether a product complies with requirements. Testing fabric composition can be used to improve fabric quality and achieve

compliance to international, regional or retailer-specific standards, especially to provide good support in product safety management.

The traditional way of testing composition for single-layered fabrics was to identify the fibres in the fabrics. But currently there are number of different new types of fabrics in the market, such as industrial fabrics and technical fabrics of high-performance fibres, multilayer fabrics with different combinations of materials such as non-wovens, wovens, films and paper, phase change fabrics, electrically conductive fabrics and so on. For these fabrics, testing fabric composition needs new methods besides traditional ones based on traditional textile fibre identification. Of course, when testing composition for any fabric, fibre identification is necessary first. Much of the information presented in this chapter focuses on some new testing methods for fabric composition such as 'quantitative fibre mixture analysis' for fabrics by scanning electron microscopy (SEM), using the environmental scanning electron microscope (ESEM) method to characterize the surface, interface and dynamic properties of fabrics. Other methods covered include micro IR spectroscopy, the near infrared spectral image measurement system for water absorbency of woven fabrics, the technique using capillary electrophoresis/mass spectrometry (CE/MS) for identification of dyed textile fibres, thermogravimetry (TG) analysis and computer image processing technology on fabric testing, as well as the traditional methods such as burning, chemical, optical, staining and density tests. The discussion included in this chapter indicates general procedures and only suggests interpretation.

3.2 Methods of testing fabric content and composition

Testing composition of fabrics is a skilled activity, especially for blended fabrics and multilayer fabrics, where the fibre mixture must first be visually identified by a microscope and then by chemical tests. The amount of each fibre is then determined either by physical separation – where the mixture is created by twisting yarns together or by sewing panels of fabric together – or by chemically extracting one fibre at a time using gravimetric analysis to give a composition result.

Qualitative identification of textile fibres of a specific fabric can be difficult and may require several tests. Simple tests that can be used in identification are described here along with brief comments about their use and importance. In addition to their use in fibre identification, some tests yield insight into problems of processing and care of textile products.

Testing of composition of fabric needs modern laboratories with sophisticated testing and analytical instruments. The methods of testing can be grouped under the following headings:

- Traditional methods
  - Optical test
  - Density test
  - Chemical test
  - Staining test
  - Burning test
- New methods
  - Environmental scanning electron microscope (ESEM) technology
  - Near infrared spectral image measurement system
  - Capillary electrophoresis/mass spectrometry (CE/MS) technique
  - Thermogravimetry (TG) analysis
  - Computer image processing technology

Microscopic evaluation by optical test is a little more specific and in some cases may be accurate enough to identify individual fibres in the fabrics; and the density test or physical separation or chemical extraction, especially chemical solubility, may be accurate enough to categorize fibres in the fabrics into generic groups. Instruments used in more precise and accurate identification are also mentioned above. Investigators who wish to be able not only to state what fibre type in the fabrics is involved but also to identify a specific fibre would usually need instrumental evaluations as well as those described herein.

3.3 Traditional testing methods

For single-layer fabrics having traditional textile fibres, testing fabric composition is almost testing for fibre identification. In other words, certainly, when testing composition for any fabric, fibre identification is necessary first.

The traditional ways of fibre identification can be divided into five smaller groups or tests as above. They are optical, density (Table 3.1), chemical, staining, and burning tests (Table 3.1). Each test has its own advantages and disadvantages. Most of them are cheap and simple identification techniques and are easy to use.

3.3.1 Optical tests: visual identification – microscopy

Optical tests are the simplest tests available, and the use of a microscope allows the observer to see the fabrics up close. This is valuable because certain fibres have particular shapes which can be identified when viewed under a microscope. However, not much information can be obtained from the longitudinal sections alone and viewing the cross-section helps greatly, but preparing cross-sectional samples takes great skill and time. Although

Table 3.1 Physical properties of fibres

	Density (g/cm^3)	Melting point (°C (°F))
Natural fibres		
Cellulose	1.51	None
Silk	1.32–1.34	None
Wool and other hair	1.15–1.30	None
Artificial fibres		
Acetate (secondary)	1.32	260 (500)
Acetate (tri)	1.30	288 (550.4)
Acrylic	1.12–1.19	None
Modacrylic	1.30 or 1.36	188 (370.4) (not sharp) or 120 (248)
Nylon 6	1.12–1.15	213–225 (415.4–437)
Nylon 66	1.12–1.15	256–265 (492.8–509)
Polyester	1.38 or 1.23	250–260 (482–500) or 282 (539.6)
Polypropylene	0.90–0.92	170 (338)
Rayon	1.51	None

definite information about the fibres can be obtained from their shapes, for some fibres, especially artificial fibres with similar shapes, additional analysis is required for specific identification. Therefore, photomicrographs of selected fibres may be used for comparison. Microscopic examination is indispensable for positive identification of the several types of cellulosic and animal fibres, because the infrared spectra and solubility techniques will not distinguish between different species.

Analyses by infrared spectroscopy and solubility relationships are the preferred methods for identifying artificial fibres. The analysis scheme based on solubility is very reliable. The infrared technique is a useful adjunct to the solubility test method. The microscopic examinations are generally not suitable for positive identification of most artificial fibres and are useful primarily to support solubility and infrared spectra identifications.

The American Association of Textile Chemists and Colorists (AATCC) publishes a *Technical Manual* annually. It has test methods for the identification of textile fibres qualitatively and quantitatively along with a number of other test methods and evaluations. The photomicrographs are very helpful as are the various schemes for identification, including solubility. The ASTM *Identification of Fibres*, D276, is also very helpful but has no photographs.

3.3.2 Density tests: physical separation

The density test offers a simple test of preparing a liquid in which the fibres will either sink or float, but porous fibres and fibre blends will skew the

density results. The density gradient column is now widely used and necessitates observing the level to which a test specimen will sink in a column of liquid, the density of which increases uniformly from top to bottom. The column should be about 40–50 mm high and normally graduated from 0 at the top to 100 cm at the bottom. Up to three such columns can be positioned in a water bath controlled at 23 ± 1°C. A valuable attribute of this method is that the columns, when prepared, can be accurately calibrated with glass beads of known density.

Various liquids are used to cover a spread of working densities (Table 3.1) depending on the density of the test material.

3.3.3 Chemical tests: chemical extraction

Chemical tests are cheap and simple methods, but the tests are not quantitative. Also, the number of elements that can be detected is limited. So for more accurate analysis, better and more expensive equipment is needed.

The solubility of a fibre extracted from a fabric in specific chemical reagents is frequently a definitive means of specific fabric identification. Frequently, however, this process identifies only generic groups or categories of fibres in the fabrics. If one combines the results of the microscopic evaluation, the burning test, which will be introduced in later sections, and the chemical solubility test, it is possible, in many cases, to positively identify specific fibres in the fabrics. The solubility behaviour of fibres in various solvents is given in Table 3.2.

3.3.4 Staining tests

Staining tests can help to show changes in fibre structure from one process to another. If the fibre structure is changed, the dye shade will be different from batch to batch. A characteristic that can be obtained from dyeing is whether the fibre is hydrophobic or hydrophilic, because hydrophilic fibres are easier to dye. Staining can be used to group fibres into three groups: cellulosic, protein-based, or artificial fibres, but the process is not good on deep-dyed samples, and chemical finishes can interfere with the process.

When fibres are white or off-white or when colour can be stripped from fibres, staining techniques may be used as a part of identification. Specially prepared mixtures of dyes are used to stain the fibres for a specified time and at a specified temperature. After staining, the fibre, yarn or fabric pieces are dried and then compared with a known sample.

3.3.5 Burning tests

The burning test is a good preliminary test for fabric identification. It provides valuable data regarding appropriate care and will help place a fibre

Table 3.2 Solubility behaviour of fibres in the fabrics

	Acetone 100%	Hydrochloric acid 20%	Sulfuric acid 60%	Sulfuric acid 70%	Chlorine bleach 5%	Formic acid 90%
Acetate	Soluble	Insoluble	Soluble	Soluble	Insoluble	Soluble
Acrylic	Insoluble	Insoluble	Insoluble	Insoluble depending on type	Insoluble	Insoluble
Cotton	Insoluble	Insoluble	Slightly soluble	Soluble	Insoluble	Insoluble
Hair	Insoluble	Insoluble	Insoluble	Insoluble	Soluble	Insoluble
Hemp	Insoluble	Insoluble	Slightly soluble	Soluble	Insoluble	Insoluble
Linen	Insoluble	Insoluble	Slightly soluble	Soluble	Insoluble	Insoluble
Modacrylic	Soluble or insoluble depending on type	Insoluble	Insoluble	Insoluble	Insoluble	Insoluble
Nylon	Insoluble	Soluble	Soluble	Soluble	Insoluble	Soluble
Olefin	Insoluble	Insoluble	Insoluble	Insoluble	Insoluble	Insoluble
Polyester	Insoluble	Insoluble	Insoluble	Insoluble	Insoluble	Insoluble
Ramie	Insoluble	Insoluble	Slightly soluble	Soluble	Insoluble	Insoluble
Rayon	Insoluble	Insoluble	Soluble	Soluble	Insoluble	Insoluble
Silk	Insoluble	Partially soluble	Soluble	Soluble	Soluble	Partially soluble
Wool	Insoluble	Insoluble	Insoluble	Insoluble	Soluble	Insoluble

in the fabrics into a specific category. A burning test can help determine the class to which a fibre belongs by observing its burning behaviour. Observing how things smell and char when they are burnt are qualities that can help. To identify a fabric that is unknown, a simple burn test can be done to determine whether the fabric is made of a natural fibre, an artificial fibre, or a blend of natural and artificial fibres. The burn test is used by many fabric stores and designers and generally requires practice to determine the exact fibre content. However, an inexperienced person can still determine the difference between many fibres to narrow the choices down to natural or artificial fibres. This elimination process will give information necessary to decide the care of the fabric.

The following procedure may be used to carry out the burning test for fabrics:

1. Select one or two yarns from the warp of a woven fabric or unravel a length of yarn from a knitted fabric.
2. Untwist the yarn so that the fibres are in a loose mass.
3. Hold the loosely twisted yarn in forceps; move them towards the flame from the side (i.e., approach the flame from its own level, not by bringing the sample down into the flame).
4. Observe the reaction as the yarn approaches the flame.
5. Move the yarn into the flame, and then pull it out of the flame and observe the reaction. Does the yarn start to burn as it nears the flame? Does it start to melt? Does it shrink away from the flame? Does it burn quickly or slowly? Does it have a sputtering flame, a steady flame, no flame at all? When removed, does it continue to burn? Is it bright red or coloured to indicate that it has reached a high temperature? Does the flame go out when removed from the source? What type of ash or residue, if any, is formed?
6. Notice any odour given off by the fibre both while it is in the flame and after it is removed.
7. Observe the ash or residue formed and what characteristics it has. Is it brittle? Is it bead-shaped? Is it fluffy? Is it the shape of the yarn? Or is there nearly no residue?
8. Repeat for the filling yarn of woven fabrics.
9. If the fabric does not have yarn structure, or if it is impossible to 'deknit' a length of yarn from complex knitted structures, a small sliver of fabric can be cut and used in place of the yarn.

3.4 Burning behaviour of fibres

All fibres will burn but asbestos-treated fibres are, for the most part, fireproof. The burning test should be done with caution. A small piece of fabric is preferred. The fabric should be held with tweezers but not with fingers.

Some fabrics will ignite and melt. The result is burning drips which can adhere to fabric or skin and cause a serious burn.

3.4.1 Natural fibres

Cotton is a plant fibre. When ignited it burns with a steady flame and smells like burning leaves. The ash left is easily crumbled. Small samples of burning cotton can be blown out as you would with a candle.

Linen is also a plant fibre but different from cotton in that the individual plant fibres which make up the yarn are long where cotton fibres are short. Linen takes longer to ignite. The fabric closest to the ash is very brittle. Linen is easily extinguished by blowing on it as you would with a candle.

Silk is a protein fibre and usually burns readily, not necessarily with a steady flame, and smells like burning hair. The ash is easily crumbled. Silk samples are not as easily extinguished as cotton or linen.

Wool is also a protein fibre but is more difficult to ignite than silk as the individual 'hair' fibres are shorter than silk and the weave of the fabrics is generally looser than with silk. The flame is steady but more difficult to keep burning. The smell of burning wool is like that of burning hair.

3.4.2 Artificial fibres

Acetate is made from cellulose (wood fibres), technically cellulose acetate. Acetate burns readily with a flickering flame that cannot be easily extinguished. The burning cellulose drips and leaves a hard ash. The smell is similar to that of burning wood chips.

Acrylic, technically acrylonitrile, is made from natural gas and petroleum. Acrylics burn readily due to the fibre content and the lofty, air-filled pockets. A match or cigarette dropped on an acrylic blanket can ignite the fabric which will burn rapidly unless extinguished. The ash is hard. The smell is acrid or harsh.

Nylon is a polyamide made from petroleum. Nylon melts and then burns rapidly if the flame remains on the melted fibre. If you can keep the flame on the melting nylon, it smells like burning plastic.

Polyester is a polymer produced from coal, air, water and petroleum products. Polyester melts and burns at the same time; the melting, burning ash can bond quickly to any surface it drips on, including skin. The smoke from polyester is black with a sweetish smell. The extinguished ash is hard.

Rayon is a regenerated cellulose fibre which is almost pure cellulose. Rayon burns rapidly and leaves only a slight ash. The burning smell is close to that of burning leaves.

Blends consist of two or more fibres and, ideally, are supposed to take on the characteristics of each fibre in the blend. The burning test can be used but the fabric content will be an assumption.

In order to determine the fibre content in a fabric, a piece of fabric of area approximately 1 square inch (6.5 cm^2) is ignited using a butane lighter, holding it with a pair of tweezers over a non-flammable surface in a well-ventilated area. The quality and colour of the flame, the odour produced and the quality of the resulting ash or cinder are observed carefully. Table 3.3 may be used to determine the fabric's content.

The burning test is a simple test to start with when testing the fibre content of fabrics. However, there are many ways to interpret the results. Incorrect interpretation, of course, will lead to false information. Whether a fibre burns or self-extinguishes is not dependent upon whether it is a 'natural' fibre or a 'synthetic' fibre. For example, because of their chemical make-up, both silk and wool will self-extinguish when the flame is removed. Rayon is regenerated cellulose, so even though it is an artificial fibre, it burns extremely well and will continue to do so after the flame is removed. It will burn until the sample is exhausted if unhindered. The smell given off when rayon burns will be similar to that of paper (also cellulose based), but silk will smell like burning hair.

Silk fabrics will shrink away due to the heat given off even before they burn from contact with the flame. The best way to view this 'shrinking' of silk is to slowly bring it close to the flame but not into the flame. While a synthetic like polyester will also self-extinguish, it does not behave in the same manner as silk when exposed to the flame. Silk will 'shrink' away from the flame and form small beads on the ends of the fibres after the flame is removed. Polyester will also form beads but it does not shrink away from the flame (it does melt, but it doesn't 'jump back' like silk). The colour, shape and size of the beads at the end of comparable-sized threads of polyester and silk will also differ.

Certain artificial fibres are not easily identified by any of the testing procedures cited. Positive verification of some fibres depends on the use of one or more sophisticated instrumental techniques. These include testing for melting point, refractive index, index of birefringence, the use of X-ray diffraction machines, infrared spectrophotometers, chromatographs of various types, electron scanning microscopes and polarizing microscopes. These are standard equipment in many university laboratories, testing laboratories and research laboratories. Although they may not be available in departments where textile science is taught, they may be available in chemistry departments.

3.5 New testing methods

In this section a detailed discussion is provided on the principles and procedures of new testing methods such as environmental scanning electron microscope (ESEM) technology, near infrared spectral image measurement system, the capillary electrophoresis/mass spectrometry (CE/MS)

Table 3.3 Flammability behaviour of fabrics

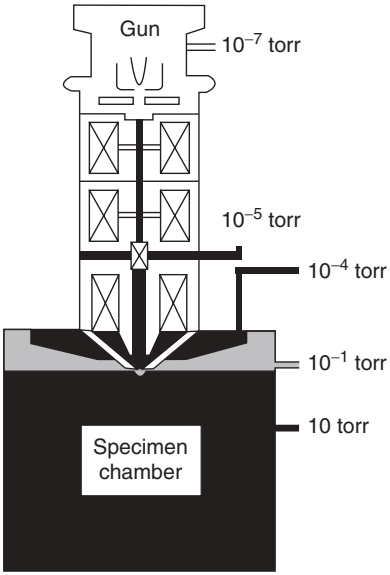
Fabric	Flame quality	Odour	Ash quality	Comments
Wool	Orange colour, sputtery	Burning hair or feathers	Blackish, turns to powder when crushed	Flame will self-extinguish if flame source removed, no smoke
Silk	Burns slowly	Burning hair or feathers	Greyish, turns to powder when crushed	Burns more easily than wool but will self-extinguish if flame source removed
Cotton	Yellow to orange colour, steady flame	Burning paper or leaves	Greyish, fluffy	Slow-burning ember
Linen	Yellow to orange colour, steady flame	Burning paper or leaves	Similar to cotton	Takes longer to ignite than cotton but otherwise very similar
Rayon	Fast orange flame	Burning paper or leaves	Almost no ash	Ember will continue to glow after flame source removed
Polyester	Orange flame, sputtery	Sweet or fruity smell	Hard shiny black bead	Black smoke
Acetate	Burns and melts, sizzly	Acidic or vinegary	Hard black bead	Will continue to burn after flame source removed
Nylon	Burns slowly and melts, blue base and orange tip, no smoke	Burning celery	Hard greyish or brownish bead	Will self-extinguish if flame source removed
Acrylic	Burns and melts, white-orange tip, no smoke	Acrid	Black hard crust	Will continue to burn after flame source removed
Polypropylene (olefin)	Burns and melts	Not defined	Hard, round bead, maybe light brown	Shrinks quickly

technique, thermogravimetry (TG) analysis and computer image processing technology.

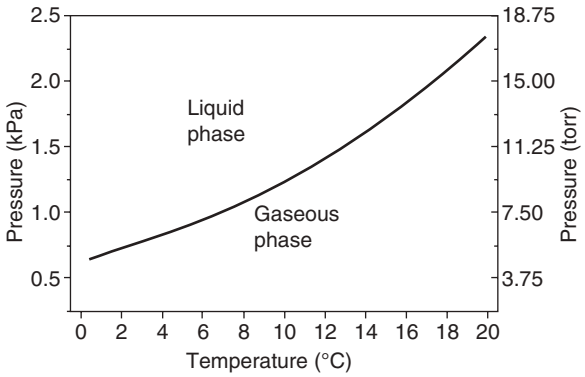
3.5.1 Environmental scanning electron microscope technology

Environmental scanning electron microscope (ESEM) technology was introduced in the mid-eighties. This technology has improved over time. The ESEM now can offer full functionality in three modes of operation: High Vacuum, Low Vacuum and ESEM mode. Conventional high vacuum SEM is also available on the ESEM. This mode can be used for the examination of vacuum-compatible or gold/carbon-coated non-conductive samples. A low vacuum mode is suitable for the examination of uncoated non-conductive samples. The ESEM mode allows very high chamber pressures of up to 50 torr. This is achieved by the differential pumping system, as illustrated in Fig. 3.1 [1].

In both low vacuum and ESEM mode, the specimen sits in a gaseous atmosphere in the ESEM chamber. Ionization of the gas by electrons emitted from the specimen results in the neutralization of the charge build-up on the specimen surface. As a result, non-conductive samples can be imaged. The ESEM mode is appropriate for the examination of hydrated, oily or outgassing samples, where it is desirable to observe the sample in its



3.1 Differential pumping system.



3.2 Water phase curve.

natural state. Samples are examined uncoated, with a gaseous secondary electron detector (GSED) [2], within a gaseous environment.

In the ESEM, specimens can be hydrated or dehydrated by controlling the temperature of the specimens and the chamber pressure in favour of water condensation or evaporation at different relative humidity, as presented in Fig. 3.2 [3].

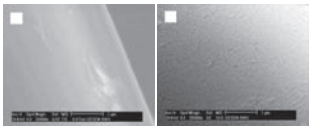
The ESEM is specifically suited to dynamic experimentation at the micron scale and below. ESEM technology allows dynamic experiments at a range of pressures and temperatures and under a variety of gases/fluids. Some accessories can also be added into an ESEM to expand its observation capacity.

Application of environmental scanning electron microscope for surface characterization of uncoated textile materials

It is well known that fibre surface characteristics affect wetting, stiffness, strength, dyeing, wrinkling and other performance properties, to a large extent. Based on the understanding of fibre surface properties, novel fibres and their applications may be created or engineered.

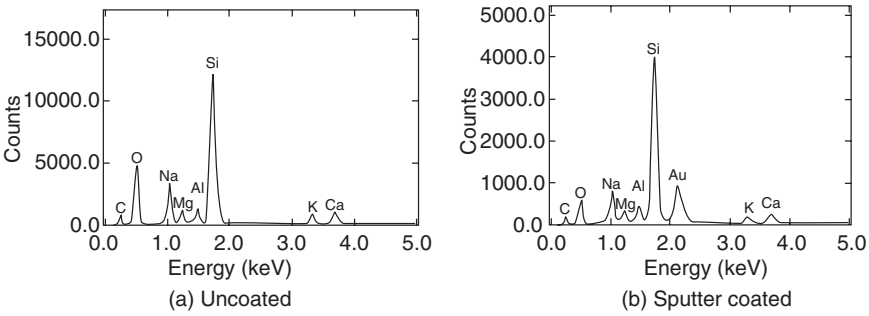
Philips XL30 ESEM-FEG at Heriot-Watt University, UK, offers high-resolution secondary electron imaging of wet, oily, dirty, outgassing and non-conductive samples in their natural state without significant sample modification or preparation. Some new techniques to characterize textile materials have been developed.

The ESEM is able to physically examine virtually any textile materials without any special preparation or conductive coating. The ESEM images in Fig. 3.3 [4] present the different surface characteristics of glass fibre before and after gold coating. The image in Fig. 3.3(a) shows the relatively



(a) Uncoated (b) Sputter coated

3.3 ESEM images of glass fibres: (a) uncoated, (b) sputter coated.



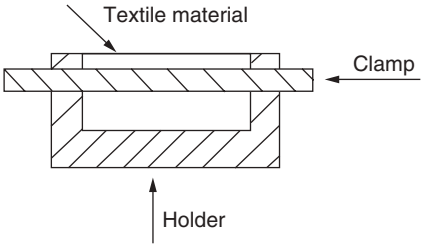
(a) Uncoated (b) Sputter coated

3.4 EDX spectra of glass fibres: (a) uncoated, (b) sputter coated.

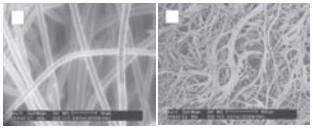
smooth surface of the glass fibre with some particle-like dots, but next the fibre surface is covered with the gold cluster (Fig. 3.3(b)) after sputter coating at 20 mA for 60 s. The coating has also changed the chemical composition, revealed by dispersive X-ray analysis (EDX) in the ESEM. The Philips XL30 ESEM-FEG equipped with a Phoenix energy dispersive X-ray analysis system (EDX) was used to examine the chemical compositions of the glass fibres, and an accelerating voltage of 20 kV with accounting time of 100 s was applied. Figure 3.4(a) [4] shows the EDX spectrum at an area of the uncoated glass fibre observed in Fig. 3.3(a). It can be seen that the fibre predominantly consists of Si, O, Ca, Mg, Na and K. A significant amount of Au on the fibre surface can be observed after coating (Fig. 3.3(b)) compared to the original fibre (Fig. 3.4(b)) [4].

Interface characterization of textile materials

In many applications of textile materials, interfaces are formed between two phases of either the same or different materials. The characteristics of interfaces are usually different from those of the bulk phase(s). The goal of textile interface studies is to facilitate the manufacture of technological textiles with optimized properties on the basis of a comprehensive understanding of interfacial behaviour of textile materials and their resulting influence on material processes.



3.5 Sample holder.



(a) Wet state (b) After drying

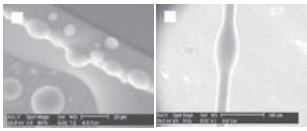
3.6 ESEM of wet samples: (a) alginate sorbent in wet state, (b) alginate sorbent after drying.

The Philips XL30 ESEM-FEG is able to image not only non-conductive but also wet samples without any need for coating or preparation. Therefore it is an important tool for the interfacial studies of textile materials.

To improve the image of interfacial characteristics of textile materials, a special specimen holder was designed as illustrated in Fig. 3.5 [4]. The ESEM image in Fig. 3.6(a) [4] illustrates the absorption of wound exudate by alginate fibres. The image was taken at 20 kV at a temperature of 5°C and a pressure of 5.0 torr. Direct observation avoids artefacts or destruction, which may be caused by drying and coating the samples in a normal SEM as shown in Fig. 3.6(b) [4].

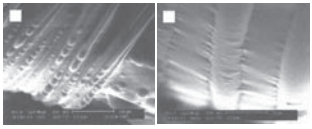
When a liquid comes in contact with the surface of a fibre, the liquid will either spread out and 'wet' the fibre surface, or it will form droplets that are 'repelled' from the surface. The wettability of a textile fibre is of importance in such systems as filters, coalescent units, sorbents, composite and biomedical materials. The wetting of fibres by a liquid is governed by the interfacial energies between the three phases of the liquid/vapour, solid/vapour and solid/liquid interfaces [5]. The angle formed at the edge of these droplets where the liquid contacts the solid surface, and the surface energy that affects this angle, form the basis of modem liquid–solid interface technology.

In the ESEM, specimens can be hydrated or dehydrated by controlling the temperature of the specimens and the chamber pressure in favour of water condensation or evaporation at different relative humidities. In the water wetting experiment, the pre-cooled fibre specimen is placed onto the



(a) Water wetting (b) Oil wetting

3.7 Wetting of PP fibre in ESEM: (a) water wetting, (b) oil wetting.



(a) Untreated (b) Plasma-treated

3.8 ESEM images of PET fibres: (a) untreated, (b) plasma-treated. Water droplets of different shapes are visible on the fibre surfaces.

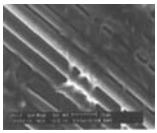
Peltier cooling stage in the ESEM chamber. The relative humidity can be adjusted by changing the pressure or the temperature of the Peltier stage within the chamber. As the relative humidity reaches 100%, water condensed onto the surface of the sample will appear. Observations on water droplets on the material can then be made at each point of interest, and the dynamic wetting process of the material can be recorded. The image in Fig. 3.7(a) [4] reveals the hydrophobic properties of the polypropylene fibre surfaces. High contact angles can be observed from the ESEM image [6].

However, the ESEM image of the same fibres shows the hydrophilic properties of the surfaces with low contact angles for oil, as presented in Fig. 3.7(b) [4]. In this oil wetting experiment, oil was added using a micro-injector [7], which can be mounted on the specimen chamber. The injection needle of the micro-injector can be placed just above the specimen. Different kinds of liquid can be used for wetting observations in the ESEM.

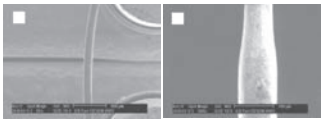
The fibres untreated and treated by plasma activation also show different wetting behaviours, as illustrated in Fig. 3.8 [4]. In the ESEM chamber, as relative humidity reaches 100%, the condensation of water is initiated by forming small water droplets on the fibre surfaces. It can be seen that the droplets are formed on the untreated material and fibre systems at the microscopic level *in situ*. An example of bacteria cells on PLLA fibres is presented in Fig. 3.9 [4].

Dynamic characterization

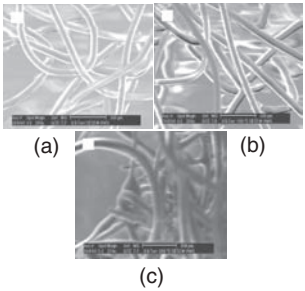
An ESEM equipped with a tensile stage can be used to examine the dynamic tensile behaviour of textile materials ranging from individual fibres to



3.9 Bacterial cells on PLLA fibres.



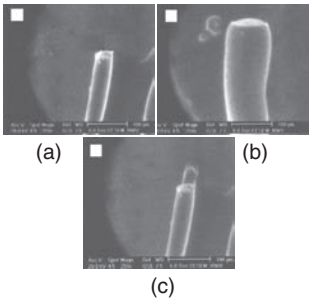
3.10 Tensile testing of single PP fibre: (a) fibre on the tensile stage, (b) necking of PP fibre.



3.11 Dynamic bonding process of bicomponent fibres: (a) at room temperature, (b) at about 100°C, (c) at about 200°C.

fabrics made by different processes. The tensile stage can be placed in the ESEM chamber. The tensile process can be video-recorded, while the strain–stress curve is obtained. Figure 3.10(a) [4] illustrates polypropylene fibre on the specially designed tensile stage. The fibre was wound onto the pins, which are fixed on two movable plates in the tensile stage. In Fig. 3.10(b) [4], necking is observed as the tensile force is applied to the fibre. This observation gives insight into the neck profile and the structural features of the necked region.

Textile materials in fabric form can be easily examined by tensile stage in the ESEM [8]. ESEM technology also allows dynamic experiments at a range of pressures and temperatures and under a variety of gases/fluids. An ESEM equipped with a heating stage can be used to observe the dynamic thermal process of textile materials. Figure 3.11 [4] shows an example of thermal bonding of the PET/CoPET bicomponent fibre web (a carded web without bonding) as observed by the ESEM. The sample was placed on the heating stage. The heating stage was then fixed in the ESEM chamber. The



3.12 Water absorption of fibre structure: (a) experiment starts at 75% RH, (b) adsorption phase at 100% RH, (c) desorption at 75% RH.

heating rate was set at 10°C/min and the soaking time was set for 5 minutes. The heating process was video-recorded. The ESEM images show that the PET/CoPET bicomponent fibre web shows no obvious change from room temperature to 100°C, as presented in Fig. 3.11(a) and (b). It can be seen that when the temperature reaches about 200°C, the fibres are bonded together at fibre intersections, as illustrated in Fig. 3.11(c). It can be seen that fibre surface morphology has also changed due to the thermal bonding.

A series of micrographs taken during hydration and dehydration of the sodium polyacrylate fibre (shown in Fig. 3.12 [4]) also illustrates dynamic characterization. The pre-cooled sample fibre was placed onto the Peltier stage. The specimen temperature was set at 5°C, as this minimized the risk of accidental freezing. The sample was observed at 75% RH (5.0 torr) and 100% RH (6.6 torr) at 5°C. On reversal of the process, the ramping down was halted at 75% RH at 5°C. This clearly shows the effects of relative humidity on fibre structure. As can be seen from Fig. 3.12(a)–(c), the fibre diameter increased from about 43 μm to over 100 μm during adsorption at 100% RH. The swelling in the cross-section was much higher than that in the fibre axis. When the relative humidity was lowered from 100% to 75%, dehydration took place and the fibre rapidly shrank to the previous state.

Dynamic experiments can be conducted at a range of pressures and temperatures, and in a variety of gases/fluids. Different combinations of temperature, pressure and gases/fluids provide more opportunities for the study of textile materials.

3.5.2 Near infrared spectral image measurement system

For the textile industry, infrared spectroscopic methods that are based on diffuse reflectance measurements can be used for the non-destructive analysis of polymer composition of the fabric materials including their auxiliaries.

Heise *et al.* [9] used mid-infrared spectroscopy in combination with the diffuse reflectance (DR) technique for quantification of the textile finishing auxiliaries that were applied for improving various fabric characteristics. The results of a quantitative analysis of a reactive auxiliary (cyclodextrin derivative) applied on cotton fabrics up to 5% (by weight) are satisfactory, but limitations of the diffuse reflectance measurement technique still exist. Multivariate calibration based on partial least squares was employed using the specific bands of the cyclodextrin derivative within the spectral interval of 1900–1480 cm^{-1}, providing prediction results with around 5% of relative standard prediction error, based on mean sample population concentrations.

Yotsuda *et al.* [10] developed the near infrared spectral image measurement system for water absorbency of woven fabrics. This system consists of a pair of near-infrared light sources, a series of optical apparatus, a near-infrared camera, and an image processor. The developed measuring system is adequate for testing the time-dependent water absorbency of the materials by using the model samples and several woven fabrics. It could be expected that the sensed information obtained by the spectral image could control the quality of the water absorbency more precisely and effectively than the conventional test methods.

Wang *et al.* [11] studied the analysis methods of fibre by micro IR spectroscopy. In the study, 20 different kinds of fabric fibres analysed by micro IR spectroscopy were discussed.

Attenuated total reflection (ATR) is a convenient mode for single-fibre analysis by infrared microspectroscopy, particularly when transmission spectra are difficult to obtain or when surface preference sampling is desirable. Textile finishes such as spin finishes, anti-static finishes and permanent press finishes can be revealed by ATR techniques. Bicomponent fibres may be analysed by a combination of ATR techniques, transmission techniques and spectral subtraction [12].

3.5.3 Capillary electrophoresis/mass spectrometry technique

Capillary electrophoresis/mass spectrometry (CE/MS) has been used in forensic fibre comparison. CE/MS can separate extracted dye components on forensically relevant fibre samples and provide semi-quantitative estimates of dye amounts as well as qualitative information to identify the dye present (via the molecular weight and mass spectra) (https://www.facss.org).

Fibre evidence is frequently used in forensic science to associate a suspect to a victim or crime scene. The fibres are found as trace evidence in crimes of personal contact such as homicide, assault, sexual offences and hit-and-

run accidents. In forensic fibre comparison, fibres are screened by visual inspection using optical microscopic techniques such as polarized light microscopy (PLM) and by spectroscopic methods such as UV/visible and fluorescence microspectrophotometry. If spectra of the known and questioned fibres are consistent, the hypothesis that the fibres originate from a common source should not be rejected. The premise of the method presented here is that additional discrimination may be achieved by extraction of the dye from the fibre, followed by trace analysis by a high-resolution separation technique.

A sensitive and selective technique such as capillary electrophoresis/mass spectrometry (CE/MS) is needed to analyse the small amount of dye (2–200 mg) present on forensically relevant fibre samples. CE/MS can separate extracted dye components and provide semi-quantitative estimates of dye amounts as well as qualitative information to identify the dye present (via the molecular weight and mass spectra). A decision tree for extraction of unknown dyes from textile fibres has been developed that employs three capillary electrophoresis methods with diode array detection for the separation and identification of dyes from the six major textile dye classes. Although this approach is destructive to the sample, only an extremely small sample is required (1–2 mm of a single 15 micron diameter fibre). Automated micro-extractions and CE offer the forensic analyst reproducible analyses (% RSDs ranging from 5 to 25%) with limits of detection in the picogram range. The combined extraction/CE-MS system is capable of achieving both highly discriminating and highly sensitive identification of dyes for improved discrimination of trace fibre evidence. These advances establish the chemical basis for discrimination of fibres.

3.5.4 Thermogravimetry analysis

Thermogravimetric analysis (TGA) has been used for measuring the degree of thermal degradation of fibres in the fabrics, especially high-performance fibres. Here are some application examples.

Evaluating the thermal stability of high-performance fibres by thermogravimetric analysis

The degree of thermal degradation of eight types of high-performance fibres (HPFs) was measured under nitrogen and air atmosphere by weight loss using thermogravimetric analysis (TGA), and the characteristic degradation temperatures were obtained. The kinetics of the thermal degradation have also been analysed according to the Freeman–Carroll method and the activation energies of the HPFs were estimated. The experimental results show that para-aramids (Kevlar® 29, 49 and 129, and Twaron®2000)

have similar thermal stability, but their thermal degradation temperatures and activation energies in air are different from those in nitrogen, which means that the thermostability of the fibre depends not only on its intrinsic structure but also on the atmosphere and temperature of the testing environment. Terlon® fibre shows higher degradation temperature as a copolymer of para-aramid, and its initial degradation temperature is 476.4°C in air. It can also be found that the PBO (poly(*p*-phenylene benzobisoxazole)) fibre has the highest thermal degradation temperature among the samples tested, but its activation energy is not the highest in both air and nitrogen atmosphere. The UHMW-PE (ultra high molecular weight polyethylene) fibre has the lowest thermal degradation temperature, and begins to degrade when the temperature reaches 321.8°C under air atmosphere [13].

Pyrolysis behaviour of rayon fibres treated with $(NH_4)_2SO_4/HN_4Cl$

The pyrolysis behaviour of rayon fibres treated with $(NH_4)_2SO_4/HN_4Cl$ was investigated by thermogravimetry (TG) analysis and the kinetics parameters were obtained by TG and DTG curves. It was found that the pyrolysis proceeded at a lower temperature and had a bigger yield of char when the rayon fibres had been treated with $(NH_4)_2SO_4/HN_4Cl$ than when they had been treated with $H_2SO_4/CO(NH_2)_2$. The effective part of $(NH_4)_2SO_4/HN_4Cl$ was produced at a wide range of temperature and in a tempered way, which resulted in a better effect of the catalyst. After treatment with $(NH_4)_2SO_4/NH_4Cl$, the order of the pyrolysis reaction of the rayon fibres increased from 1.1 to 3.2, while the activation energy decreased from 237 kJ/mol to 94 kJ/mol. Using this catalyst system, the rayon-based carbon fibres showed a tensile strength of 1.05 GPa [14].

3.5.5 Computer image processing technology

The recent development of computer technology makes it possible to apply pattern recognition techniques to many real textile industrial problems, including fabric composition testing. Shangtiao *et al.* [15] investigated some image processing techniques such as filtering, edge detection, boundary extraction and extracting the central line of the yarn to construct an image processing method to distinguish between cotton fibre and ramie fibre from the blended yarn fabric. An image-processing algorithm for classifying both fibres from the image data obtained from the blended yarn fabrics was developed and the results turned out to be successful.

With new fibres being developed continually, for relevant fabric composition testing, traditional fibre identification methods are not enough. New

methods have to be investigated, such as those aimed at identification of soybean protein fabric, chitin fabric, bamboo fabric, cashmere fabric, polylactic acid fabric, lyocell fabric, modal fabric, milk protein fabric, and fabrics of their fibre blended with cotton, ramie, silk and wool.

For high-performance fibres (HPFs) such as para-aramid fibres (Kevlar® 29, 49 and 129, and Twaron®2000), Terlon® fibre, PBO (poly(*p*-phenylene benzobisoxazole)) fibre, UHMW-PE (ultra high molecular weight polyethylene) fibre, basalt fibre and quartz fibre, when testing fabric composition not only the generic fibre type needs to be identified but also the chemical element discrimination and even specific distinguishing behavioural features. So fabric composition testing of high-performance fibres needs more advanced methods with more sophisticated equipment.

For newly structured, newly engineered fabrics such as multilayer fabrics, phase change fabrics and electrically conductive fabrics, more complex or complicated methods should be sought. Some applications of the achievements in the above fields will be introduced in the following sections.

3.6 Applications

3.6.1 Applications in standards on fabrics

Standard test method for extractable matter in textiles

This test method covers a procedure for determining the extractable material on most fibres, yarns and fabrics. Three options are included. Option 1 uses heat and Soxhlet extraction apparatus. Option 2 uses room temperature and extraction funnels. Option 3 uses either Option 1 or Option 2 extraction but provides for calculation of extractable matter from the loss in mass of the material due to the extraction rather than the extractable matter residue [16].

The solvents for use in this method are any solvents that the party or parties concerned agree on, such as halogenated hydrocarbon (HH), chloroform, tetrachloroethane, alcohol, etc.

3.6.2 Analysis of other vegetable textile fibres and yarns

In general, the methods and procedures described in this part deal with the identification of vegetable textile fibres of various types as well as paper yarn and woven fabrics of paper yarn. Physical characteristics, such as the decitex of yarns, the weight per unit area of fabrics, as well as the weight percent of vegetable fibres when the vegetable fibres are blended with other types of fibres, are also determined [17].

Principle

The identification of vegetable fibres in all their forms and of paper yarn is determined microscopically. The physical characteristics are visually determined then measured following prescribed methods. If required, manual or chemical identification and separation of additional fibres is performed and the resulting mass of each type of fibre is taken.

Apparatus

- Polarizing microscope comprising a light source (reflected and transmitted), a light condenser, a stage which supports the slide carrying the fibres, an ocular and objectives. A first-order red plate is desirable
- Stage movable in two directions at right angles
- Objective and ocular, capable of providing at least 100× magnification
- Low-powered stereo microscope
- Micro projector (optional), equipped with a fixed body tube, a focusable and movable stage responsive to coarse and fine adjustments, a focusable substage with condenser and iris diaphragm, and a vertical light source to give a precise magnification of up to 500× in the plane of the projected image on a flat surface
- Image analysis system (optional)
- Stage micrometer calibrated in intervals of 0.01 mm for accurate setting and control of the magnification
- Scanning electron microscope (optional)
- Suitable sectioning apparatus
- Suitable mounting media
- Cover-glass slips
- Reference samples of flax, true hemp, jute (and other textile bast fibres), sisal (and other textile fibres of the genus *Agave*), coconut, abaca (manila hemp), ramie, paper, etc.
- Analytical balance, with a range up to 200 g and accurate to 0.0001 g.
- Precision balance, with a minimum capacity of 1000 g and a readability of 0.1 g.
- Yarn reel, precision ruler or any other apparatus giving similar results
- Shirley crimp tester, or any other length-measuring apparatus giving similar results
- Ultraviolet (UV) light source
- Dissecting needles, picks or other equipment giving similar results.

3.7 Identification of new textile fibres

The differences in composition such as macrostructure and microstructure between new fibres such as lyocell fibre, modal fibre, soybean protein fibre,

bamboo fibre, milk protein fibre and chitin fibre must result in discrepancies in macroscopic features, physical and chemical properties, which can be used to distinguish different fibres. Some efficient methods to identify the six new textile fibres listed above are presented.

3.7.1 Identification of lyocell fibre

The nature or generic type of a cellulosic material may be determined by a burning test and then the longitudinal feature may be observed by microscopic examination, referring to the information from fibres such as modal, bamboo, chitin, cotton and regular viscose fibres. Sodium hypochlorite may be used as a solvent to investigate the dissolution behaviour further. In addition, a tensile test may be carried out to find out the tenacity of the fibre, as the tenacity of lyocell fibre is the highest among the cellulosic fibres [18].

3.7.2 Identification of modal fibre

The nature or generic type of a cellulosic material may be determined by a burning test and then the longitudinal feature may be observed by microscopic examination, referring to the information from fibres such as modal, bamboo, chitin, cotton and regular viscose fibres. In addition, the modal fibre cross-section may be observed by microscope taking the reference as bamboo fibre and regular viscose. Subsequently, 75% sulfuric acid may be used as a solvent to observe the solubility. Tensile and wet elongation tests may be performed to determine the tenacity [18].

3.7.3 Identification of soybean protein fibre

Firstly, the nature or generic type of a protein fibre may be determined by a burning test. Then, an iodine–potassium iodide staining test may be performed to exclude wool and silk. A solution of boiling 5% sodium hydroxide may be used as a solvent to find out the dissolution behaviour: soybean protein fibre does not dissolve, milk fibres swell and become moist, and chitin fibre dissolves. Finally, boiling dimethyl formamide (DMF) may be used as a solvent to examine the protein fibre further [18].

3.7.4 Identification of bamboo fibre

Firstly, the nature or generic type of a cellulosic material may be determined by a burning test and then the longitudinal feature may be observed by microscopic examination, referring to the information from fibres such as modal, bamboo, chitin, cotton and regular viscose fibres. Subsequently, 37%

hydrochloric acid may be used as a solvent to observe the solubility at normal temperature: modal fibre dissolves quickly, while regular viscose dissolves slowly and bamboo fibre dissolves partially. Finally, a density test may be used (using a density grading column) to determine the density. The density of bamboo fibre is lower than those of regular viscose, lyocell, modal and cotton fibres [18].

3.7.5 Identification of milk protein fibre

Firstly, the nature or generic type of a protein fibre may be determined by a burning test. Then an iodine–potassium iodide staining test may be performed to exclude wool and silk. Microscopic observation may help reveal surface features. While the surface of milk fibres appears smooth and non-microporous, soybean protein fibres are not smooth and show random microporous surfaces with a spot welding effect. Subsequently, boiling dimethyl formamide (DMF) may be used as a solvent to find out the dissolution behaviour. Milk fibres moisten and swell, whereas other protein fibres such as wool, silk, chitin and soybean protein fibres exhibit no changes [18].

3.7.6 Identification of chitin fibre

Firstly, a burning test may be used to observe the fibre's burning behaviour. Chitin fibre does not melt or shrink upon being subjected to a flame, but it burns rapidly like a cellulosic fibre with the odour of burning a protein fibre. The distinguishing features of chitin compared to other fibres are that it burns rapidly to black while keeping its original shape, the ash produced being greyish in colour and easily crumbled. After initially observing its burning behaviour by a burning test, the surface may be observed using a microscope. The surface of the fibre is characterized by small openings and cracks. An iodine–potassium iodide test may reveal important information: while in a wet state, lyocell, modal, bamboo and regular viscose fibres look alike, but upon drying, iodine on the chitin fibre sublimes easily, resulting in a blackish-blue to red-brown colour. As in other protein fibres, 5% boiling sodium hydroxide may be used as a solvent to observe the solubility. Chitin fibre dissolves in this solvent. Alternatively, 88% boiling formic acid may be used: here only chitin fibre dissolves, whereas all other fibres show no dissolution [18].

3.8 Case study: identification of ancient textile fibres

Two-thousand-year-old archaeological single fibres from textile fragments excavated in the Cave of Letters in the Dead Sea region were investigated

by a combined approach using microscopy (optical and SEM), X-ray microbeam diffraction and X-ray microbeam fluorescence. In comparison with modern reference samples, most of the fibres were identified as wool, some as plant bast fibres (flax). The molecular and supermolecular structure of both keratin (wool) and cellulose (flax) were found completely intact. In many fibres, mineral crystals were intimately connected with the fibres. The fluorescence analysis of the dyed wool textiles suggests the possible use of metal-containing mordants for the fixation of organic dyes [19].

3.9 Identification of cashmere and wool fibre scale frequency using fast Fourier transform

Sometimes fine wool may be found in 'pure' cashmere garments, and wool and synthetic fibre blends are sometimes labelled as pure wool products. Therefore, both wool and special animal fibre industries require accurate classification of animal fibres. Animal fibres can be distinguished using the patterns of their cuticular scales and other techniques such as analysing their unique physical and chemical properties. The recognition of characteristic features of scales is still the most useful method to distinguish animal fibres such as Merino, mohair and cashmere. Natural animal fibres possess cuticle surface morphology. The cuticle is composed of flat, plate-like cells called scales. Scale patterns provide very important information about the identities of animal fibres for classification. Scale frequency is an important feature of animal fibre cuticle surface morphology. It is defined as the number of scale separations per 100 μm fibre length in the direction of the fibre axis. Robson [20] reports that using fibre scale frequency alone, 659 cashmere and wool fibres among a population of 800 'unknown' fibres can be correctly classified. When combined with fibre diameter, the accuracy for correct fibre type classification is even higher [21].

Fibres of different types possess different fibre diameter ranges and scale frequencies as shown in Table 3.4 [21]. Compared to wool fibre, cashmere is finer and has a lower scale frequency. Therefore, fibre diameter and scale frequency are often used to identify wool and cashmere.

Animal fibre scale patterns and profiles are often observed under an optical microscope or a scanning electron microscope (SEM) to determine the fibre types. Therefore, image enhancement techniques and computer aided image recognition are also used for better fibre classification. However, this process is time-consuming and tedious, making fibre classification costly. The Fourier transform provides a link between a time domain signal and a frequency domain signal. According to the Fourier theory, any signal can be expressed by a sum of sine and cosine waves of various frequencies and amplitudes. The contribution of each frequency to the total effect (i.e. the signal) is determined by the amplitude of its Fourier coefficient. Therefore,

Table 3.4 Fibre diameter and scale frequency of some animal fibres

Fibre type	Fibre diameter (μm)	Scale frequency (scales/100 μm)
Vicuna	10	11
Cashmere[1]	13–18	6–8
Cashmere[2]	15.3	7
Wool[1]	16–39	7.6
Wool[2]	17.9	9.1
Yak hair	19	9–10
Cashgora	17	6–7
Camel hair	19	9–10
Huacaya alpaca	16.6–40.1	10.5
Alpaca	23	10

[1] Chinese white cashmere, Australian fine and coarse Merino wool.
[2] Australian white cashmere, Australian fine Merino wool.

if the scale edges show a regular pattern on the rightmost and leftmost edges of a fibre projection image, the scale frequency can be readily found out by means of the fast Fourier transform (FFT) from the fibre diameter profile signal. A simple method that measures the fibre diameter profile of a single animal fibre will be introduced in the following sections. Subsequently, we will analyse the diameter profile using the FFT technique to determine whether data from the diameter profile and FFT results can be used to quantify the scale frequency of different animal fibres [21].

3.9.1 Testing for cashmere and wool fibre scale frequency

Greasy cashmere and wool fibres were sampled from sale lots, then scoured under identical conditions. They were used to measure the profiles of single-fibres. Single-fibre diameter profiles were measured by a Single Fibre Analyser (version 1: SIFAN1; version 2: SIFAN2) instrument. SIFAN1 gives more accurate measurements but fewer data points than SIFAN2. The SIFAN measures a fibre diameter profile at a set interval along the fibre length in less than a minute. The scanning intervals of 5 μm for SIFAN1 and approximately 0.4 μm for SIFAN2 were used in this work.

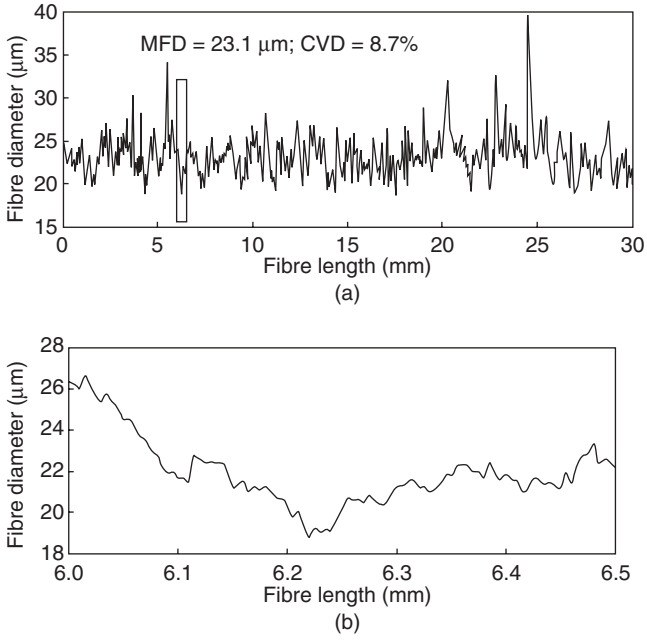
After scanning the profiles of single fibres by the SIFAN, their scale frequencies were measured using either an Olympus SZX12 microscope with

an Olympus DP10 digital camera or a Leo 1530 field emission gun scanning electron microscope.

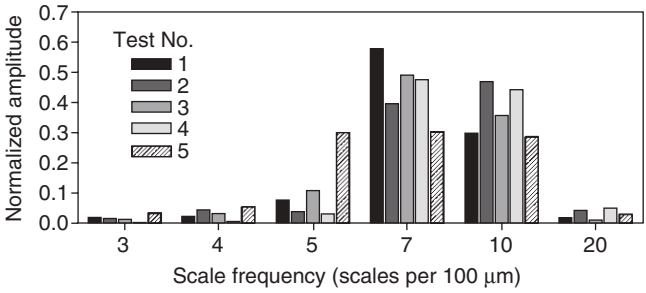
The fibre diameter profile digital signals were first filtered using a Butterworth bandpass digital filter, to remove components that were outside the range of 2.5 to 15.5 scales per 100 μm, as animal fibre scale frequency is in the range of 6 to 11 scales per 100 μm (Table 3.4). The order of the filter was set to 5. A Hamming window was applied to the diameter profile signal. This was to reduce the truncation effect normally encountered in data acquisition [21].

Figure 3.13 [21] shows the diameter profile of a 30 mm long wool fibre measured with the SIFAN1 at a scanning interval of 5 μm. Figure 3.13(b) [21] is a zoom view of the boxed section in Fig. 3.13(a). It can be seen from Fig. 3.13(a) that the fibre diameter is highly irregular along the fibre length and the fibre scale frequency cannot be determined by simply observing either Fig. 3.13(a) or Fig. 3.13(b).

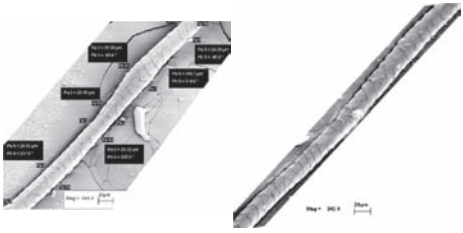
The wool fibre was repeatedly measured five times with the same test parameter settings and the diameter profiles were then transformed into a power spectrum as shown in Fig. 3.14 [21]. From Fig. 3.14, it can be seen that the fibre scale frequency was between 5 and 10 scale edges per 100 μm and the measurements had good repeatability.



3.13 Diameter profile of a wool fibre (SIFAN1 at 5 μm interval) and the zoomed profile of a 0.5 mm segment of fibre.



3.14 FFT analysis of five diameter profiles repeatedly measured using the same wool fibre.



(a) (b)

3.15 Micrographs of two sections of the fibre used for diameter profile measurement in Fig. 3.13.

In Fig. 3.15(b) [21], 380 μm long of wool fibre used reveal that the fibre scale frequency is approximately 7.6 scales per 100 μm, which is in the range of 7–10 scales per 100 μm (Fig. 3.13). This suggests that FFT analysis has great potential to determine the animal fibre scale frequency.

One of the disadvantages of the scanning electron microscope or optical microscope is the tendency to acquire fibre surface information from a few, not necessarily representative, samples. The wool fibre used in Fig. 3.13 sets an example. Its mean fibre diameter measured by SIFAN1 is 23.1 μm (Fig. 3.13) while by five measurements using the SEM images in Fig. 3.13 the diameter is 25.3 μm in Fig. 3.15(a) and 22.9 μm in Fig. 3.15(b) respectively. This suggests that due to diameter irregularity along the fibre length and limited fibre length for imaging, the mean fibre diameter measured with a microscope or SEM may not represent the fibre population, and a large sample size is needed for more accurate measurement. For this reason, the fibre diameter profile and its FFT result may have an advantage in determining fibre diameter and scale frequency as the SIFAN uses large samples (up to the whole fibre length) at a fast testing speed.

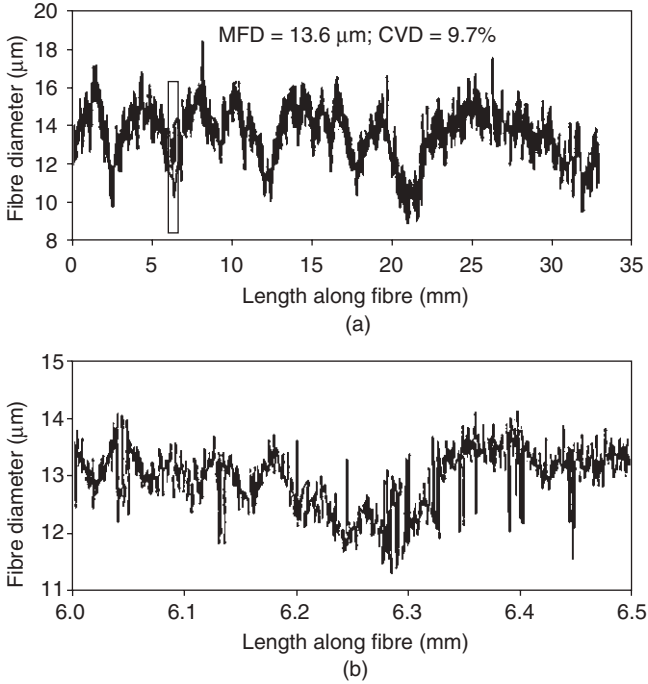
Because the resolution of the 5 μm scanning interval is too coarse, the FFT result may not cover the full scale frequency spectrum in detail.

Therefore, the scale frequency in Fig. 3.14 does not include data between 5 and 10 scales per 100 μm, which would not help to identify an animal fibre as most animal fibres have a scale frequency in the range of 6 to 11 (Table 3.4). A finer scanning interval is also necessary to analyse scale frequencies of more than 10 scales per 100 μm.

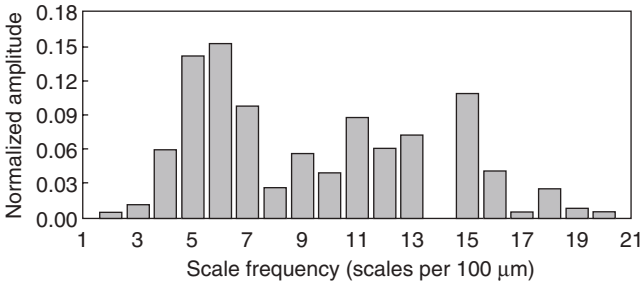
Figure 3.16 [21] shows a cashmere fibre diameter profile at 0.37 μm sampling interval and the zoomed Fig. 3.16(b) shows more details of the fibre profile compared to Fig. 3.16(a). Regardless of the fibre profile scanning intervals, the fibre scale frequency still cannot be determined by observing the diameter profile figures only.

The FFT result in Fig. 3.17 [21] suggests that the cashmere fibre has a scale frequency between 5 and 7, and the frequency of 6 scales per 100 μm is most likely the case. Optical microscope observation of the cashmere fibre revealed that the fibre has a scale frequency of 6.1, which confirms the FFT result in Fig. 3.17.

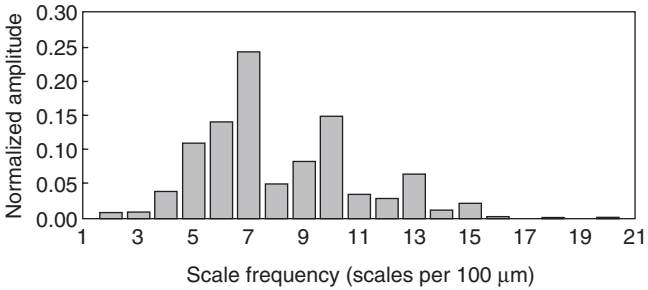
A 19 μm fine wool fibre was also analysed. The FFT result in Fig. 3.18 [21] indicates that the wool fibre has a scale frequency of 7 scales per



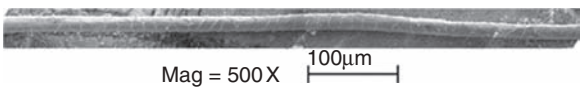
3.16 Diameter profile of an Australian cashmere fibre (SIFAN2 at 0.37 μm sampling interval) and the zoomed profile of a 0.5 mm segment of fibre.



3.17 FFT analysis of the cashmere diameter profile shown in Fig. 3.16.



3.18 FFT analysis of the diameter profile of a 19 μm wool fibre.

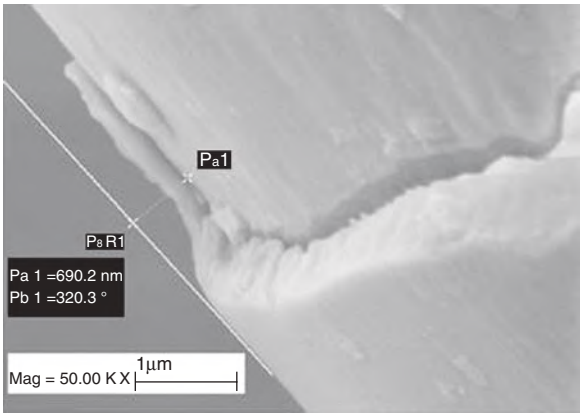


3.19 A section of the wool fibre used for the FFT result in Fig. 3.18.

100 μm. The SEM image in Fig. 3.19 reveals that the fibre has a scale frequency of 7.3 scales per 100 μm, which agrees well with the FFT result in Fig. 3.18.

Figure 3.19 [21] also reveals that the diameter of the fibre on the SEM image is approximately 18 μm. Again, due to the fact that the SIFAN can measure a longer fibre segment than the SEM, fibre diameter results measured from the SIFAN are more representative.

The instrument for the fibre diameter measurement should have a high resolution in order to accurately measure the differences due to scale protrusion, as some fibres have small fibre scale height; for example, the scale height of Huacaya alpaca is only 375 nm, that of wool 1.1 μm [22] and that of cashmere around 600 nm (Fig. 3.20) [21]. As this section presents only a few samples of wool and cashmere, we will further evaluate the method using more animal fibres to examine its robustness. The latest SIFAN,



3.20 Scale height of an Australian brown cashmere fibre (fibre diameter 14 µm).

version 3, which has a claimed resolution of 0.1 µm, will be employed for fibre diameter profile scanning.

The sampling interval greatly affects the accuracy of the scale frequency measurement: a smaller sampling interval gives more detailed spectra, hence better estimation of scale frequency. The SIFAN instrument works best on a sampling interval of 5 µm or more. For high-resolution sampling (for example 300 nm or less), the reliability of the testing system needs to be investigated first to ensure accurate results.

3.10 Testing of high-visibility fabrics

'High-visibility materials for safety garments' are specified by the following three types of materials:

- Retroreflective materials (Class R)
- High daylight visibility coloured materials, which covers fluorescent and non-fluorescent colours (Class F)
- Combined retroreflective–fluorescent coloured materials (Class RF).

Safety garments are expected to be worn frequently, often under rough conditions. AWTA (Australia Wool Testing Authority) Textile Testing can perform the full range of tests for Class F colours in-house.

It is recommended that fluorescent colours be tested for colour (luminance and chromaticity) first, because of the difficulty of achieving the required shade and luminance. Dyers should note that a recipe that works on one fabric might not work on another fabric of the same fibre composition. Fabric is measured as a single layer over a very dark backing. The more

open or transparent the fabric, the less of the bright fabric and the more of the dark backing is measured.

Measurement of retroreflective performance (CIL) requires specialized equipment, mainly used in non-textile fields. AWTA Textile Testing conducts the durability tests and prepares specimens for measurements, then sub-contracts the CIL measurement to a specialist laboratory. There are several standards covering this field, for example:

- AS/NZS 4602:1999 'High visibility safety garments' is a specification which refers to the materials covered in AS 1906.4:1997.
- EN471:1994 'High visibility warning garments' combines material specifications and garment design. The concepts are similar but the detail is different from the Australian Standards.

3.11 Fourier transform infared and thermal analysis of cashmere and other animal fibres

Animal fibres such as cashmere, wool and alpaca are composed of keratin of a similar structure. Cashmere is an extremely fine and luxury material, in comparison with most other animal fibres. For reducing the cost of cashmere products, fine wool is sometimes blended with cashmere in products labelled as pure cashmere. Fibre identification between cashmere and fine wool has been a tedious and difficult process. Microscopic methods have been largely employed by the textile industry and forensic services. The surface morphological differences between wool and cashmere have been observed by many researchers with the help of a scanning electron microscope (SEM). An image processing system and a hybrid artificial neural network (ANN) combined with images from an optical microscope to undertake scale feature extraction and discrimination of animal fibres have been applied [23].

The chemical constitutions of animal fibres have been analysed and the results show that the contents of amino acids, particularly the cystine component, in cashmere are different from those of wool and alpaca. The DNA amplification technique has also been explored to identify speciality animal fibres. However, DNA analysis was shown to be influenced by the amount of substances extracted from the fibres (i.e. chemical-treated fibres). Bioengineering methods (e.g. species-specific monoclonal antibodies produced by proteins extracted from different animal fibres) have also been used for anti-fraud identification. Because of the complexity among fibre varieties, satisfactory results have not been achieved so far. All of these operations also involve a time-consuming preparation process [23].

Fourier transform infrared (FTIR) microscopy, differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) techniques are rela-

tively new in material characterization. From an FTIR spectrum, particular chemical bands can be precisely located at a certain wavelength. Raw and chlorinated or reductive chemical-treated wool have been examined by FTIR for specifying the chemical changes in treated wool. Thermodynamic properties of materials such as melting temperatures, transition enthalpies, phase transformations, etc., can be analysed by DSC. In addition, thermal stability and composition of materials can be determined by TGA. The following section will introduce the application of FTIR and DSC/TGA analysis in animal fibre identification. FTIR and thermal analysis techniques were investigated for differentiating cashmere from other animal fibres. The FTIR spectra and TGA as well as DSC curves were analysed and the differences between Chinese cashmere and other animal fibres produced in Australia were examined [23].

3.11.1 Testing for thermal properties of cashmere and other animal fibres

Both Chinese cashmere and Australian cashmere of different diameters were sampled to compare with other animal fibres, which include Chinese camel hair, Australian Merino wool and alpaca fibres. All samples were extracted by ethanol twice to remove the residual grease content. Fibre diameter profiles were measured by OFDA 100 and the results are listed in Table 3.5 [23].

Thermal properties of all samples were measured by a NETZSH STA409PC instrument (NETZSH Gerätebau GmbH, Germany) for obtaining TGA and DSC curves. Aluminium crucibles were used to hold 6–9 mg of 2 mm-long fibre snippets for measurements. Argon gas was employed for purging samples at 30 ml/min and for protection at 10 ml/min. The temperature was increased at 10°C/min after 25°C, and 500°C was set as the maximum.

A Vertex 7.0 Fourier Transform Infrared Spectroscope (FTIR) (Bruker Optics Inc., Germany) was used in the attenuated total reflectance mode. Each fibre specimen was scanned at a resolution of 4 cm^{-1} 32 times to acquire an ATR spectrum between 4000 cm^{-1} and 600 cm^{-1} wavelength. Five spectra were obtained for each sample.

3.11.2 Thermal properties by thermogravimetric analysis

Figure 3.21 [23] shows that the mass of fibres changed with an increase in temperature. For all animal fibres examined, two main phases of mass change are shown on each TGA curve. The first mass loss occurred at about 60°C and was caused by moisture evaporation from fibre structures, and the second loss resulted mainly from thermal decomposition of the fibres. Some

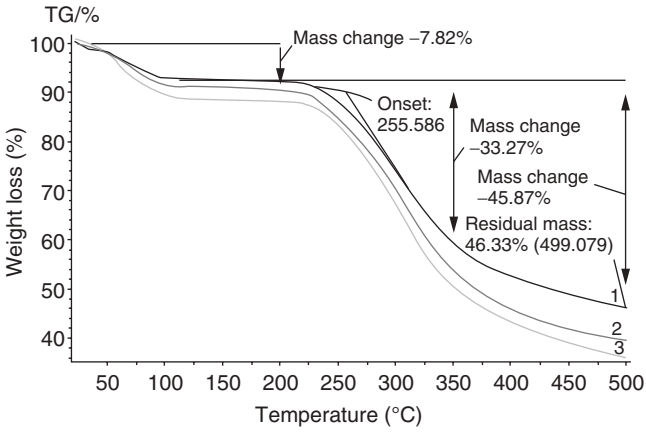
Table 3.5 Fibre diameter profiles and production regions

Sample no.	Label	Description	MD (μm)*	CVD (%)*
1	Aus_cashmere	Australian white cashmere	15.16	21.3
2	Aus_cashmere	Australian white cashmere	15.60	20.6
3	Aus_cashmere	Australian white cashmere	17.51	22.6
4	CN_cashmere	Chinese white cashmere	14.16	21.3
5	CN_cashmere	Chinese white cashmere	14.21	22.5
6	CN_grey cashmere	Chinese grey cashmere	20.25	29.1
7	CN_camel	Chinese brown camel hair	19.11	27.0
8	Aus_alpaca	Australian white alpaca	23.65	23.0
9	Aus_alpaca	Australian white alpaca	34.96	23.3
10	Aus_alpaca	Australian white alpaca	23.14	24.4
11	Aus_alpaca	Australian white alpaca	22.19	22.7
12	Aus_fine wool	Australian fine Merino wool	20.33	17.7
13	Aus_fine wool	Australian fine Merino wool	19.59	23.1
14	Aus_coarse wool	Australian coarse Merino wool	31.32	22.3
15	Aus_coarse wool	Australian coarse Merino wool	32.78	18.0
16	Aus_fine wool	Australian fine Merino wool	16.36	17.2

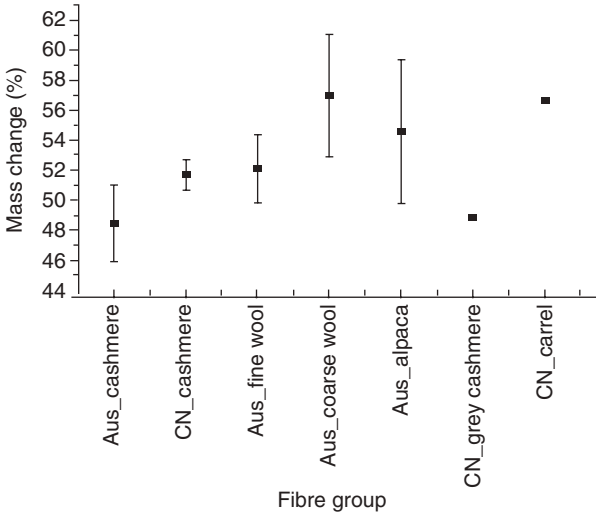
* MD: mean diameter of fibres; CVD: coefficient variation of diameter.

residual mass remained at the end of the temperature rise. A ratio of mass change within any temperature range as well as an associated onset temperature can be obtained from a TGA curve as shown in Fig. 3.21.

Based on the TGA curves, the rapid mass changes occurred between 200°C and 350°C, as a result of thermal degradation. Figure 3.22 [23] shows the average mass change within this temperature range for different fibre groups. It is clearly seen that Australian cashmere and Chinese grey cashmere have a smaller mass change than other fibres. Chinese white cashmere



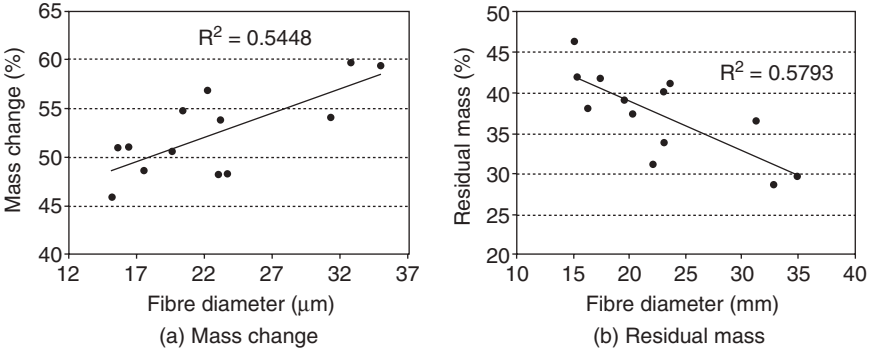
3.21 Typical TGA curves of cashmere and wool produced in China and Australia (curve 1: Australian cashmere; curve 2: Chinese white cashmere; curve 3: Australian fine wool).



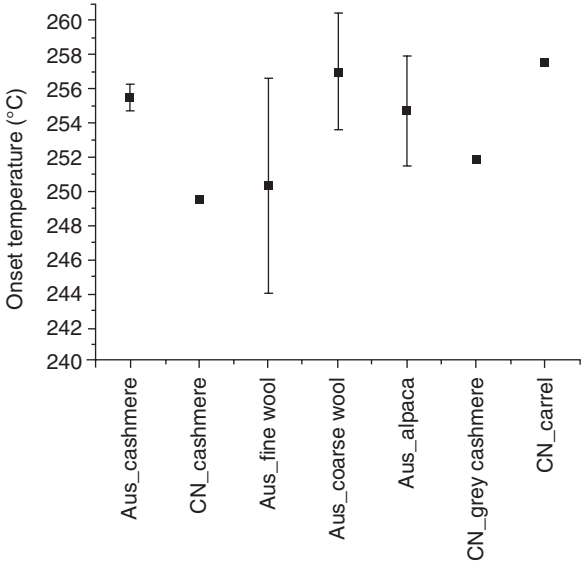
3.22 Mass changes of animal fibres in groups.

and Australian fine Merino exhibit a similar mass change, with the coarse Australian Merino wool showing the largest mass change within groups.

Fibre diameter may have some effect on the mass change. For Australian cashmere, wool and alpaca fibres, there exists a moderate linear relationship between the mass change and fibre diameter (Fig. 3.23(a)) [23]. The coarser fibres tend to have a larger mass change than finer fibres. Conversely, the residual mass of the fibres has a moderate and negative linear relationship with fibre diameter (Fig. 3.23(b)) [23].

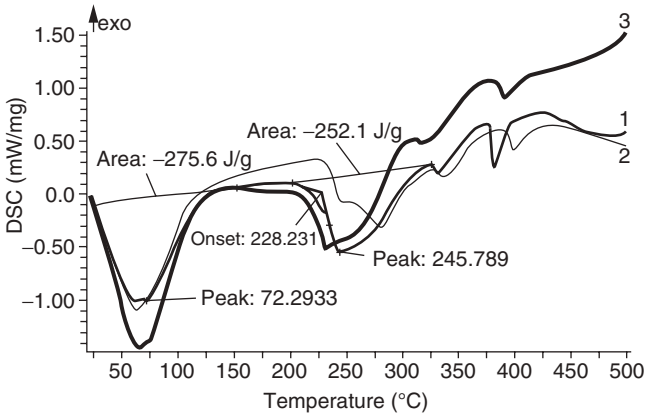


3.23 Relationships of fibre mass change and residual mass with fibre diameter.



3.24 Fibre onset temperatures of mass change in groups.

Along with the associated fibre mass changes, onset temperatures within the same temperature range (200–350°C) are shown in Fig. 3.24 [23]. Chinese cashmere and Australian fine Merino wool demonstrated almost the same onset temperature, which is lower than those of the other fibres tested. Australian cashmere fibres were thermally degraded at a high temperature, as were Australian coarse wool, alpaca fibres and Chinese camel hair. However, there are considerable variations within some fibre groups, as indicated by the large error bars.



3.25 Typical DSC curves of cashmere and wool produced in China and Australia (curve 1: Australian cashmere; curve 2: Chinese white cashmere; curve 3: Australian fine wool).

3.11.3 Thermal properties by differential scanning calorimetry analysis

The heat transfer process can be viewed from differential scanning calorimetry (DSC) curves of the fibres as shown in Fig. 3.25 [23]. Corresponding to the mass change, there are two main heat transfers during the process of temperature increase. The first endothermic heat peak occurred at around 60°C due to moisture evaporation from inside the fibres. The second endothermic heat peak occurred at around 250°C, resulting in the thermal decomposition of the fibres. The onset temperature (T_o) and the peak temperature (T_p) as well as the amount of endothermic heat (ΔH) can be calculated from the DSC curve. The results for all the fibres tested are listed in Table 3.6 [23].

In Table 3.6, Australian cashmere, like Chinese camel hair, starts to absorb heat much later than the other fibres tested before the thermal decomposition of the fibres starts. The Australian alpaca fibres have the lowest T_0. Except for Chinese grey cashmere, both Australian and Chinese cashmere fibres have a very small ΔT and ΔH, which means the white cashmere fibres were thermally degraded in a shorter time and with a lower endothermic heat than others. On the other hand, Chinese camel hair is more resistant to thermal degradation.

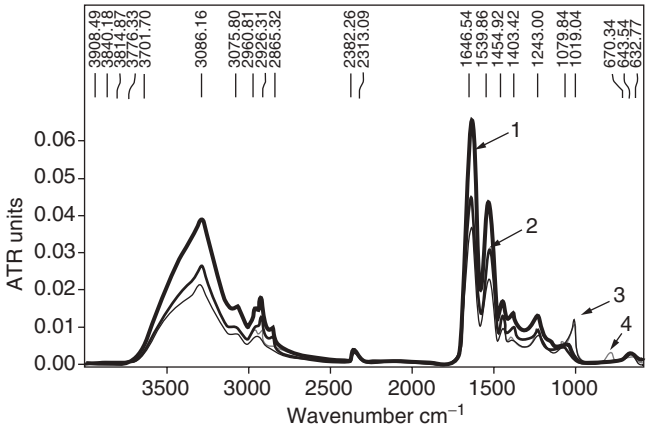
3.11.4 Fourier transform infared analysis

The ATR spectra of fibres are shown in Fig. 3.26 [23]. Apparently, differences between Chinese cashmere and Australian cashmere as well as wool

Table 3.6 Results of DSC analysis in fibre groups

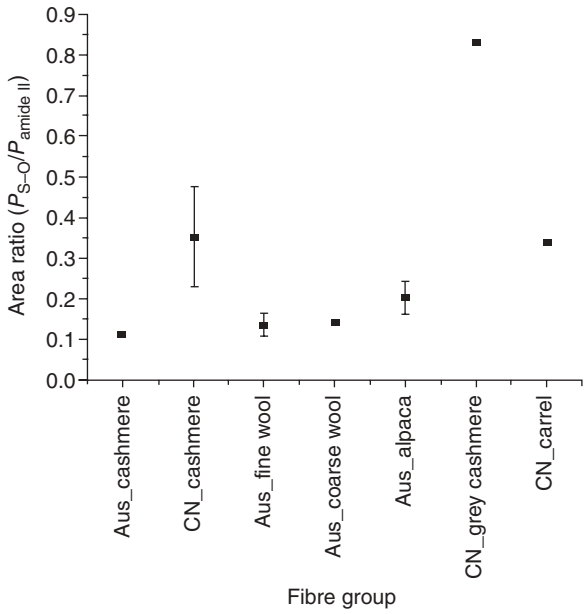
Fibre group (see Table 3.5)	T_o (°C)*	T_p (°C)*	ΔT (°C)*	ΔH (J/g)*
Aus_cashmere	230.28	260.59	30.30	247.13
CN_cashmere	229.73	263.01	33.29	209.90
Aus_fine wool	228.91	286.07	57.16	393.83
Aus_coarse wool	224.83	285.31	60.47	411.85
Aus_alpaca	220.55	281.94	61.39	529.25
CN_grey cashmere	228.31	283.68	55.38	414.00
CN_camel	231.15	295.25	64.70	693.80

* T_o: onset temperature of endothermic heat; T_p: peak temperature; ΔT: $T_p - T_o$; ΔH: endothermic heat.



3.26 ATR spectra of cashmere and wool (curve 1: Australian cashmere; curve 2: Australian fine wool; curve 3: Chinese white cashmere; curve 4: Chinese grey cashmere).

clearly exist in a peak near the 1040 cm^{-1} wavelength which relates to the S–O stretching component of cysteic acid residues ($R–SO_3^-$). $R–SO_3^-$ is usually derived from an oxidation of disulfide bonds of cystine. Because of the mass effect, steric interactions and resonance from adjacent atoms, this peak may be shifted away from the 1040 cm^{-1} wavelength. In the present research, Chinese white cashmere had a strong absorption near 1019 cm^{-1}, while Australian cashmere and Merino wool had a weak absorption but the peak was shifted left to 1079 cm^{-1}. For Chinese grey cashmere, besides its strong absorption near 1019 cm^{-1} (same as Chinese white cashmere), there was an apparent extra peak at about 800 cm^{-1}, indicating the presence of melanin pigment inside the fibre.



3.27 Normalized S–O stretching peak of animal fibres in groups.

A normalization of the spectrum peak near 1040 cm^{-1} (P_{S-O}) to the peak at 1539 cm^{-1} ($P_{amide\ II}$) for the amide II backbone group may reveal the difference between the fibres in a relative manner. Figure 3.27 [23] clearly shows that the animal fibres produced in China have a significantly larger amount of $R–SO_3^-$ group than the fibres produced in Australia. In particular, the Chinese grey cashmere has the highest amount of $R–SO_3^-$ group in all the fibres tested. In addition, Australian cashmere has a relatively lower amount of $R–SO_3^-$ group than wool and alpaca fibres. These differences may imply that the content of $R–SO_3^-$ formed in these animal fibres is closely related to the region where the animals are farmed.

3.12 References

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4

Physical and mechanical testing of textiles

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Abstract: This chapter describes the key physical and mechanical properties of fabrics and the associated test methods. It covers fabric weight and thickness, fabric strength, fabric stretch and abrasion resistance, as well as properties related to fabric aesthetics. A brief account of future trends in this area is also provided.

Key words: fabrics, physical properties, mechanical properties, abrasion resistance, aesthetic properties.

4.1 Introduction

Fabrics made from both natural and manufactured fibres have been extensively used for clothing, decoration and industrial applications. The physical and mechanical properties of these fabrics are affected by the fibre type, yarn construction and fabric structure, as well as any treatment that may have been applied to the materials. A range of fabric performance parameters are assessed for different end-use applications.

Unlike other homogeneous materials, fabrics are heterogeneous materials. The test results differ when a fabric specimen is tested in different directions (e.g. warp or weft for wovens, course or wale for knits). While different test standards are applied to different types of fabric tests, it is important to note that the three important factors for any test are the sampling protocol, the conditions of measurement, and the instrumentation and measurement procedure.

This chapter is focused on the physical and mechanical tests of fabrics. Specifically, it covers the following tests:

- Weight and thickness
- Tensile strength
- Tear strength
- Seam strength and seam slippage
- Burst strength
- Stretch properties
- Abrasion resistance
- Drape
- Bending

- Shearing
- Compression.

While the principles of these tests have not changed much over the past 70 years, there has been considerable advance in the instrumentation used to test properties such as strength, abrasion and fabric handle. For each test and where appropriate, the different test methods and standards are introduced and compared in this chapter. The applications and future trends of these tests are briefly discussed.

4.2 Fabric weight and thickness

Weight measurement of a fabric is often a prerequisite for subsequent tests of other fabric properties. If fabric weight or dimension is not kept constant or normalised then the test results will not be comparable.

The thickness of a fabric is one of its basic properties, giving information on its warmth, weight and stiffness. Thickness measurements are very sensitive to the pressure and sample size used in the measurement, which will be briefly discussed in the section on fabric handle. In practice, fabric mass per unit area is often used as an indicator of thickness.

4.2.1 Methods for testing fabric weight and thickness

Weight can be determined by a mass per unit area or a mass per unit length of fabric. Specimens of known dimensions are taken by a cutting device or a template, to obtain a consistent specimen size. The larger the specimen size, the more accurate the measurement, and most test standards require an area of 10 000 mm^2 or more to be measured. The accuracy of cutting the specimen should be within 1% of the area.

Five specimens should be selected from each fabric sample. Specimen selection should avoid taking samples from the fabric selvedge or close to the ends of a fabric piece. Testing should be conducted in a conditioned atmosphere with preconditioned samples and care should be taken to avoid the loss of fibres/threads during weighing. Results are commonly reported in grams per square metre (g/m^2).

$$m_{\text{ua}} = \frac{m}{a} \tag{4.1}$$

where m_{ua} = mass per unit area, in g/m^2; a = specimen area, in m^2; and m = mass of specimen, in g.

If mass per unit length is required then the following formula is used:

$$\bar{m}_{\text{ul}} = \bar{m}_{\text{ua}} \times \bar{w} \tag{4.2}$$

where $\bar{m}_{ul}$ = the mean mass per unit length, in g/m, and $\bar{w}$ = the mean width, in m.

The standards used for the weight test include:

- ASTM D3776-96(2002) Standard test methods for mass per unit area (weight) of fabric
- ISO 3801-1977 Textiles – Woven fabrics – Determination of mass per unit length and mass per unit area
- AS 2001.2.8-2001 Determination of mass per unit area and mass per unit length of fabrics.

4.3 Fabric strength

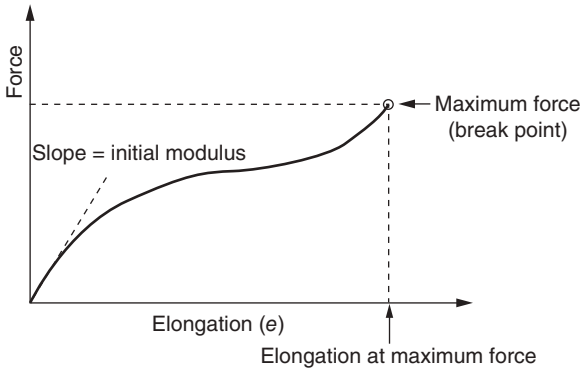
The strength tests covered in this section include tensile, tear, seam and burst strength. These mechanical properties are important for all textile users including fabric processors, garment manufacturers, designers and customers.

4.3.1 Tensile strength

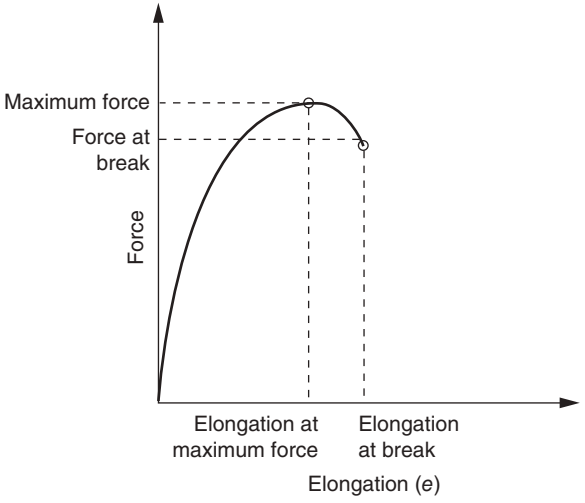
Measurement of tensile stress–strain properties is the most common mechanical measurement on fabrics. It is used to determine the behaviour of a sample while under an axial stretching load. From this, the breaking load and elongation can be obtained. The principle of the tensile strength test is simple: a test piece is held in two or more places and extended until it breaks. The tensile properties measured are generally considered arbitrary rather than absolute. Results depend on specimen geometry, the fibre type and arrangement, as well as the fabric structure.

Break modes

There are two common types of tensile breaks: sharp break (Fig. 4.1) and percentage break (Fig. 4.2). A sharp break is a sudden drop in load. This test is normally called pull to break. A percentage break is generally shown as a gradual reduction in the load from its maximum as further extension is applied. A percentage drop from maximum load is often used to define an end point or break point. This test is normally called pull to yield and can have all of the same setup parameters as a pull to break. Modern tensile test instruments can be set up in both of the break modes. Most test methods report both maximum load and load at break, as the breaking strength is not always the maximum strength for the material, especially for soft and elastic fabrics.



4.1 Tensile strength test curve (sharp break).



4.2 Tensile strength test curve (percentage break).

Extension

Extension is defined as the change in length of a material due to stretching. When a fabric of original length l_0 is stressed along its axis, it extends an amount dl. The strain in the sample is dl/l_0 (viz. the ratio of the extension of a material to the length of the material prior to stretching). The symbol e is normally used to represent strain, and can be referred to as elongation. Strain is a dimensionless quantity, often reported as a percentage.

Initial modulus

Young's modulus or the initial modulus (IM) is a measure of the amount of deformation that is caused by a small stress. Materials with a high modulus, often called stiff or hard materials, deform or deflect very little in the presence of a stress. Materials with a low modulus, often called soft materials, deflect significantly. In the case of fabric, initial modulus is related to the fabric handle. A higher IM means a stiffer or harsher fabric handle whereas a lower IM provides a softer fabric handle.

Tensile testing machine

Most tensile testing machines can operate in three modes:

- Constant-rate-of extension (CRE)
- Constant-rate-of traverse (CRT)
- Constant-rate-of-load (CRL).

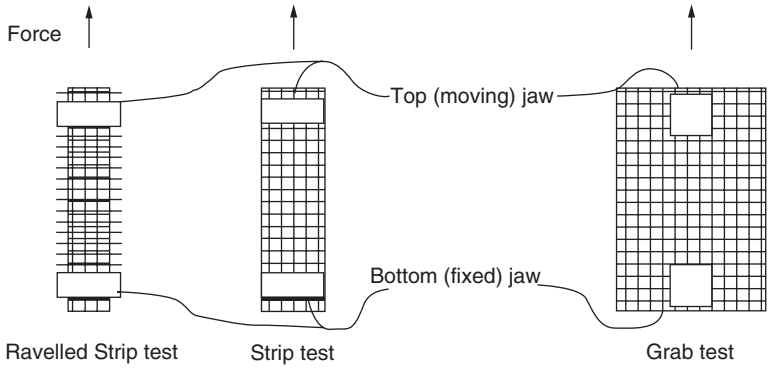
The most commonly used mode is the CRE mode and is often required by the test standards. The main factors that need to be considered are the size and accuracy of the load cell (0.5–25 kN), the distance of cross-head travel (0.1–2 m) and the rate of cross-head travel (0.1–500 mm/min). Common tensile results include maximum load, deflection at maximum load, load at break, and deflection at break. Other data can be calculated from these results, such as work at maximum load, stiffness, work at break, stress, strain and Young's modulus. Most modern machines utilise a computer program to capture the data and calculate any additional results.

Tensile strength at break is not necessarily the best indicator of fitness for purpose. In some cases (i.e. web, linoleum and rope) the work to rupture (or break) is more important. The work to rupture is the energy absorbed by the material up to the point of rupture and is measured in joules. Work to rupture may be used to indicate fabric toughness.

Methods for testing tensile strength

Three methods (see Fig. 4.3) have been commonly used to measure tensile strength:

1. *Grab test*. In the grab test, the width of the jaws is less than the width of the specimen. An example would be for a 100 mm wide specimen where the centrally mounted jaws are only 25 mm wide. This method is used for woven high-density fabrics and those fabrics with threads not easy to remove from the edges. The grab method is used whenever it is desired to determine the 'effective strength' of the fabric in use.



4.3 Sample gripping methods.

2. *Modified grab test*. The mounting geometry is the same as for the grab test; however, lateral slits are made in the specimen to sever all yarns bordering the portion to be strength tested, reducing to a minimum the 'fabric resistance' inherent in the grab method. This method is desirable for high-strength fabrics.
3. *Strip test*. There are two types of strip test: the ravelled strip test and the cut strip test. In both tests the entire width of the specimen is gripped in both the upper and lower jaws. The ravelled strip test is only used for woven fabric and specimens are prepared by removing threads from either side of the test piece until it is the correct width. The cut strip test is used for fabrics that cannot have threads removed from their sides such as knits, non-wovens, felts and coated fabrics. The test specimens are prepared by accurately cutting to size.

There is no simple relationship between grab tests and strip tests since the amount of fabric resistance depends on the fabric structure, fabric count, mobility of yarns and many other factors. The strip tests can provide information on tensile strength and elongation of fabric; however, the grab test can only give the breaking strength.

Factors affecting the tensile strength

It should be noted that many factors can affect the tensile test results. These include the number of test specimens, the gauge length used, the extension rate for the test, jaw slippage and damage to the specimen by the jaws that may cause 'jaw break'. These factors should be carefully considered when undertaking the tensile tests of fabrics.

1. *Number of test specimens*. With any test method the number of specimens tested will dictate the precision of the results. The higher the number of tests, the more precise the results.

2. *Gauge length*. A change in gauge length of a fabric will result in a change in the values obtained for maximum load, breaking load and initial modulus. The longer the gauge length, the lower the initial modulus result. The gauge length should be consistent for all tests if comparisons are to be made from test to test.
3. *Extension rate*. The extension rate (or the cross-head traverse speed) influences the elongation and break force of the fabric. Results of tests conducted at different rates of extension will not be directly comparable; however, fabrics of different elastic moduli require different test speeds.
4. *Jaws or grips*. Jaws are the part of the clamping device that grip the fabric during a test. They should be capable of holding the test piece without allowing it to slip; however, they should not over-grip, causing damage. Smooth, flat or engraved corrugated jaws can be used for clamping. Suitable packing materials can be used in the jaws (i.e. paper, leather, plastics or rubber) to avoid slip or damage during clamping. Where the test piece slips asymmetrically or slips by more than 2 mm, the results need to be discarded. To avoid slippage of smooth fabrics, capstan or self-locking jaws with an appropriate clamping face may be used.
5. *Jaw break*. Jaw break often happens before the fabric is stretched to its full potential. The test result should be discarded if the test piece breaks within 5 mm of the jaw face. In the case of a repeated jaw break, modification of the jaw material or clamping force should be considered.

Standards commonly used for tensile strength tests are as follows:

- ISO 13934-1:1999 Textiles – Tensile properties of fabrics – Part 1: Determination of maximum force and elongation at maximum force using the strip method
- ISO 13934-2:1999 Textiles – Tensile properties of fabrics – Part 2: Determination of maximum force using the grab method
- ASTM D5034-95 Standard test method for breaking strength and elongation of textile fabrics (grab test)
- ASTM D5035-95 Standard test method for breaking strength and elongation of textile fabrics (strip test)
- AS 2001.2.3.1-2001 Physical tests – Determination of maximum force and elongation at maximum force using the strip method
- AS 2001.2.3.2-2001 Physical tests – Determination of maximum force using the grab method
- AS 4878.6-2001 Determination of tensile strength and elongation at break for coated fabrics.

4.3.2 Tear strength

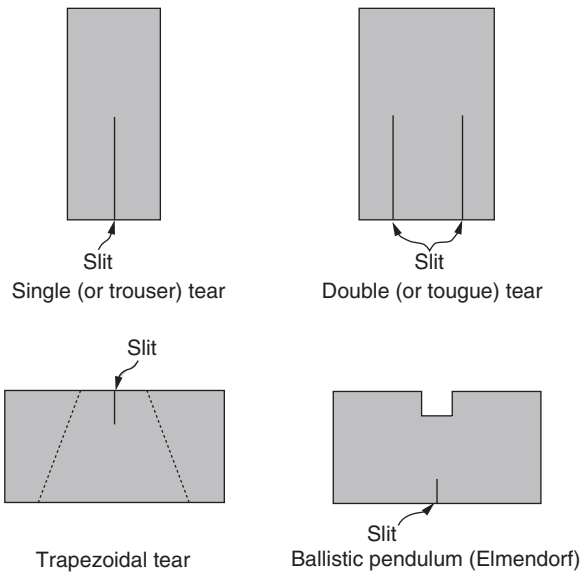
Tearing of a fabric can occur in a wide range of products and is involved in fatigue and abrasion processes as well as the catastrophic growth of a cut on application of a force. Tear strength is the tensile force required to start, continue or propagate a tear in a fabric under specified conditions. A tear strength test is often required for woven fabrics used for applications including army clothing, tenting, sails, umbrellas and hammocks. It may also be used for coated fabrics to evaluate brittleness and serviceability.

Methods for testing tear strength

The following methods are in use or being developed: trouser or single tear, double or tongue tear, wing tear, trapezoidal tear, ballistic pendulum (Elmendorf), puncture or snag tear, tack tear, and wounded burst tear. The test specimen shall be cut according to the design shown in Fig. 4.4, and the required dimensions are specified in relevant test standards.

The standards used worldwide for tear tests are:

- ISO 4674-1998, part 1: Determination of tear resistance
- ISO 13937-3-2000 Textiles – Tear properties of fabrics – Part 3: Determination of tear force of wing-shaped test specimens



4.4 Different tear testing methods.

- ISO 13937-1-2000 Textiles – Tear properties of fabrics – Part 1: Determination of tear force using the ballistic pendulum method (Elmendorf)
- BS 3424 Method 7C, Single tear, 1973
- EN 1875-3 Determination of tear resistance – Part 3: Trapezoid tear, 1997
- ASTM D1423-83 Tear resistance of woven fabrics by falling pendulum (Elmendorf)
- ASTM D751 Tack tear, 1995
- ASTM D751 Puncture resistance, 1995
- ISO 5473 Determination of crush resistance, 1997
- AS 2001.2.10-1986 Determination of the tear resistance of woven textile fabrics by the wing-rip method
- AS 2001.2.8-2001 Determination of tear force of fabrics using the ballistic pendulum method (Elmendorf).

Two devices have been commonly used for tearing tests: the Elmendorf tearing tester and the CRE tester.

The Elmendorf tearing tester

The falling (ballistic) pendulum (Elmendorf) method is used for the determination of the average force required to continue or propagate a single-rip-type tear starting from a cut in a woven fabric by means of a falling pendulum (Elmendorf) apparatus. Part of the energy stored in the pendulum is used to produce the tearing (and any deformation of the test piece). The magnitude of this is indicated by the energy lost compared to the energy of the falling pendulum without a test piece in place. The weight attached to the pendulum can be selected based on the fabric tested and the standard used.

The basic characteristics of this test are that stresses are applied by subjecting the test piece to a sudden blow; hence the test speed (strain rate) is relatively high compared to that of a CRE machine (see below). This method is not suitable for knitted fabrics, felts or non-woven fabrics. It is applicable to treated and untreated woven fabrics, including those heavily sized, coated or resin treated.

An initial slit is made in the centre of the specimen. The principal reason for this slit is to eliminate edge tear forces and to restrict the measurement to the internal tearing force only. Cutting can be considered as the precursor to tearing.

The constant-rate-of-extension tester

The tear test can be performed on a normal tensile instrument. For the tongue method a rectangular specimen is cut in the centre of the shorter

edge to form two 'tongues' (or 'tails'). Each tongue is gripped in the clamps of a constant-rate-of-extension (CRE) machine and pulled to simulate a rip. The force to continue the tear is calculated from readings as the average force to tear.

The force registered in a tear test is irregular. The reading represents the force required for tear initiation, the subsequent reading being the force to propagate the tear. For a woven fabric, the average of the warp and weft direction tests is given as the result. The tearing force can rise rapidly; therefore the response characteristics of the apparatus are particularly important. The rate of tear is normally 100 mm/min.

The different tests in part reflect the different stress concentrations found in different products, but in many cases they are somewhat arbitrary. Consequently, the measured tear strength is not an intrinsic property of the material, and it can be difficult to correlate directly the results of laboratory tests with service performance.

The main problems encountered in carrying out tear testing are that sometimes the tear does not propagate in the direction of the jaw traverse. Tearing can occur towards the sample edge. In the tongue or double slit test, the tongue may be stretched and a tensile effect occurs, or threads may get pulled out rather than break. Under these conditions an alternative specimen shape may be chosen or a larger test piece taken and the procedure repeated. Non-woven and knitted substrates are often tested using larger samples than those initially specified in the method.

Factors affecting the tear strength

In a normal pull to break tensile test the force measured is the force to produce failure in a nominally flawless test piece. In a tear test, the force is not applied evenly but concentrated on a deliberate flaw or sharp discontinuity. In this case the force to produce a continuously new surface is measured. The force to start or maintain tearing will depend on the geometry of the test piece and the nature of the discontinuity.

The main factors that affect tear strength are yarn properties and fabric structure. The mechanism of fabric tearing is different from linear tensile failure and relates to the ability of individual yarns to slide, pack together or 'jam' into a bundle, increasing the tearing force. Thus an open fabric structure contributes to more yarn sliding and jamming, and higher tear strength. An increase in yarn density in a woven fabric will decrease the tear strength of a fabric as yarns are broken individually as they have more restriction, preventing yarn slide.

A tightly mounted fabric is easier to tear than a slackly mounted fabric because the tear force propagates from yarn to yarn as the linear force in

the yarn restricts yarn slide. Staple yarn has a lower tear strength compared to filament yarn. In a trapezoid tear test, an increase in ends and picks increases tear strength. Tear resistance can also be affected considerably by the speed of the test.

4.3.3 Seam strength

The quality and performance of a sewn garment depend on seam strength and seam slippage along with appearance and other mechanical properties. Failure of the seams of the garment by breaking of the sewing thread or by seam slippage affects serviceability. The strength of the seam or its ability to resist seam opening is an important fabric property and is needed to determine seam efficiency and the optimum sewing conditions. These can include seam type, stitch type, number of stitches per unit length of seam, sewing thread size and needle size.

Seam strength relates to the force required to break the stitching thread at the line of stitching. It is often used to test the strength of a sewing thread or test joins in strong industrial fabrics.

Seam slippage is defined as the tendency for a seam to open due to the application of a force perpendicular to the seam direction. It is a measure of the yarn slippage in a fabric at the seam. Sometimes it refers to breakage of the thread used to stitch the seam. The seam slippage test is also referred to as the seam opening test. Seam slippage may occur in a garment or household item for different reasons, including:

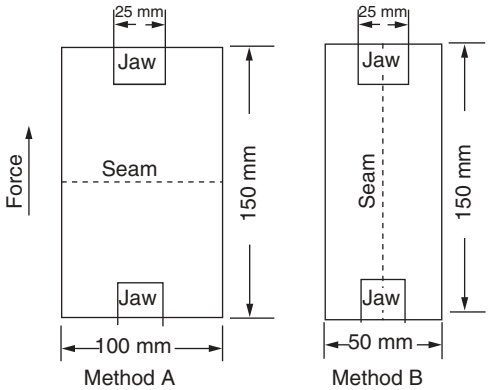
- a low number of warp or weft threads in relation to particular yarn and fabric construction characteristics
- seam allowance too small
- high force requirements placed on the seam due to use
- improper seam selection or construction
- insufficient elasticity of the seam.

Methods for testing seam strength and seam slippage

The CRE machine is normally used and the test specimen is held the same way as in a conventional grab test. The sewn seams may be taken from sewn articles such as garments or may be prepared from fabric samples.

Seam strength

There are two geometries used for the seam strength test, transverse and longitudinal, and these are shown in Fig. 4.5. The transverse direction (Method A) is applicable to relatively inextensible fabrics, such as woven



4.5 Seam strength tests.

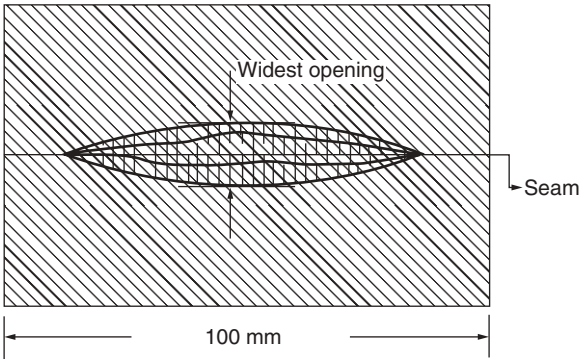
and stable warp knit structures. The longitudinal direction (Method B) is applicable to extensible fabrics, such as knitted, elastic and highly resilient fabrics. Sample preparation is different for tests in the transverse direction compared to the longitudinal direction as shown in Fig. 4.5. A straight rather than curved seam line is required for a test in the longitudinal direction. The seam line of the seamed samples must be parallel to either the warp or weft yarns.

The test specimen is mounted centrally between the upper and lower jaws with the seam perpendicular or parallel to the jaws depending on the test method. The sample is then stretched at a constant rate until rupture occurs. In a traverse test this is when the seam ruptures, and in the longitudinal test this is when the first sign of seam rupture occurs. In the case of stitched seams, this implies the first stitch breakage. The maximum force applied to the specimen is recorded for both methods as the seam breaking force. If the fabric ruptures prior to the seam rupturing, then a statement to this effect should be made in the test report. If the specimen slips in the jaws or breaks in or at the jaws, the test result for that specimen must be discarded.

Seam slippage

Specimens for seam slippage tests are prepared according to the following steps:

1. Cut the fabric sample to rectangular specimens 175 ± 100 mm for both warp and weft directions.
2. Fold the specimens in half by placing the two shorter edges together and sew a lockstitch seam parallel to and at a distance of 12 ± 1 mm from the fold.
3. Cut the specimen along the fold after sewing.



4.6 Measurement of seam opening.

Preparation of sewn seam test specimens from fabric samples requires prior specification of sewing details. These can be taken directly from the standard or can be set by the parties interested in the test results. These details often vary with the fabric end-use and include seam allowance (seam width), stitch type, stitch frequency, needle size and tread parameters.

The machine setup for the seam slippage test is similar to that for the seam strength test, except that a cross-head speed of 50 mm/min is usually used. The specimen is mounted centrally in the width of each set of jaws with the seam midway between and parallel to the horizontal edges of the jaws. The load is then increased until the selected load is reached. The jaw movement is stopped at that point, and the width of the seam opening at its widest place is measured to the nearest 0.5 mm within 10 seconds, in the direction of the applied force (Fig. 4.6). Then the force on the specimen is reduced to 2.5 N and after an interval of 2 minutes the seam opening at its widest place is re-measured. The measuring device can be a small transparent rule or a divider.

An alternative method is to increase the load until a seam opening of 6 mm is reached, at which point the load is recorded for each specimen. This method is applied to a single seam on woven fabrics. If a sample from a commercial garment has multiple seams, then an opening of 3 mm is used.

The standards commonly used for seam tests are as follows:

- ASTM D1683 Standard test method for failure in sewn seams of woven fabrics, 1990
- ASTM D751 Seam strength, 1995
- BS 3320:1988 Method for determination of slippage resistance of yarns in woven fabrics: Seam method

- AS 2001.2.20-2004 Determination of seam breaking force
- AS 2001.2.22-2006 Physical tests – Determination of yarn slippage in woven fabric at a standard stitched seam.

4.3.4 Burst strength

Burst strength testing is the application of a perpendicular force to a fabric until it ruptures. The force is normally applied using either a ball or a hydraulically expanded diaphragm. The fabric is clamped in place around the device that applies the force by a circular ring. The material is stressed in all directions at the same time regardless of the fabric construction. Ball burst testing is used as an alternative to tensile testing for materials that are not easily prepared for tensile testing or have poor reproducibility when tensile tested. These fabrics include knits, lace, non-wovens and felts.

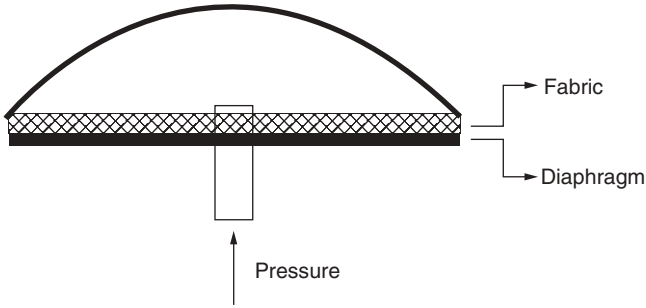
There are fabrics which are simultaneously stressed in all directions during service, such as parachute fabrics, filters, sacks and net. A fabric is more likely to fail by bursting in service than it is to break by a straight tensile fracture, as this is the type of stress that is present at the elbows and knees of clothing. Results obtained from tensile and burst testing are not directly comparable.

When a fabric fails during a bursting strength test, it does so across the direction which has the lowest breaking extension. When a burst test is undertaken, all directions in the fabric undergo the same extension, so the fabric direction with the lowest extension at break is the one that will fail first. This is not necessarily the direction with the lowest strength. Elongation cannot be determined from a burst strength test.

Methods for testing burst strength

Ball burst method

The ball burst method uses a CRE machine to apply the perpendicular force. The attachment for the CRE machine comprises two parts: a lower fixed clamping device of fixed aperture diameter and an upper moving ball that impacts on the fabric surface. The clamping device has an upper and a lower clamp with concentric grooves and crowns that intermesh with the test piece to provide grip. Test specimens can be cut into square or circular pieces, but must be of sufficient size to protrude outside the annular rings around the complete circumference of the lower clamp. The face of the rings should be perpendicular to the direction of the application of the force. The centre portion pushes against a polished steel ball at a constant rate until it ruptures. The burst strength is then calculated from the force of rupture F and the internal cross-sectional area A of the test piece, F/A. Current



4.7 Simple principle of hydraulic diaphragm method.

research shows that a larger ball diameter of 38 mm would improve reproducibility; however, most standards still use a 25 mm diameter ball.

Hydraulic diaphragm method

The hydraulic diaphragm test method uses a diaphragm inflated by hydraulic pressure to apply the perpendicular force to the fabric. The aperture size is normally different from that used for ball burst tests. The diaphragm, normally made of rubber, is mounted below the clamped test piece (Fig. 4.7). The clamping device should provide distributed pressure sufficient to prevent specimen slippage during a test. During a test hydraulic fluid is introduced behind the rubber diaphragm at a known rate and the burst pressure (M) at rupture is measured using a pressure gauge. The upper clamp and sample is then removed and the tare pressure (T) to distend the diaphragm is recorded. The tare pressure (T) is subtracted from the burst pressure at rupture (M) to give the actual burst pressure (B) of the test piece, viz. $B = M - T$. The burst pressure is expressed in kilopascals. From this method, bursting distension can be measured in millimetres, immediately prior to rupture, from the height change of the centre of the upper surface above the starting plane.

The above two methods are set out for determining the bursting pressure of both wet and dry fabrics. The two methods may not give the same results, as the mechanism of force application is slightly different between the two test apparatus.

The relevant standards commonly used are listed below:

- ISO 3303-1995 Determination of bursting strength
- ISO 2960 Textiles – Determination of bursting strength and bursting distension – Diaphragm method
- BS 4768 Method for determination of the bursting strength and bursting distension of fabrics

- BS 3424 Methods of test for coated fabrics – Wounded burst test
- ASTM D3787 Standard test method for bursting strength of knitted goods – constant-rate-of-traverse (CRT) ball burst test
- AS 2001.2.19-1998 Determination of bursting force of textile fabrics – Ball burst method
- AS 2001.2.4-1990 Physical tests – Determination of bursting pressure of textile fabrics – Hydraulic diaphragm method.

4.4 Fabric stretch properties

These properties are particularly important for elastic fabric and stretch fabric. Elastic or elastomeric fabric is made from an elastomer either alone or in combination with other textile material. Elastomers include polymers such as rubber, polybutadiene, polyisobutylene and polyurethanes. Because the glass transition temperature of these polymers is below room temperature, these materials are soft or rubbery at room temperature and can easily return to their original shape after stretching. Due to the nature of these materials they do not always return to their original shape after prolonged deformation. Tests should measure size change (kickback) after long periods of extension. The tension to stretch an elastic material and the percentage stretch achievable are also important variables to be measured.

Stretch fabric is usually accomplished by incorporating a small percentage of elastomeric fibres or filaments into a conventional woven or knitted textile fabric. Stretch fabric can also be achieved without elastromeric fibres by fabric construction or yarn selection. There are two types of stretch fabrics: comfort stretch (5–30%) and power stretch (30–50%) (Lyle, 1977). Comfort stretch fabrics are designed for low loads, and power stretch for considerably higher loads. Stretch is important in sportswear such as swimwear or other active sports clothing, which is required to be a close fit to the body. The stretch requirements of a fabric can be gauged from the typical values of stretch that are encountered during the actions of sitting, bending or flexing of knees and elbows.

Both elastic fabric and stretch fabric require good elasticity; consequently fabric tends to recover its original size and shape immediately after removal of the force causing deformation. The three main factors of interest when testing a fabric with recoverable elongation are elongation at load, force for elongation, and recovery after load.

- Elongation at load is the amount that a fabric stretches in length from its original length after a fixed load is applied. This is commonly used to define the level of stretch within the fabric. Woven fabrics have much less stretch than knitted fabrics.

- Force for elongation defines the amount of force required to extend a fabric a certain distance in elongation. It can be called power or tension of the fabric at elongation and is important for comfort factors in garment design.
- Recovery after load is the amount a fabric returns to its original dimensions after the elongation load is released.

Recovery is possibly the most important factor as it defines whether a fabric is stretch or not. Fabrics without elastic properties are often tested for stretch and recovery to quantify the effect of stretching the fabric in use. A 100% cotton single jersey fabric will generally stretch significantly when a load is applied; however, its recovery after stretch is poor. The addition of an elastomeric fibre will increase the level of recovery, which can then define this fabric as a stretch fabric.

Recovery is often measured after a long period of load. Elastomers can break down when loaded for a long time. This is observed as a loss in fabric recovery or tension at load. This type of test is often used for elastic tapes or fabrics where the tension is an integral part of the garment design. An example is underwear where the product is rendered useless if the elastic waistband no longer holds the garment in place.

There are two main ways by which fabrics are measured for stretch and recovery. These are dynamic and static measurements. In dynamic measurement the fabric is applied with a fixed load or a fixed extension at a controlled rate of extension. Dynamic measurements can be cycled through a series of extensions before the results are taken. The CRE machine is an example of a machine used for dynamic testing. Dynamic tests generally measure tension at elongation as well as elongation and relaxation.

A static test is conducted by clamping one end of a fabric on a flat plane. The other end is then displaced by applying a fixed load or by stretching to a set elongation. Static tests generally only provide elongation and load information. However, they are commonly used to measure recovery after a long period of loading.

4.4.1 Methods for testing fabric stretch

Test for elongation of elastic fabric

When a CRE machine is used for testing tension and elongation of an elastic fabric, a straight wide or narrow elastic fabric, or a loop specimen, is prepared. The specified loads and cross-head speeds are applied to cycle (loading and unloading) the fabric for a required number. For low elongation fabrics (below 100%), use of a slower cross-head speed should be agreed. Three properties should be examined: elongation (percentage stretch), tension (power) and recovery.

Test for fabric stretch

There are a number of tests devised for stretch fabrics by various organisations, all following similar procedures but differing widely in many of the important details, such as load applied, number of stretch cycles before the actual measurements, time held at the fixed load, and time allowed for recovery. Here are some comparisons between the BS 4952:1992 and ASTM D3107-1980 standards. Two quantities are generally measured:

- The extension at a given load, which is a measure of how easily the fabric stretches
- Growth or residual extension, which measures how well the fabric recovers from stretching to this load.

In the British standard (BS4952:1992), five specimens from warp and weft directions each are tested. Two different dimensions of specimen in clamps are required for woven and knitted fabrics respectively: a width of 75 mm for both woven and knit, and a gauge length of 75 mm for knit and 200 mm for woven (as L_1). The fabric is to be stretched at a specified force (30 N for knit and 60 N for woven) at a rate of 100 mm/min, and the load is maintained for 10 s; the extension (cross-head movement) is then recorded as L_2. The sample is removed from the clamps and allowed to relax on a flat, smooth surface and its length is re-measured after 1 min as L_3. If a longer period of relaxation is required, the length is re-measured as L_4 after 30 min. The stretch and recovery results can be calculated as follows:

Stretch:

$$\text{Mean extension percent, } E = 100L_2/L_1 \qquad 4.3$$

Recovery:

$$\text{Mean residual extension after 1 min, } R_1 = 100(L_3 - L_1)/L_1 \qquad 4.4$$

$$\text{Mean residual extension after 30 min, } R_{30} = 100(L_4 - L_1)/L_1 \qquad 4.5$$

In the American standard (ASTM D3107-1980), apart from the different sample size for woven (width of 51 mm and gauge length of 500 mm), a weight of 1.8 kg also hangs at the bottom clamp. Both edges of the clamps are marked as the lower and top bench marks, and the original distance between the two marks is recorded as length A. The fabric specimen is stretched by cycling three times from 0 to 1.8 kg load with 5 s interval, then the full load is applied at the fourth time and the extension (B) is then measured. Afterwards, the weight and bottom clamp are removed and the distance between the two marks is measured after 30 s as C. The percentage fabric stretch and immediate fabric growth are calculated as follows:

$$\text{Fabric stretch percent} = \frac{B - A}{A} \times 100 \quad 4.6$$

$$\text{Fabric growth percent} = \frac{C - A}{A} \times 100 \quad 4.7$$

Standards commonly used for the stretch test are as follows:

- ASTM D2594-2004 Standard test method for stretch properties of knitted fabrics having low power
- ASTM D3107-1980 Standard test method for stretch properties of fabrics woven from stretch yarns
- ASTM D6614-2007 Standard test method for stretch properties of textile fabrics – CRE method
- BS 4952-1992 Methods of test for elastic fabrics.

4.5 Fabric abrasion resistance

Abrasion is defined as the wearing away of any part of the fabric by rubbing against another surface. Fabrics are subjected to abrasion during their lifetimes and this may result in wear, deterioration, damage and a loss of performance. However, the abrasion resistance is only one of several factors contributing to wear performance or durability. Abrasion can occur in many ways and can include fabric to fabric rubbing when sitting, fabric to ground abrasion during crawling, and sand being rubbed into upholstery fabric, and it is difficult to correlate conditions of abrasion of a textile in wear or use with laboratory tests. This may explain the reason why there are many different types of abrasion testing machines, abradants, testing conditions, testing procedures, methods of evaluation of abrasion resistance and interpretation of results.

The methods used may be described by the equipment, the test head movement or testing device setup. These include (a) inflated diaphragm; (b) flexing and abrasion (i.e. the Stoll Flex Tester); (c) oscillatory cylinder; (d) rotary platform; (e) uniform abrasion; and (f) impeller tumble. Presentations of the fabric to the abradant include in plane (or flat), flex, tumble or edge abrasion or a combination of more than one of these factors.

There are two general approaches for assessment of abrasion resistance: (1) to abrade the sample until a predetermined end-point is reached, such as the breaking of two threads or the generation of a hole, while recording the time or number of cycles to achieve this; and (2) to abrade for a set time or number of cycles and assess the fabric for change in appearance, loss of mass, loss of strength, change in thickness or other relevant property. The length of the test for the first approach is indeterminate and requires the sample to be regularly examined for failure. This need for examination

is time consuming as the test may last for a long time. The second approach provides for simpler measurements; however, the change in properties such as mass loss can be slight.

4.5.1 Factors affecting abrasion resistance

A fabric's resistance to abrasion is affected by many factors, such as fibre type, the inherent mechanical properties of the fibres, the dimensions of the fibres, the structure of the yarns, the construction and thickness of the fabrics, and the type and amount of finishing material added to the fibres, yarns or fabrics.

For example, fibres with high elongation, elastic recovery and work of rupture have a good ability to withstand repeated distortion, hence a good degree of abrasion resistance. Nylon is generally considered to have the best abrasion resistance, followed by polyester, polypropylene, wool, cotton and acrylic. Longer fibres incorporated into a fabric confer better abrasion resistance than short fibres because it is harder to liberate them from the fabric structure. Flat plain weave fabrics have better abrasion resistance than other weaves because the yarns are more tightly locked in a plain weave structure and the wear is spread more evenly over all of the yarns in the fabric. Fabrics with a loose structure have a lower abrasion resistance than those with a tight structure.

The resistance to abrasion is also greatly affected by the conditions of the tests, such as the nature of the abradant, variable action of the abradant over the area of specimen abraded, the tension of the specimen, the pressure between the specimen and the abradant, and the condition of the specimen (wet or dry).

Abradants can consist of anything that will cause wear. The most common solid abradants are abrasive wheels (vitreous and resilient), abrasive papers or other fabrics, stones (aluminium oxide or silicon carbide) and metal 'knives'. The nature of abradants and the type of action will control the severity of the test. It is important that the action of the abradant should be constant throughout the test and the tension of the mounted specimen should be reproducible, as this determines the degree of mobility of the sample during abrasion. The pressure between the abradant and the sample affects the severity and rate at which abrasion occurs. Accelerated destruction of test samples through increased pressure or other factors such as heat generation may lead to false conclusions on fabric behaviour.

4.5.2 Methods for testing abrasion resistance

Three methods have been widely used over the years: the Martindale tester, the Taber abrader (rotary platform double-head abrader) and the accelerator.

The Martindale tester

The Martindale tester is designed to give a controlled amount of abrasion between fabric surfaces at comparatively low pressures in continuously changing directions. The results required determine the test and assessment method used. Assessments can include determination of specimen breakdown, mass loss or appearance change.

For the methods applying assessment of specimen breakdown or mass loss, specimens are circular of either 38 mm or 140 mm in diameter. Normally the abradant is silicon carbide paper or woven worsted wool mounted over felt. The small test specimen is sitting on the large abradant and then cycled backwards and forwards in a Lissajous motion producing even wear. A force of either 9 or 12 kPa is applied to the top of the specimen to hold it against the abradant. If assessment of appearance change needs to be carried out, then larger test pieces (140 mm in diameter) are required. The roles are reversed and the abradant is placed in the holder with the specimen as the base platform. The standard abradant should be replaced at the start of each test and after 50 000 cycles if the test is to be continued beyond this number. Behind the abradant is a standard backing felt which is replaced at longer intervals.

For assessment, the specimen is examined at suitable intervals to see whether two threads have broken, mass has changed or appearance has changed. Different fabric structures or components will require different inspection intervals. Some bias may occur if a fabric has a low abrasion resistance. Hosiery may be tested using a modified specimen holder, which stretches the knitted material, thus effectively accelerating the test. A flattened rubber ball is pushed through the sample as the holder is tightened, thus stretching it.

The Taber abrader

The rotary platform abrader (Taber abrader) applies two abrasive wheels (13 mm thick and 51 mm in diameter) under controlled pressure to a circular sample (110 mm in diameter) mounted on a rotating table or platform. The fabric is subjected to the wear action by two abrasive wheels pressing onto a rotating sample. The wheels are arranged at diametrically opposite sides of the sample so that they are rotated in the opposite direction by the rotation of the sample. These are available in different abrasive grain sizes. The load used can be 125, 250, 500 or 1000 g (or 1.23, 2.45, 4.9 or 9.81 N). The test specimen is abraded until damage (broken threads or hole) occurs or there is a visual change in the surface appearance (loss of texture, pile

or surface coating). The number of cycles is recorded when the end point is reached.

The accelerator abrasion tester

The accelerator abrasion tester has an action that is quite different from most other abrasion testers. In the test a free fabric specimen is driven by a rotor inside a circular chamber lined with an abrasive cloth. The specimen suffers abrasion by rubbing against itself as well as the liner. Evaluation is made on the basis of either weight loss of the specimen or the loss in grab strength of the specimen broken at an abraded edge. For evaluation by loss in strength, two specimens measuring 100 mm × 300 mm are used for grab tests. Each specimen is numbered at both ends and then cut in half. One half is used for determining the original grab strength and the other half for determining the grab strength after abrading.

Many different standards are used worldwide for abrasion resistance tests, including:

- ASTM D3884 Standard guide for abrasion resistance of textile fabrics (rotary platform, double-head method)
- ASTM D4966-1998(R04) Standard test method for abrasion resistance of textile fabrics (Martindale abrasion tester method)
- ISO 12947-1-1998 Textiles – Determination of the abrasion resistance of fabrics by the Martindale method – Part 1: Martindale abrasion testing apparatus
- ISO 12947-2-1998 Textiles – Determination of the abrasion resistance of fabrics by the Martindale method – Part 2: Determination of specimen breakdown
- AS 2001.2.25.1-2006 Physical tests – Determination of the abrasion resistance of fabrics by the Martindale method – Martindale abrasion testing apparatus
- AS 2001.2.25.2-2006 Physical tests – Determination of the abrasion resistance of fabrics by the Martindale method – Determination of specimen breakdown
- AS 2001.2.25.3-2006 Physical tests – Determination of the abrasion resistance of fabrics by the Martindale method – Determination of mass loss
- AS 2001.2.25.4-2006 Physical tests – Determination of the abrasion resistance of fabrics by the Martindale method – Assessment of appearance change
- AS 2001.2.26-1990 Physical tests – Determination of flat abrasion resistance of textile fabrics (flexing and abrasion method)

- AS 2001.2.27-1990 Physical tests – Determination of abrasion resistance of textile fabrics (inflated diaphragm method)
- AS 2001.2.28-1992 Physical tests – Determination of abrasion resistance of textile fabrics (rotary platform, double-head method)
- AS 2001.2.30-1994 Physical tests – Determination of abrasion resistance of coated textile fabrics (oscillatory cylinder method).

4.6 Testing the aesthetic properties of fabrics

Fabric aesthetic properties include the optimised handle of fabric, good appearance in the garment and good appearance in wear. Fabric properties like thickness, compressibility, bending properties, extensibility, dimensional stability and surface properties are associated with fabric aesthetics. Generally, the aesthetic characteristics of fabrics can be measured by a mixture of subjective evaluation and objective tests.

When assessing fabric handle subjectively, the assessor usually strokes the fabric surface with one or several fingers and then squashes the fabric gently in the hand. Subjective characteristics are assessed by the sensations of smoothness or roughness, hardness or softness, stiffness or limpness. These feelings may determine whether a fabric is comfortable or uncomfortable to a wearer. However, there are many factors that influence the characters of a fabric observed through handling, for instance the type of fabric being assessed, which may be different in the material used, and differences in fabric structure made specially for apparel, upholstery or industrial uses. This subjective hand evaluation system requires years of experience and can obviously be influenced by the personal preferences of the assessor. A fabric may feel light, soft, mellow, smooth, crisp, heavy, harsh, rough, furry, fuzzy or downy soft. So there is a need to replace the subjective assessment of fabrics by experts with an objective machine-based system which will give consistent and reproducible results.

The theoretical primary hand values (PHV) of a fabric can be calculated from its mechanical properties according to the Kawabata method (Kawabata, 1980). The PHV values include *koshi* (stiffness), *shari* (crispness) and *fukurami* (fullness and softness). These hand values relate to the shear and bending properties, and consequently to the inherent fibre properties and fabric geometry. The Kawabata Evaluation System for Fabric (KES-F) consists of four specialised instruments: FB1 for tensile and shearing, FB2 for bending, FB3 for compression and FB4 for surface friction and variation. A total of 16 parameters are measured at low levels of force. The measurements are intended to mimic the fabric deformations found in use.

A set of the Fabric Assurance by Simple Testing (SiroFAST) instruments developed in Australia is used to measure the mechanical properties of

wool fabrics and to predict their tailoring performance. SiroFAST gives similar information on the aesthetic characteristics of fabric as KES-F does, but in a simple manner, and is more suited to a mill environment. The SiroFAST system includes SiroFAST-1 for thickness, SiroFAST-2 for bending, SiroFAST-3 for extensibility and SiroFAST-4 for dimensional stability. The SiroFAST PressTest has also been added to complement these tests. Through the objective measurements of fabric and a data set on a chart or 'fingerprint', manufacturers can identify fabric faults, predict the consequences of those faults and identify re-finishing routes or changes in production.

The tests considered relevant to fabric hand in this chapter include drape, bending, shearing and compressibility. Different testing methods applied over many years are compared in the following sections.

4.6.1 Fabric drape

Drape is the term used to describe the way a fabric hangs under its own weight. Fabric drapability is an important factor from an aesthetic point of view. The quality of 'drape' is important to a designer as it influences a garment's appearance. The draping qualities required from a fabric will differ depending on its end use, e.g. knitted fabrics are relatively floppy and garments made from them will tend to follow the body contours. Woven fabrics are stiffer than knitted fabrics, so they are used in tailored clothing where the fabric hangs away from the body and disguises its contours. Uses such as curtains, tablecloths or women's clothing need to exhibit good drape shape and appearance. Good draping leads to the fitting of a fabric over a surface without undesirable wrinkling or tearing. Measurement of a fabric's drape assesses its ability to hang in graceful curves.

The drape coefficient (F) has been developed to describe the degree of drape and drape shape (configuration, modality). A lower F value means the fabric is softer, and its drapability is better. In other words, the higher the drape coefficient (F) the stiffer the fabric is. The drape coefficient is relevant to the drapability of fabrics but is not sufficient for characterising drape formation. Fabrics with the same drape coefficients may form different drape shapes. Hence other parameters such as number of nodes (folds) and node dimensions are also used to describe the drape quality.

The drape formation process is experimentally found to consist of three stages (Mizutani *et al.*, 2005): node generation (node appearance in the early stage), development (drapes growing from these nodes) and stabilisation (static stabilised drapes). The generation of nodes and the development process must be considered in relation to the mechanical properties of the fabrics.

When a fabric is draped, it deforms with multidirectional curvature. Draping qualities are related to fabric bending stiffness and shear properties. Factors such as fibre content, yarn structure, fabric structure and type of finish affect the drape behaviour. For example, fabric thickness (T) affects drape in different ways (Chen *et al.*, 2005): when $T < 0.4$ mm, increasing T causes a decrease in F because the weight effect imparts more influence than rigidity and flexibility at these thicknesses. This factor is reversed for $0.4 < T < 0.8$ mm, as changes in bending rigidity influence F more, causing it to rise with increased thickness. When $T > 0.8$ mm, the fabric is rigid, so the drapability is poor.

Methods for testing fabric drapability

Drape test systems currently used worldwide include the Peirce's cantilever method, the Rotrakote-CUSICK drape tester, the Fabric Research Liberating method (FRL drapemeter) (Japan), and the 3D body scanner.

The cantilever method measures fabric bending characteristics and then converts them into a measure of fabric drape. The FRL drapemeter also works on a similar principle. The cantilever method and FRL drapemeter only reflect a fabric's two-dimensional characters, and as fabric drape is actually a three-dimensional phenomenon, they are now less widely used.

The CUSICK drape tester is a simple but apt instrument which uses a parallel beam of light to cast a shadow from a circular piece of fabric, supported by a smaller circular disc. The area of shadow (A_S) is measured and compared with the area of the sample (A_D) and that of the supporting platform (A_d). The drape coefficient F is defined as

$$F = \frac{A_S - A_d}{A_D - A_d} \times 100\% \qquad 4.8$$

In the actual test, the light beam casts a shadow of the draped fabric onto a ring of highly uniform translucent paper supported on a glass screen. The surface drape pattern area on the paper ring is directly proportional to the mass of that area. So the drape coefficient (F) can be calculated in a simple way:

$$F = \frac{\text{mass of shaded area}}{\text{total mass of paper ring}} \times 100\% \qquad 4.9$$

There are three standard diameters of specimen that can be used for different types of fabrics:

- 24 cm for limp fabrics (drape coefficient below 30% with the 30 cm sample)
- 30 cm for medium fabrics
- 36 cm for stiff fabrics (drape coefficient above 85% with the 30 cm sample).

A fabric should be tested initially with a 30 cm specimen in order to see which of the above categories it falls into. When test specimens of different diameter are used, the drape coefficients measured from them are not directly comparable with one another.

The CUSICK drape tester can be fitted with a video camera and computer for instantaneous measurement of the drape coefficient. This is a trend that is adopted by most new drape measurement systems as it enables computer-aided analysis of the drape shape of fabrics and the numbers of nodes. A new apparatus (the drape elevator), designed by Japanese researchers, can also be used to evaluate drape properties continuously during the process of drape formation.

The 3D body scanner is another adaptation of the computer-aided capture of drape characteristics. A circular piece of fabric is hung over a circular disc, which allows the fabric to drape as in a CUSICK drape tester. Two scanners (one rotated 90° from the other) take around 12 seconds to capture the complete configuration (point cloud data) of the draped sample. The captured data is then processed using the Geomagic™ software to generate a 3D surface of the scanned object. The drape coefficient along with other useful drape parameters can be extracted from the processed data.

Intricate software has been developed to utilise the results obtained by electronic drape measurement in the computer design of a textile product. Drape characteristics can be simulated in a range of different designs and applications in both static and dynamic simulations.

4.6.2 Fabric bending

A bending test measures the severity of the flexing action of a material. The test can vary between bending the material sharply to bending it over a large radius and small amplitude. For thin flexible materials such as fabrics, the deformation is always intended to be at constant strain amplitude rather than stress amplitude. Resistance to bending or flexural rigidity is defined as flex stiffness. This property can influence the aesthetic appearance as well as the comfort of a fabric.

The bending length is a measure of the interaction between fabric weight and fabric stiffness in which a fabric bends under its own weight. It reflects the stiffness of a fabric when bent in one plane under the force of gravity, and is one component of drape. Thus bending length is also called drape stiffness.

The bending rigidity, which is related to the perceived stiffness, is calculated from the bending length and mass per unit area. Fabrics with low bending rigidity may exhibit seam pucker and are prone to problems in cutting out. They are difficult to handle on an automated production line. A fabric with a higher bending rigidity may be more manageable

during sewing, resulting in a flat seam, but may cause problems during moulding.

The bending length is dependent on the weight of the fabric and is therefore an important component of the drape of a fabric when it is hanging under its own weight. The stiffness of a fabric in bending is very dependent on its thickness. The thicker the fabric, the stiffer it is, if all other factors remain the same. The bending modulus is independent of the dimensions of the strip tested, so that by analogy with solid materials it is a measure of 'intrinsic stiffness'.

Methods for testing fabric bending

Three methods are often used to test the stiffness of fabrics: the Cantilever test, the hanging loop test and the pure bending test conducted on a KES-FB2 bending tester. These methods are more suitable for testing woven fabrics than for testing knitted ones.

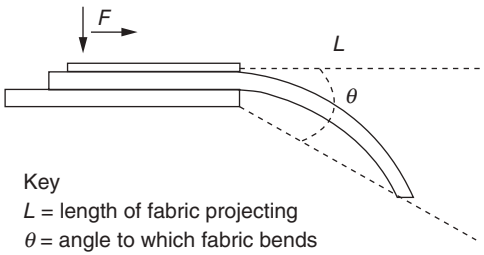
For the Cantilever test (Fig. 4.8), the Shirley Stiffness tester or the Gurley Stiffness tester is commonly used. The tester is based on the cantilever principle. In the test a rectangular strip (25 mm wide × 200 mm long) supported on a horizontal platform is clamped at one end and the rest of the strip is allowed to overhang and bend under its own weight. The bending length (C) is read from a calibrated scale in millimetres when the tip of the specimen reaches a plane inclined at 41.5 degrees. The higher the bending length is, the stiffer the fabric. The bending modulus (q) and the flexural rigidity (G) can be calculated from the bending length, the mass per unit area and fabric thickness:

$$\text{Flexural rigidity } G = 9.8MC^3 \times 10^{-6} (\mu\text{Nm}) \tag{4.10}$$

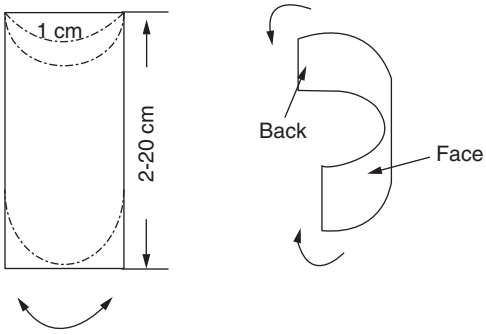
where C is bending length and M is mass per unit area.

$$\text{Bending modulus } q = \frac{12G \times 10^3}{t^3} (\text{N/m}^2) \tag{4.11}$$

where G is the flexural rigidity and t is the cloth thickness in mm.



4.8 Cantilever testing principle.



4.9 Pure bending testing principles.

If some fabrics are too flexible or limp, the hanging loop method may be used. Different shapes of hanging loops are used: ring loop, pear loop and heart loop. One end of the fabric is brought against the other end by bending through angles of 180° (pear), 360° (ring) and 540° (heart) and joined together. The length of this loop is measured when it is hanging vertically under its own weight. This hanging length is inversely related to the bending stiffness.

The KES-FB2 bending tester is a different approach used for determining stiffness and hysteresis of fabric specimens under pure bending. The precise bending momentum of the specimen can be detected. A standard size specimen 20 cm × 20 cm is mounted on two clamps (one is fixed and the other is free to move), which have a space of 1 cm between them (Fig. 4.9). The sample is then bent at a constant bending deformation rate of 0.5 cm^{-1}/s through a controlled curve pattern at a fixed torque by moving one of the clamps. The bending moment vs curvature curve can be obtained from the tester.

The digital pneumatic stiffness tester determines fabric stiffness using the ASTM circular bend test method. A plunger of 25.4 mm (1 in) diameter pushes the fabric through a 38 mm (1.5 in) diameter orifice for a distance of 57 mm (2.25 in) in 1.7 seconds and the maximum force is recorded. The machine is provided with a pneumatic cylinder, controls and a battery-operated digital force gauge of 50 kgf, 500 N or 100 lb (switchable) with peak-hold facility.

Standards commonly used for the bending stiffness test are as follows:

- ASTM D1388-2007 Standard test method for stiffness of fabrics
- BSI BS 3356-1991 Determination of bending length and flexural rigidity of fabrics (AMD 6337)
- AS 2001.2.9-1977 Determination of stiffness of cloth.

4.6.3 Fabric shearing

Shear deformation is very common during wear as the fabric needs to be stretched or sheared to various degrees as the body moves. The ability of a fabric to deform by shearing enables fabric to undergo more complex deformations than two-dimensional bending. Shearing enables a fabric to conform to complex shapes, such as the contours of the body in clothing applications. As a shearing force or moment is applied to a fabric, in-plane rotation of the yarns at the cross-over of the weave occurs along with yarn slippage at the interlacing points of warp and weft yarns, causing angle change. The shear mechanism is one of the important properties influencing the draping, pliability and handle of woven fabrics. It also affects their bending and tensile properties in various directions.

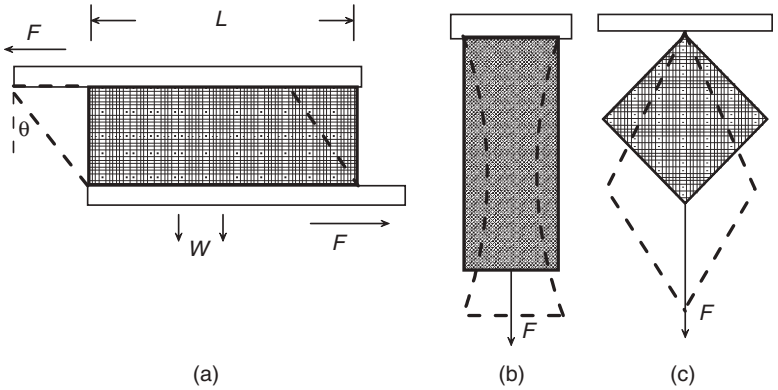
The shear behaviour of a woven fabric can be characterised by two shear parameters: shear rigidity and shear hysteresis. Shear rigidity determines fabric stiffness or softness. Fabric with low values of shear rigidity distorts easily, giving rise to difficulties in laying up, marking and cutting. A high value of shear rigidity means that a fabric is difficult to mould. Shear hysteresis is the energy loss when the direction of shear is reversed within a shear deformation cycle. This is due to the fact that when a fabric is sheared, most of the force expended is used in overcoming the frictional forces that exist at the intersection of warp and weft. Shear hysteresis can be related to various handle characteristics such as crispness, scroopiness, and how noisy the fabric is when handled. There is a strong linear relationship between shear rigidity and shear hysteresis.

The shear deformation depends upon the frictional and elastic forces within a fabric, so the values of shear properties are greatly affected by the fabric structure and finishing process. For example, the values of shear rigidity and shear hysteresis increase with the increase in the weft density of woven fabrics. The finishing process releases residual bending stress existing in the yarns, thus it can reduce the shear rigidity of the finished fabric.

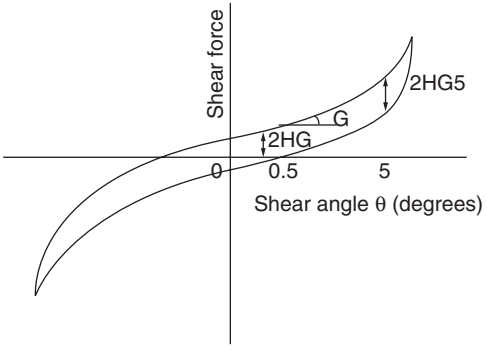
Methods for testing fabric shearing

Several simplified methods for testing the shear of fabrics have been developed by workers in this area, i.e. KES-FB1 (Japan) and SiroFAST-3 (Australia) as illustrated in Fig. 4.10. Method (a) in Fig. 4.10 is based on the test principle employed by the KES-F system. A rectangular fabric sample is subjected to a pair of equal and opposite stresses F which are acting parallel to its edges. The fabric deforms to a slant position, though its area remains constant. This is in-plane shear. Figure 4.11 shows a typical shear stress vs shear strain curve. The shear strain is defined as the tangent of the angle θ of shear. That is:

$$\text{Shear strain} = \tan\theta$$



4.10 Shear testing methods.



4.11 Shear hysteresis.

The shear rigidity (G) is the slope of the shear stress–strain curve:

$$G = F / \tan\theta$$

However, the shear deformation is not always a simple shear at constant area. Fabrics subjected to compressive forces in the plane of the material tend to buckle at very low values. In order to delay the onset of buckling, a vertical force W is applied to the fabric by using a weighted bottom clamp. The horizontal force F which is required to move the bottom clamp laterally is measured together with the shear angle θ. Then:

$$\text{Effective shear force} = F - W\tan\theta$$

The shear stress is defined as the shearing force divided by the sample width (L). A height:width ratio of 1:10 is considered to be the limit for practical measurements. The shear hysteresis parameters 2HG and 2HG5 are used in this method (2HG = hysteresis of shear forces at 0.5°, 2HG5 = hysteresis of shear forces at 5°).

Although the principle of method (a) in Fig. 4.10 is relatively simple, in practice it can be rather complicated to perform. Because the bias extension to a fabric is actually equivalent to shear, the test for it is easy to carry out on a CRE machine. Methods (b) (based on the test principle of SiroFAST-3) and (c) (a CRE machine can be used) are therefore the most appropriate for industrial use. The uniaxial tension is applied to a bias-cut specimen. Shear rigidity can be calculated from the extension of a fabric in the bias direction. For example, using a 5 gf/cm (or 4.9 N/m) tension (the same as that required in a SiroFAST-3 tester), if the extension on the bias (45°), EB5, is measured in %, then the shear rigidity (G) in N/m is simply calculated as $G = 123/EB5$.

It has been found experimentally that there were inconsistencies between the fabric properties measured in simple shear and by bias extension, due to a number of factors including the geometry of the test specimen, the assumption in the analysis that the threads were inextensible, and the variation that takes place in the normal stress during bias extension.

4.6.4 Fabric compression

The compression test for fabric is used to determine the fabric thickness at selected loads, and reflects the 'fullness' of a fabric. When measuring compression properties of fabric, it must be appreciated that all fabrics contain air as well as fibres and yarns. When a fabric is compressed, three distinct stages in the deformation of a fabric have been identified (Saville, 1999):

1. Individual fibres protruding from the surface will become bent and/or compressed. The resistance to compression in this region comes from the fibre bending stiffness.
2. The yarns come into close contact and are flattened and straightened, at which point the inter-yarn and inter-fibre friction as well as the yarns' bending stiffness provide the resistance to compression until the fibres are all in contact with one another.
3. The yarns are compacted, and the individual fibres are squashed against each other. The resistance is controlled mainly by the transverse properties (or lateral compression) of the fibres themselves.

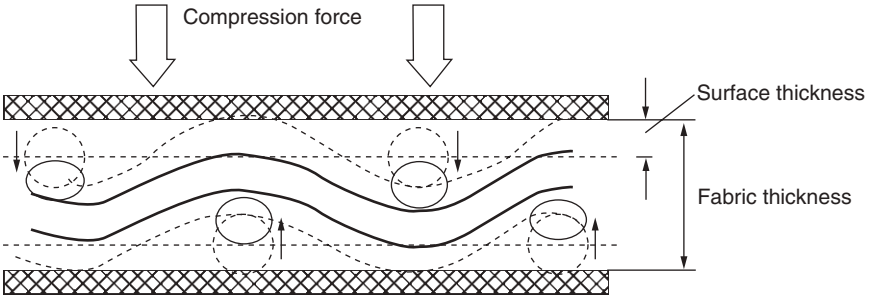
These stages of compression involve elastic deformation, frictional forces and also elastic recovery of the fibres from bending and lateral compression. So the compression property contains information about the handle of the fabric. The greater the radius of curvature of the transition between the first and third stages, the softer is the fabric in compression.

Methods for testing fabric compression

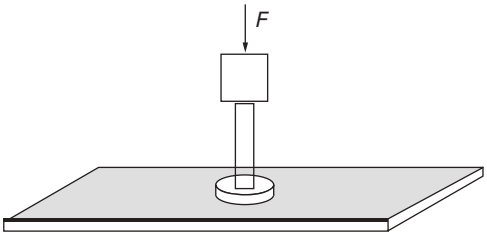
The SiroFAST-1 compression meter and the KES-FB3 compression instrument are commonly used for measuring fabric thickness and compressibility. Older methods may rely on making direct observations of the fabric cross-section using a microscope, but these have mostly been abandoned because of the difficulty of identifying the edges of the fabric sample.

In the SiroFAST system, compression property tests include fabric thickness, fabric surface thickness and released surface thickness as shown in Fig. 4.12. The fabric is considered to consist of an incompressible core and a compressible surface. The fabric thickness is measured on a 10 cm^2 area at two different pressures, firstly at 2 gf/cm^2 (equivalent to 0.195 kPa or 19.6 mN/cm^2) and then at 100 gf/cm^2 (equivalent to 9.807 kPa or 981 mN/cm^2). The difference between these two values gives a measure of the thickness of the surface layer. The fabric thickness measurements are repeated after steaming on an open Hoffman press for 30 s in order to determine the stability of the fabric finish.

From the KES-FB3 tester, the compression energy, compressibility, resilience and thickness of a specimen can be obtained. A circular compressing board of 2 cm^2 attached with a sensor is used to apply the force on the fabric specimen (Fig. 4.13). The applicable compression force is 0.1 gf/cm^2



4.12 Compression test principle based on the SiroFAST system.



4.13 Compression test on the KES-F system.

(minimum) to 2.5 kgf/cm^2 (maximum) and the machine is running at different compression deformation rates from 0.1 mm/s to 10 mm/s.

4.7 Applications and future trends

Fabric objective measurements provide a scientific means to quantify the quality and performance characteristics of fabrics. This forms the basis for fabric specification, product development, process control, product failure analysis and quality assurance. It also facilitates communication between consumers, manufacturers, designers and researchers in the whole textile chain.

The tests and results can be used to simulate and predict fabric performance in use. For example, fabrics with a low tensile strength and low tear strength may be susceptible to mechanical damage. This can occur when tension is put on the fabric during wear or cleaning. Sharp objects in contact with a fabric may also cause rips, tears or holes. In some cases, mechanical damage may be attributed to the basic construction of the fabric itself. Early identification of the problems in fabrics allows remedial action to be taken before the cost of rejects becomes an issue.

One fabric may have very different performance properties due to the interactions of durability factors. If the fabric durability is affected by environmental influences, such as ultraviolet radiation and atmospheric temperature, not only is the fabric aesthetic property changed, but also the breaking strength may change because of the deterioration of fibres. For example, fibre deterioration in curtain, drapery and sportswear fabrics results from exposure to either direct or indirect rays of the sun. Hence, one test method may or may not predict how a fabric may perform in consumer use. It is often necessary to test a combination of fabric properties.

On the other hand, the interrelationships of all mechanical properties are complex and are affected by many factors such as fabric geometry, setting, finishing, coating, laminating and so on; they can influence performance properties in very different ways. For instance, if other factors such as fibre type and fabric finish are held constant, a tight fabric construction generally contributes to high tensile strength but also lower tear strength and vice versa. A moderate structure, not too tight or too loose, could be expected to yield best abrasion resistance. Thereby, the early tests for the fabric properties enable the best processing route to be selected from the outset, to produce the optimal performance for an intended application.

Developments in modern fabric testing instrumentation have followed two broad routes: simplicity and versatility. This trend will continue, but with increased objectivity and intelligence built into the instruments. Generally, simplicity is preferred in the industry while research organisations prefer versatile test instruments, which are often complex. The chal-

lenge to researchers and instrument developers has been to quantify a complex fabric attribute with a simple parameter. A good example is fabric handle, which is affected by many factors. A simple approach to measuring fabric handle involves extracting a fabric specimen through a fixed diameter nozzle using a CRE machine (Alley, 1978; Alley and McHatton, 1976). A quantity termed 'handle modulus' is calculated from the force–displacement data, the geometric considerations of the nozzle, fabric coefficient of friction and fabric effective thickness. Studies have shown that results from the nozzle measurement are in fairly good agreement with those from other more complicated hand evaluation systems, such as the KES-F system and physical tests related to fabric hand. Other simple techniques include the ring or slot test (Grover *et al*., 1993) and the pulling force measurement by pulling a fabric through a set of parallel pins (Zhang *et al*., 2006). These methods consider the combined effect of fabric surface properties and bending stiffness. More developments are likely in this direction, with increased intelligence and sophistication (Pan, 2006).

4.8 Sources of further information and advice

In addition to the references, the following materials and websites provide good sources of further information on fabric testing:

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