

Types and properties of fibres and yarns used in weaving

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Abstract: This chapter reviews the types of fibres used in spinning, from natural to regenerated and synthetic fibres. It discusses key fibre properties such as length, linear density/fineness, cross-section and crimp. The chapter also reviews yarn properties such as linear density, diameter, packing and twist as well as fabric properties such as cover, mass, volume and thickness.

Key words: natural fibres, regenerated fibres, synthetic fibres, fibre properties, yarn properties, fabric properties.

1.1 Introduction

Woven fabrics consist of interlacements of yarns in two mutually perpendicular directions. Their structure permits a variation in the length and distribution of interlacements, resulting in a range of fabric deformations. Such control also offers scope for the generation of a diverse range of patterns and properties in fabrics. Triaxial fabrics are a special class of woven fabrics in which the warp threads constitute two sheets inclined at different angles, instead of being vertical. The weft thread is interlaced horizontally with the warp; this configuration thus has yarns in the fabric in three axes, hence the term 'triaxial' fabrics.

The building block of a woven fabric is yarn but the basic unit is fibre. Strength, extension, fineness, length and surface properties are some of the primary attributes of fibres which, using different types or blends of fibres, create a wide spectrum of useful and desirable physical and mechanical properties in the yarn and fabric produced. There are two basic types of fibres or filaments used in yarn:

- discontinuous fibres, i.e. short/staple fibres (including most natural fibres); and
- continuous fibres (such as silk and synthetic fibres).

Natural fibres have traditionally offered a variety of physical and mechanical properties. Using a natural, regenerated and synthetic filament yarn increases the range of physical and mechanical properties available and, indeed, allows functional properties to be tailor-made for a particular end use. Man-made filaments can be modified by texturing to alter bulk or stretch, or cut to a

desired length to produce staple fibres which, either alone or blended with other fibres, are then blended as spun yarns. A knowledge of fibre properties enables a design engineer to select the proper materials to create fabrics for specific end uses.

1.2 Types of natural and regenerated fibres

Cotton, wool, flax and silk are the most important natural textile fibres, followed by fibres such as jute and kenaf. Natural fibres vary in length and in their other properties. They are not consistent and contain unwanted impurities from their original source. Such fibres need to be processed to remove these impurities and reduce the variation in their length. Such fibres can be made coherent, continuous and load bearing by providing sufficient twist to the strand.

The mechanical properties of silk fibres are a combination of high strength, extensibility and compressibility. Jute and kenaf are strong fibres, exhibiting brittle fracture and with a small extension at break; they have high initial modulus but show very little recoverable elasticity. Cotton is the most important natural cellulosic textile fibre. Length and fineness are important measures of fibre quality. Cotton fibres range in dimensions from a length of 5 cm to 1.5 cm and a linear density of 1 dtex to 3 dtex. Amongst its many important properties, cotton fibre is hydrophilic and porous; on immersion in water, it swells and its internal pores fill with the water. Chemical modification can add many desired properties to a cotton fabric, including colour, permanent press, flame resistance, soil release and antimicrobial properties.

Regenerated fibres are manufactured from natural polymers. Two of the most widely used regenerated fibres are rayon and acetate. There is a wide variety of different rayon fibres, including regular rayons, high-tenacity rayons, low wet modulus rayons, high wet modulus and modal rayons, high-strength/high-elongation rayons, polynosic rayons, flame-retardant rayons, high absorbency (alloy rayons), hollow rayons and cuprammonium rayons. High-tenacity rayons are used where strength, toughness and durability are required. These fibres are dimensionally stable when used as reinforcement in tyres, conveyor belts, drive belts and hoses. Other applications for this type of rayon include industrial sewing threads, tent fabrics and tarpaulins.

A range of cross-sectional shapes such as round, flat, Y-shaped, E-shaped, U-shaped, T-shaped and irregular (crenulated) shaped fibres are produced in rayon. It is generally accepted that the crenulated structure is formed by greater shrinkage of the fibre skin than of the core. Given its aesthetic properties, particularly its silk-like sheen, finer denier fibres are used for shawls, scarves, blouses and coat linings. Blends with cotton, polyester and flax help overcome inherent defects such as poor dimensional stability and mushy hand. Polynosic rayon fibres have high wet and dry strength, low

elongation (8–11%), relatively low water retention and a very high wet modulus of 1 g/den. They have the firm and crisp hand of cotton in fabrics.

Cellulose acetate and triacetate textile fibres produce fabrics with an excellent hand, good dyeability, softness (comfort) and draping quality. The traditional market for cellulose acetate and triacetate fabrics is women's apparel. Acetate yarns are used for both tricot knit and woven constructions. Principal products within women's apparel include dresses, blouses and lingerie. Acetate has replaced rayon as a liner in men's suits and in non-apparel applications such as curtains. Cellulose triacetate offers the unique combination of 'ease-of-care' and aesthetic properties. A particularly important application of triacetate is in surface-finished fabrics such as fleece, velour and suede-like fabrics for dresses. Triacetate is also desirable for print fabrics as it produces bright sharp colours. Cellulose acetate and triacetate fibres are blended with nylon and polyester for numerous end-uses to compensate for the lower strength and durability of the weaker acetate and triacetate fibres. Yarns of this type, which are textured by air entanglement and bulking processes, have unique characteristics and aesthetics which permit their use in upholstery fabrics. Triacetate–nylon blended filament yarns are lightweight with good strength and bulk, and are useful in producing silk-type woven fabrics, such as plain taffetas, fine crepes and delicate jacquard figured styles for blouse and lingerie wear.

1.3 Types of synthetic fibres

An understanding of the chemistry and physics of natural textile fibres led to the creation of a range of man-made fibres such as viscose, rayon, nylon, polyester, acrylic and polypropylene. These synthetic fibres provide a range of specific properties, depending on purpose. Because they are manufactured, synthetic fibres can be produced consistently and are free of natural impurities. Synthetics have much to offer in terms of ease of care and durability but the problems of garment comfort, fabric cover, lustre, drape and garment tailorability have been major obstacles limiting the types of woven apparel fabrics made from 100% synthetic filament yarn. Instead, man-made/synthetic filaments are often cut into regular short lengths (staples) so that they are compatible with natural fibres and can be blended and spun into yarns with the right mix of properties for apparel applications.

1.3.1 Polyester

Polyester fibre, specifically polyethylene terephthalate (PET), is the most important synthetic fibre worldwide in terms of production volume¹ due to its low cost, the ease with which it can be processed and excellent performance. Amongst its properties, PET is a strong fibre (5 g/decitex). Polyester fibres

need to be treated with surface finishes or lubricants to allow high-speed processing. The various processing steps such as drawing, bulking and spinning would be impossible without spin finishes which alter the frictional properties of the fibre.

Polyester technology is responsible for a large number of products that range from cotton-blended staple to high-performance tyre cord. Drawn filament yarn can be treated in a number of ways. It can simply be twisted on a ring frame, or bulked by a process such as false-twist texturing. Many apparel filament yarns need to be textured to give desirable aesthetic properties, particularly for women's wear markets. The principle of false-twist texturing is to create minor side-to-side variations across a filament yarn, causing the yarn to bend during controlled thermal shrinkage to create a 3D structure with a bulky feel. For industrial use, such as for tyre cord, high-tenacity yarns are drawn under conditions where low heat shrinkage, low extension and high modulus products are produced. Polyester staple fibre can also be crimped to blend with cotton, wool or other natural fibres at the carding stage to prepare appropriate yarn blends. PET staple blends with wool and cotton are highly successful but, in a low twist yarn, the fibre has many loose ends and pill formation can take place.

Synthetic fibres like PET and nylon are normally round in cross-section (whilst natural fibres have different cross-sections). These fibre shapes affect yarn and fabric aesthetics in terms of feel, drape, handle and appearance. Trilobal polyester yarns glitter because incident light reflects off the fibre surface. By contrast, octalobal yarns produce fabrics with an opaque matte effect, as light is effectively absorbed by multiple reflections off the many acute angles in the yarn. Sharp-edged filaments have the same prized rustle and high frictional characteristics of pure silk. Flat rectangular filaments give fabrics an unpleasant slimy handle. Synthetic fibres in general, and PET in particular, are hydrophobic materials. PET has a moisture regain of 0.4% at 65% RH and rapidly builds up static electrical charges by friction to give a very unpleasant electric shock. Static charges can also lead to the attraction of dust and dirt, and, to avoid these problems, polyester is blended with wash-fast hydrophilic materials.

1.3.2 Polyamides (including nylon)

Polyamide textile fibres include nylon 6,6 and nylon-6. Excellent mechanical properties, strength, fatigue resistance and good adhesion to other materials such as rubber are some of the reasons for the predominance of polyamide fibres in a wide range of applications. Nylon fibres, for example, offer a number of attributes such as high strength, abrasion resistance, lustre, chemical and oil resistance, washability, elasticity and dyeability in a wide range of colours. In general, most nylon fibre products require high strength and

round cross-sections. However, for textile and carpet applications, fibres with modified cross-sections have been developed to achieve different aesthetics (such as lustre, opacity and better insulation).

Polyamides are used for women's hosiery, intimate apparel and stretch fabrics such as blouses, dresses, lingerie, ski apparel and swimwear. Polyamides have also been used for house furnishings such as bedspreads, carpets, curtains and upholstery. Other technical applications include truck and airplane tyres, seat belts, parachutes, ropes, fishing lines, nets, sleeping bags, tarpaulins, tents, sewing thread, ropes, monofilament fishing line and dental floss. High strength, toughness and abrasion resistance are also the main factors for selecting polyamide fibres for a wide range of military applications. In general, most nylon fibre products require high strength and round cross-sections. However, for textile and carpet applications, fibres with modified cross-sections have been developed to achieve different aesthetics (such as lustre, opacity and better insulation). In the area of general apparel, polyester has gained considerable significant market share at the expense of polyamides because of its easy-care characteristics.

1.3.3 Acrylic

Acrylics exist in a range of cross-sections, from almost perfectly round to dog-bone-shaped. Dry-spun acrylic fibres have a lower bending modulus due to their dog-bone shaped cross-section; as a result, a softer yarn with better fabric aesthetics can be obtained at a comparable fibre denier. The dog-bone-shaped cross-section prevents the fibres from packing closely to give a bulky yarn. Acrylics have a high resistance to sunlight, making continuous filament acrylics valuable in outdoor applications such as for tents and awnings.

In the general apparel markets, continuous filament acrylics and modacrylics find use as artificial fur; the fibres in these applications are made in a coarse denier with a special cross-section and surface modification to simulate natural animal hairs. Continuous filament yarn in very fine deniers is valued as a silk replacement for high-fashion dress fabrics, satins and poplins or to produce a cloth suitable for surface raising to give a suede or fine velour effect. Fine-denier filaments may also be used to produce fabrics with very high filament density and low air permeability, useful as insulating material, for example, in quilted interliners for parkas and outerwear for skiing. Other prominent uses for acrylics include rugs, curtains and upholstery.

1.3.4 Polypropylene

Some properties, such as toughness, low density and chemical stability are inherent to all polypropylene products. Others, such as colour stability,

UV and thermal stability result from the use of additives. The quality of polypropylene fibre has been improved to enhance properties such as light weight, mouldability, light stability, coloration, flame resistance and antistatic properties. Polypropylene is increasingly used for automotive interior furnishings whilst, for furniture, the current trend is to produce upholstery with a polypropylene tufted fabric of medium-denier using both air-textured and draw-textured yarn.

Woven fabrics from low denier polypropylene fibre (<1.5 dpf) are effective for thermal protection. They provide good aeration during perspiration and are waterproof. In apparel, their use can prevent skin dryness and body odour from perspiration, thus providing comfort and personal hygiene. Its major usage lies in winter wear, sportswear for hiking and skiing, work clothes and underwear. A smaller amount of this fibre is used in blends with nylon or acetate fibres for fashion wear. Polypropylene fibre itself does not ignite but shrinks, melts and pulls away on exposure to a flame, thus making it a more fire-retardant fibre than most synthetic fibres. A high-shrinkage fibre fabric processed at high temperature gives greater fibre density and bulk. There are two types of high-shrinkage polypropylene staple: cotton and wool types. Cotton staple is typically a 0.13 tex filament and 38 mm long. Wool staple is typically a 0.39 tex filament and 60 mm or 90 mm long. High-shrinkage polypropylene fibre is mixed with conventional fibres in spinning to yield a fluffy yarn.

1.4 Key fibre properties and how they are measured

To be suitable as a textile yarn, a fibre must have some essential and other desirable properties. The most important fibre characteristics² affecting fabric appearance, properties and performance include:

- length/linear density (fineness)
- cross-sectional shape
- surface characteristics
- crimp
- moisture content/regain
- shrinkage
- lustre/colour
- strength
- stiffness (flexibility)
- elastic recovery
- tenacity/elongation
- abrasion/chemical/flame resistance.

The moisture regain and tenacity/elongation of fibres are given in Tables 1.1 and 1.2. The following sections focus on fibre length/linear density, cross-section and crimp.

1.4.1 Fibre length and fineness/linear density

Length is a very important parameter for staple fibres affecting processability, as well as governing the physical and mechanical properties of the spun yarn itself. The lengths of staple fibres used in the production of spun yarns vary. Examples are:

- for polyester/viscose, 31–51 mm (for ring spinning) and 60–90 mm (for a worsted system)
- for cotton, 20–45 mm (for ring spinning).

Table 1.1 Moisture regain for fibres

Fibre	Moisture regain (%)
Wool	13.6
Silk	11.0
Rayon	11.0
Linen	8.75
Cotton yarn	7.0
Cellulose acetate	6.5
Nylon	4.5
Cellulose triacetate	3.5
Acrylic	1.5
Polyester	0.4

Table 1.2 Tenacity/elongation for fibres

	Tenacity (g/den)	Elongation (%)
Nylon (regular)	4.5–5.0	25–18
Nylon (high tenacity)	6.5–7.7	20–14
Nylon (staple)	3.8–4.5	37–25
Dacron polyester	4.4–5.0	22–18
Dacron polyester	3.0–3.9	40–25
Orlon acrylic	4.7–5.2	17–15
Orlon acrylic	2.0–2.5	45–20
Viscose (regular)	1.5–2.4	30–15
Viscose (high tenacity)	2.4–4.6	20–9
Acetate rayon	1.3–1.5	30–23
Wool	1.0–1.7	35–25
Cotton	2.0–5.0	7–3
Silk	2.2–4.6	25–10

Length variability is generally high for natural fibres (40% for cotton), but it should be as low as possible to improve yarn regularity. Longer fibres are advantageous since they require less twist for a desired yarn strength than shorter fibres. Low twist makes it possible to produce bulkier yarns.

The linear density, that is, the fineness of fibres, is expressed in decitex for natural fibres or denier for synthetic fibres. Examples include: cotton (1.4 decitex); silk (1 decitex); wool (1.7 decitex); and synthetic fibres (0.7–1.6 dpf). Many important properties of a yarn, such as packing and flexural rigidity, are influenced by fibre linear density. Finer fibres have a greater specific surface area which helps to improve the cohesion between fibres and gives better capillary action within the yarn structure. The total potential area of contact between fibres is governed by the specific surface area (surface area/unit volume) of fibres. The cohesion between fibres depends on the degree of inter-fibre contact generated by lateral pressure as a result of twist or wrapping. Torsional resistance of fibres also increases rapidly with increase in linear density. A coarser fibre is more difficult to twist and, once twisted, stores a higher level of torsional strain energy than finer fibres. This may be manifested in a yarn in the form of kinks and snarls in a relaxed state.

The uniformity of a yarn improves with a greater number of fibres in the yarn cross-section. For a given linear density of yarn, there will be greater number of finer fibres in the yarn cross-section. A uniform yarn automatically reduces the variation in other properties too. To spin a yarn successfully there should be a minimum number of fibres in the yarn cross-section (40–90 for ring spinning; 100 in rotor spinning).

Rigidity and cohesion contribute significantly to yarn strength. Strength is needed to withstand the spinning and weaving processes and to give strength to the fabric. Flexibility and fineness enable the fibres to be spun and woven to give the fabric its unique draping characteristics. Bending rigidity is proportional to the square of linear density of fibres. An increase in the linear density increases resistance to bending which makes the fibres stiffer. Fibres having a linear density of less than 0.33 tex are flexible enough to be used in apparel products. For industrial applications, the linear density ranges between 0.66 and 1.66 tex or more. Higher linear density is also used to improve the abrasion resistance of yarn and fabric.

1.4.2 Fibre cross-section

A fibre's cross-section affects fabric appearance, hand, drape, flexibility and moisture transport. It also affects cohesion, bending rigidity and the packing of fibres in a yarn. Cotton fibre has a U-shaped cross-section with a thin cuticle and a primary wall on the outside, and a hollow collapsed lumen inside. Jute fibre has a polygonal shaped cross-section. Synthetic fibres can be designed with any cross-sectional shape such as a circular, trilobal/multilobal, hollow

shape, etc. The cohesion of circular cross-section fibres is generally higher than those with non-circular cross-section due to the greater surface area of contact between adjacent fibres. Cohesion depends on cross-sectional shape, fineness, and the flexural and torsional rigidity of fibres.

1.4.3 Fibre crimp

Natural fibres like cotton have crimp which facilitates processing and improves yarn bulk. Crimp (3.5–5.5 per cm) needs to be introduced in synthetic fibres to aid processing. Crimp geometry in staple fibre prevents fibres getting too close to each other and enhances yarn bulk. Fibre crimp also improves fibre cohesion.

1.5 Comparing fibre properties

The different properties of some common fibres are compared in Table 1.3. Polyester fibres have the best performance in the range of highly desired properties, followed by nylon, acrylics, cellulose and wool. Acrylic fibres score more poorly than polyester or nylon but are superior to wool and the

Table 1.3 Comparative properties of common fibres, measured on a scale of 1–5, with 5 being the best

	Polyester	Nylon	Acrylic	Wool	Cellulose
Category 1: Highly desired properties					
Abrasion resistance (durability)	4	5	3	3	3
Strength (durability)	4	5	3	2	3
Wash–wear performance	5	3	3	1	1
Wrinkle resistance	5	3	3	4	1
Pill resistance	3	1	3	3	5
Category 2: Useful properties					
Bulk (cover)	3	3	5	4	1
Water transport (HS comfort)	3	2	5	3	4
Static resistance	2	1	4	5	5
Speed of drying	5	5	5	1	1
Category 3: Properties for specific applications					
Resistance to burning	5	5	3	5	1
Resistance to degradation by dry heat	5	3	5	5	3
Resistance to degradation by wet heat	3	4	5	2	4
Resistance to degradation by sunlight	3	3	5	2	3
Resistance to insects	5	5	5	1	1
Resistance to micro-organisms	5	5	5	1	1

cellulosics. Acrylic fibres are poorer than polyester in terms of strength, abrasion resistance, wash–wear performance and wrinkle resistance. Acrylic fibres rank highest in the categories of useful and specific properties. Some of the properties in these two categories are considered more important for non-apparel markets, such as good resistance to sunlight degradation for drapery. In summary, acrylic fibres exhibit a well-rounded combination of performance properties with no major deficiencies. However, for woven apparel, the key properties of good wash–wear performance, abrasion and wrinkle resistance favour the use of polyester-cotton blends or cross-linked resin-finished cotton fibres.

1.6 New types of fibre

There are a number of emerging types of fibre, some of the most important of which are discussed below.

1.6.1 Polyester fibres based on terephthalic acid

Polybutylene terephthalate (PBT) differs only slightly from PET in chemical composition but more substantially in its properties such as its higher crystallization rate and lower melting point. It can be melt-spun at lower temperatures and is inherently whiter than PET. As a fibre, it is much more elastic and has excellent resilience and recovery from small deformations. It dyes easily with disperse dyes at the boil, unlike PET, and resists photo-oxidative yellowing. Resilience and ease of dyeing are assets for carpet fibre.

Another polyester, polytrimethylene terephthalate (PTT), is a fibre with excellent recovery properties. Carpets made from PTT show excellent resilience due to the unique spring-like crystal structure of the fibre. It has a lower static charge and is resistant to stains. It is also used in intimate apparel and inner linings for clothing, and in the automotive and upholstery industries.

1.6.2 Microfibres

One of the most important developments in recent years has been in the technology to extrude extremely fine filaments of less than 1.0 denier, while maintaining the strength, uniformity and processing characteristics expected by textile manufacturers and consumers. Microfibres are fibres finer than 1.2 dtex for polyester and finer than 1.0 dtex for polyamide. Normal polyester filament yarn is around 3–5 dpf, whilst a typical polyester microfibre is only 0.5 dpf. Such fine fibres in the form of yarn give excellent textile properties, being very flexible, and giving a soft hand and excellent drape to fabrics.

Microfibres also lend themselves very well to fabric aesthetics. Dyed fabrics have solid bright colours due to the fine size of individual filaments. The vulnerability to damage from ironing is one disadvantage, the thermal capacity of the tiny filaments being so low that it is easy to overheat them. They can snag easily and need to be handled with care in processing.

The high density of filaments in typical microfibre fabrics makes them inherently windproof and waterproof. There are only tiny gaps for air to move through and the fabrics are largely unwettable since surface tension prevents water from penetrating the interstices in the fabric. Such fabrics are comfortable to wear as water vapour from perspiration evaporates easily. Microfibre fabrics also have heat-insulating properties. A 0.5 dpf polyester filament (density 1.4 g/cm^3) has a diameter of about 7 micrometers, right in the middle of the infrared (IR) wavelength (2–20 mm). Radiation is efficiently scattered by the microfibrils and the radiation loss of body heat is reduced. As a result, microfibrils are used in outdoor clothing and sportswear (e.g. skiing or mountaineering).

1.6.3 Bicomponent fibres

Bicomponent fibres are filaments made up of different polymers. There are many geometrical arrangements. The three main configurations are:

- side-by-side
- core–sheath
- multiple core (or ‘islands in a sea’).

So-called ‘splittable pie’ configurations are also used in the production of microfibrils. Side-by-side bicomponent fibres can be used to produce self-bulking yarns. After drawing and relaxing, two PET polymers of different molecular weights (spun as a side-by-side heterofil) curl up like a bimetallic strip and give a spiral crimp. The core–sheath configuration is adaptable because many different polymers may be applied as a sheath over a solid polyester core, thus giving a variety of modified surface properties while maintaining all the major fibre and textile properties of PET. The multiple core or ‘islands in a sea’ type of heterofil is of interest in connection with microfibrils. Hollow fibres are a type of core–sheath heterofil in which the core is composed of air. For end-uses like fabric interlinings, it is desirable to stabilize a filled hollow fibre structure by incorporating an additional thermally bondable bicomponent fibre.

1.6.4 Technical/high performance fibres

There are many kinds of technical textile products produced according to particular applications.^{3,4} The variety of textile structures in technical textiles is

thus much larger than it is in apparel textiles. There is also a wider range of materials from which fibres can be manufactured. Examples are glass, ceramic and basalt filaments. Glass filament yarn can be textured, folded or cabled and finds application in aerospace, automotive, marine, civil, sporting goods and in the electrical/electronics industries. Ceramic filament is resistant to very high temperature (2000–3000°C) and finds application in thermocouples, furnace curtains/lining, seals and gaskets. Basalt filament finds application in high service temperature and high performance machinery, automobiles, ship building, aviation, cryogenic technology and on sea platforms.

Aramid and high performance polyethylene filaments are organic polymeric materials. Aramid filaments are used in bulletproof jackets, helmets, automotive, electrical/electronic and medical applications. These filaments are also used in ropes and cables, sail cloth and tennis racket strings. High performance polyethylene filaments are also used in ropes, nets and ballistic protection. Carbon is another useful quasi organic-based polymer. Its strength is its thermal stability and it has application in rockets, satellites, aircraft, fishing equipment, golf clubs, automobiles/bicycles, machinery parts and corrosion resistant equipment.

High-modulus, high-tenacity (HM-HT) fibres with a fully-extended well-oriented structure are produced in two contrasting ways. The first involves manipulation of rigid rod molecules into fibres that are already highly oriented in the as-spun state, as in the case of poly(phenylene terephthalamide) or Kevlar. The other method for manufacturing HM-HT fibres results from the ease with which flexible, inert chain molecules can be pulled out into a fully-extended, oriented form by imparting very high draw ratios. Ultra high molecular weight polyethylene (UHMWPE) fibres such as Spectra and Dyneema fall into this category.

When processed into fibres, oriented thermotropic liquid crystalline polymers (TLCP) such as Vectran (a wholly aromatic polyester) are characterized by very high specific tensile properties and intrinsically low density compared with metals, ceramics and carbon. However, they have inherent weaknesses in shear and compression. The key application areas for LCP fibres include hard armour (vehicles, helmets), soft ballistic protection (vests), cut protection (gloves) and a variety of composite uses that include honeycomb structures, pressure vessels and rubber reinforcement.

1.6.5 Biodegradable/medical fibres

Biodegradable polyesters comprise a diverse field, but the best developed fibre (monofil) market is in resorbable surgical sutures, which slowly disappear *in vivo* and do not need subsequent surgical removal. Biodegradable yarn/fibres are also used for disposable items such as wipes. These yarns are environmentally friendly and hydrolysable at temperatures up to 50°C.

Polylactic acid fibre (PLA) silk is used as an implantable suture and as scaffold for ligament tissue engineering, and is produced by electrospinning to 50–500 nm in diameter. Polycaprolactone (PCL) alginate is used to fabricate scaffolds for tissue engineering.

1.6.6 Electro-conductive fibres

Electro-conductive yarns are used as sensors, for data transfer, wireless communication and for electro-magnetic shielding in intelligent and smart textiles. These are core spun yarns in which the core is a conductive filament. Technical textile yarns such as reflective, luminescent, phosphorescent, photoluminescent and electroluminescent yarns find application in areas such as reflective clothing, road signs and markers. Such yarns are produced by lamination of a silver transfer film onto polyester.

1.6.7 Smart fibres

Fibres are flexible, mechanically strong one-dimensional structures that can be converted into a variety of two- and three-dimensional flexible structures such as ligaments (artificial muscles), woven fabrics, non-woven webs and membranes. Smart fibres, which can change shape in response to various stimuli from the environment, open up new applications in areas such as apparel which allows heat and moisture release in warm weather but retains heat at lower temperatures.⁵

1.7 Yarns and their properties

A textile yarn is a continuous linear assembly of fibres or filaments which exhibits suitable characteristics such as good specific tensile strength and high flexibility.⁶ The various parameters used to characterize a yarn are given in Table 1.4. Some of these properties are discussed in more detail below.

1.7.1 Linear density

Linear density, yarn count, yarn number and yarn size are all expressions of the ‘fineness’ of a yarn. A yarn or fibre’s fineness cannot be expressed in terms of diameter because its diameter is not stable and uniform along its length, and its cross-sectional shape may not be circular. Consequently, it is expressed either by measuring the mass of a known length of yarn or by measuring the length of a known mass of yarn. These two basic methods for expression of linear density of any textile strand are known as:

- the direct system (mass/length)
- the indirect system (length/mass)

Table 1.4 Yarn characterization

Parameter	
Dimensional parameters	Linear density Diameter No. of filaments in cross-section
Structural parameters	Twist per cm Wrap density Core content Core-sheath ratio
Special treatment	
Fibre parameters	Length Linear density Crimp Cross-section shape

These systems are discussed in more detail below.

In the direct system, the linear density of plied yarn is the simple summation of linear densities of the individual components, i.e. linear density (R) = $T_1 + T_2 + T_3 + \dots + T_N$, where $T_1, T_2 \dots T_N$ are the linear densities of n individual components expressed in tex. The tex system has units measured in grams (g) per 1,000 metres (m). As an example, 20 tex means that the mass of 1,000 m of yarn is 20 g. The higher the value, the coarser the yarn. Prefixes such as kilo and deci are used when the numbers become too large or too small to express fineness:

- 1 Ktex = 1,000 tex
- 1 decitex = 1/10 tex
- 1 militex = 1/1,000 tex

Another expression of fineness for continuous filament yarn is the denier, which is expressed as the mass in grams (g) per 9,000 metres (m). As an example, a 3 denier yarn means that the mass of 9,000 m of yarn is 3 g. In the jute system, mass is expressed in pounds (lbs) per 14,400 yards (yds); a 12-pound yarn count indicates that 14,400 yds of yarn has a mass of 12 lbs.

In the indirect system, fineness is expressed as the ratio of the number of standard lengths per unit mass. A higher designated number indicates a finer yarn. Thus, in the English system, an 840 yard length (Hank) per pound refers to the fineness of the yarn. A '30's' yarn indicates that a 1 pound mass will be 30 times 840 yards in length, that is 25,200 yard of yarn. In the metric system, the number of units of 1,000 m is determined in 1 kg of yarn. In the indirect system the relationship is: $1/R = 1/T_1 + 1/T_2 + \dots + 1/T_k$, where $T_1, T_2 \dots T_k$ are the linear densities of k individual components. Units of linear density are given in Table 1.5.

The number of filaments in a yarn is generally specified in the case of a

Table 1.5 Units of linear density

	System	Mass	Length	Unit	Symbol
Direct	tex	g	1,000 m	g/1,000 m	tex
	denier	g	9,000 m	g/9,000 m	den
	jute	lb	14,400 yd	lb/14,400 yd	lb
Indirect	English	lb	840 yd	No. of 840 yd/lb	N _e
	metric	kg	km	No. of km/kg	N _m

filament yarn. It can also be found by taking the ratio of the yarn to filament linear density:

$$n = n_t/(n_f/9) \quad [1.1]$$

where n = number of filaments/fibres, n_t = yarn linear density (tex), and n_f = fibre linear density (den). A filament yarn designated as 130/24, refers to 130 denier with 24 filaments in the cross-section.

1.7.2 Yarn diameter

It is sometimes necessary to know the approximate diameter of a yarn, even though it is well known that yarn diameter cannot be estimated accurately due to the highly compressible nature of the material. Diameter, however, gives an idea of the extent of cover achievable, or the closeness of yarn packing in a fabric. Fabric thickness also depends on yarn diameter. Yarn diameter in terms of linear density in tex for a general case is given as:

$$d = \frac{1}{280.2} = \sqrt{\frac{T}{\phi \rho_f}} \quad [1.2]$$

where d = yarn diameter (cm), T = yarn linear density (tex), ρ_f = fibre density (g/cm³), and ϕ = yarn packing coefficient.

1.7.3 Yarn packing

Packing of fibres in a yarn is an important structural parameter which affects the porosity and bulk (specific volume) of a yarn. It influences properties such as compressibility and water/air transport, etc. Compressibility influences flattening of yarn in a woven or knitted structure. Porosity affects the flow of liquid due to capillary action, whilst yarn bulk affects thickness. Packing depends on the physical/mechanical properties of the fibres, their arrangement in the yarn structure and the level of twist. The extent of packing of fibres in a yarn's cross-section is expressed by a packing coefficient. Some typical values for different yarn types are given in Table 1.6. The packing coefficient is defined as:

Table 1.6 Packing coefficient values for various yarn

Type of yarn	Packing coefficient
Monofilament	1.00
Tape	1.00
Multifilament	
Untwisted	0.25
Regularly twisted	0.60
Hard twisted	0.90
Staple yarn	
Soft twisted	0.33
Hard twisted	0.60
Ring	0.50–0.60
Rotor	0.35–0.55
Air jet	0.50–0.70
Friction	0.30–0.55
Wrap	0.40–0.70

$$\begin{aligned}\text{Packing coefficient} &= \frac{\text{specific volume of fibre}}{\text{specific volume of yarn}} \\ &= \frac{\text{density of yarn}}{\text{density of fibre}}\end{aligned}$$

For blended yarns, average fibre density is given by the following:

$$\frac{1}{\bar{L}} = \sum_{i=1}^n \frac{p_i}{p_{fi}} \quad [1.3]$$

where \bar{L} = average fibre density, p_i = mass fraction of the i th component, p_{fi} = fibre density of the i th component, and n = number of components of the blend.

1.7.4 Yarn twist

Twist is quantified by the number of turns present in a unit length of yarn. Hence, a 20 tpi means 20 turns per inch length of yarn. The unit length can be inches, centimetres or metres. The basic purpose of twist is to induce structural integrity or coherence in a staple spun yarn so that it makes the yarn strong enough to withstand various kinds of stress. In the case of multifilament yarns, the twist is primarily introduced to bind the filaments together so that it facilitates processing by preventing a tendency for filament fraying. As well as processability and strength, twist also influences many other properties of a yarn. Hence, depending upon the end use, an optimum twist level is selected. The two most important aspects of twist are its direction and level (that is, intensity).

The direction of surface fibres/filaments looking up the yarn determines the direction of twist. If the inclination of the surface fibres matches the centre portion of the letter 'S', it is termed an 'S' twist; the reverse is true for 'Z' twist. Most spun yarn has a Z twist. In a single yarn, twist direction does not influence the property of the yarn. If a plied structure is made from single yarns, the ply twist direction is generally opposite to the direction of the single yarn twist. This gives a balanced (torque free) structure when an optimum level of ply twist is chosen with respect to the single twist. However, ply twist in the same direction as a single yarn is introduced for special end uses. Plied yarns are usually designated by a number, such as 30/4, meaning that four groups of 30 single yarns have been plied together to form a single twisted structure. The specific volume of a yarn is mainly a function of twist, though fineness, crimp, flexural rigidity and length of staple fibres do have some influence. Some typical values of specific volume of different types of yarn are given in Table 1.7.

1.8 Types of yarn for spinning

There are two main types of yarn: filament and spun yarns. Filament yarns in the medium to fine count range are used in fabrics for apparel. Filament yarns in the very fine count range are more appropriate for hosiery and also for carpets, sportswear and as industrial yarns for technical textiles. Spun yarns are suitable for shirts, trousers, suits, home textiles and bed linen.

1.8.1 Filament yarns

With the exception of natural silk, continuous filament yarns are man-made. They can be sourced from natural polymers such as paper pulp to produce viscose, rayon, etc., or from synthetic polymers such as polyester, polypropylene, polyethylene, polyamide, etc. A filament yarn can be either monofilament or multifilament. There are also flat yarns.

Monofilament yarns can be solid or hollow. Monofilament yarns have a single filament with a cross-section which can vary depending on the end

Table 1.7 Specific volume of different types of yarn

Yarn	Specific volume (cm ³ /g)
Spun	
Cotton	1.10
Nylon	1.45
Polyester	1.30
Filament	
Nylon	1.35
Polyester	1.16

use. It is normally circular but can be altered to a range of other shapes (e.g., triangular, multilobal, serrated, oval or dogbone-shaped). A non-circular cross-section prevents close packing and helps wicking. Monofilament diameters are typically in the range of 0.1–2 mm. The filament yarn is chopped to a suitable length to produce staple fibres, and these staple fibres are spun alone or blended with natural fibres in to yarn.

Continuous filaments are invariably used as a multi-strand and termed a multifilament yarn. A multifilament yarn consists of a bunch of monofilaments with a nominal twist to provide coherence to the structure. Alternatively, fibres in multifilaments can be held together by intermingling or entanglement. A non-circular cross-section prevents the close packing of multifilament yarns.

Flat filament yarns can be textured to increase bulk or extension by false twisting, intermingled by an air-jet or crimped by a stuffer box. Flat yarns can be twisted or interlaced to produce different effects. Tape yarn is produced by splitting up a thin ribbon-like narrow width of polymer film. Tape yarns are used, for example, for making fabric for packaging applications. A tape yarn can be further split or fibrillated mechanically to produce a regular network of interconnected fibres, a texture similar to multifilament yarn.

1.8.2 Spun yarns

Yarns made by using short fibres (natural fibres such as cotton, wool, jute, coir, etc.), staple fibres (rayon, polyester/nylon/acrylic/polypropylene) or a blend of different fibres are designated as spun yarns. Short staple spun yarns are a linear assembly of short discontinuous fibres. Such an array of fibres cannot sustain any load unless coherence is provided by generating transverse forces. This is achieved by twist or fibre/filament wrapping. Twisted yarns are hairy due to the projecting fibre ends but the yarn surface typically shows fibres in a helical configuration. Twisting in a spun yarn is achieved by conventional ring spinning, or by more unconventional methods using rotor spinning, friction spinning, air-jet spinning and hollow spindle wrap spinning.⁷ These yarns have different structures and properties.

A yarn made using a mixture of two or more different fibres is called a blended spun yarn. The proportion of different components in the yarn depends on the desired physical and mechanical properties. The most common blends are polyester-cotton, polyester-viscose and cotton-viscose, usually in proportions of 67:33 or 50:50. A yarn designated as PC (67:33) is a 67% polyester and 33% cotton fibre blended spun yarn.

A spun yarn can either be single, or two or more of such yarns can be twisted to achieve certain desirable effects, i.e. to create a plied or folded yarn. These effects can be to increase strength or reduce hairiness, or to create colour effects by twisting single yarns of different colours. Plied/

folded yarns are an assembly of several individual yarns helically wrapped around each other to form a coherent structure. Several plied yarns are twisted (generally in the opposite direction to the twist in the plied yarn) to form a cable yarn.

1.9 Short staple spinning yarns

Short staple spinning uses 25–50 mm fibres during yarn formation by employing the following techniques.

1.9.1 Ring spun yarns

The structure of ring spun yarns gives them visual, tactile, aesthetic and elastic fabric properties suitable for a wide range of end uses. The fibres which form the body of yarn lie parallel along the Z/S twist helix (usually 'Z' twisted). The yarn can be carded or combed, with the latter having lower hairiness, a higher uniformity and strength due to longer and more parallel fibres. In compact ring spinning, the single ribbon of fibres is compacted before twisting to further reduce hairiness and increase yarn strength. These yarns can be spun from most natural or man-made fibres, or from a blend of short staple fibres in the 25–50 mm range, and to a wide count range (5–300 tex). Two ribbons of fibres separated by a small distance can be ply twisted to give a siro spun yarn, usually in the 20–100 tex (2×10 to 2×50) count range. These yarns are less hairy and more uniform and are equivalent to ply yarns.

1.9.2 Rotor spun yarns

Rotor spun yarns are bulky two-layered yarn structures. The core comprises a bulk of parallel fibres aligned with the Z twist helix, with an outer layer of wrapper fibres along the core length. The fibres in a rotor yarn are less packed than in a ring yarn. Rotor yarn is known to be 5–10% bulkier than a ring yarn. They can be spun to a moderate range from coarse to medium (25–100 tex) yarn counts.

1.9.3 Friction spun yarns

Friction spun yarns have a core sheath element. The surface of this yarn is similar in appearance to a ring spun yarn. Outside fibres in these yarns have a uniform surface appearance along a Z twist helix. The core fibres are disposed in parallel and do not contain any twist. Friction spun yarn has a high extensibility due to the large proportion of hooked and disoriented fibres in the sheath and the low level of tension at which the yarn is spun. Friction

spun yarns are the weakest yarns due to the presence of highly disoriented and folded sheath fibres with a low degree of packing. The yarns are spun in a coarse count range (over 40 tex).

1.9.4 Air-jet spun yarns

Air-jet spun yarns have a two-layered yarn structure. The core fibres have no twist and are wrapped with fibres as in a rotor spun yarn. Air-jet yarn is less extensible due to the untwisted, straight and parallel arrangement of core fibres constituting 90% of the yarn. The bending rigidity of an air-jet yarn is high due to the clustering effect of core fibres tightly wound by binding fibres which offers very little freedom of movement. Air-jet spun yarn's abrasion resistance is small, causing disintegration of the yarn once the wrapper fibres are broken. These yarns are spun in the fine count range (7–15 tex).

1.10 Long staple spinning yarns

Long staple spinning uses 51–215 mm fibres during yarn formation using the following techniques.

1.10.1 Wrap spun yarns

Wrap spun yarns consist of two component yarns, with a core of parallel, untwisted staple fibres and a binder wrap of either a filament yarn or staple fibres on the outside. The wrap provides cohesion to the staple fibre core by radial pressures along the wrap helix. The yarn has low hairiness. Surface fibre wrapping is carried out by hollow spindle wrap spinning. The yarn has a bulky and crimped appearance though under tension it is lean and smooth. These yarns are spun in the coarse to medium count range (higher than 16 tex).

1.10.2 Self-twist spun yarns

In self-twist spun yarns, two fibrous strands are separately false twisted by alternating an S and Z twist along their length. They are then plied together by an untwisting torque of single to alternating Z and S twists to create a two-fold yarn. These yarns are spun in the medium to coarse count range (20–100 tex).

1.10.3 Twistless spun yarns

Twistless spun yarn is formed by felting or adhesive bonding of fibres. An entanglement process consolidates an assembly of fibres in the form of a

felted yarn. This type of yarn is well suited for carpets. For technical textile applications, staple fibres are bonded to a core filament (glass, polypropylene, nylon or polyester) with a polypropylene resin binder.

1.10.4 Core spun yarns

Core spun yarn is a sheath–core yarn formed by twisting fibres as a sheath around an existing core of either a filament or staple spun yarn. These are two-layered structures, the core filament yarn normally providing strength and durability. Elasticated core yarn is used for stretch comfort. These yarns can be produced by ring spinning, friction spinning, wrap spinning and self-twist spinning.

1.10.5 Ply yarns

Ply yarns are produced by twisting two or more yarns. Doubling or plying helps to achieve special physical characteristics by exploiting the direction and level of the twist in plying. Twisting in a direction opposite to the single yarn enables fibres to orient along the plied yarn axis. This makes the plied yarn smoother, more uniform, lustrous, stronger, more extensible and less hairy. Twist lively plied yarn is produced by twisting in the direction of the single yarn.

1.10.6 Fancy yarns

Fancy yarns are made with a distinctive irregular profile which is different from basic single and folded yarns. This profile enhances the visual and textural properties of the fabric. Fancy yarns are also termed novelty yarns, specialty yarns, effect yarns and fashion-oriented yarns, and can incorporate deliberate ‘defects’ or variations distributed randomly or in a pre-defined order, along with colour to give visually and texturally attractive difference to the fabric. Colour effects along the yarn length are introduced by twisting different coloured yarns, spinning blended dyed fibres, or by irregularly printing/dyeing spun yarns.

Fancy yarns are invariably used to create fashion fabrics. They are used in ladies outerwear, mens jackets, knitwear, ties, furnishings, curtains and upholstery. Typical fancy yarns include snarl, spiral, loop, chenille, slub and nep. Fancy effects can also be created by changing fibre specifications such as type, length, denier, cross-sectional shape, crimp, initial modulus, colour, lustre, affinity for dyes and shrinkage, etc. A deliberate difference in length, denier, cross-section and modulus of component fibres can be exploited to position them at predetermined zones of the yarn cross-section, with short and coarse fibres occupying the yarn surface. For increased lustre, fibres

with a flat cross-section, such as trilobal and ribbon-shaped yarns, are often employed. Slubs of varying dimensions can be produced by using differential fibre length in the core and effect components.

Blending of regular polyester fibres with cationic dyeable polyester can be used to get attractive colours, contrast and fancy effects. Similarly, a blend of fibres having varying shrinkage when combined with colour difference can also give fancy effects. Manufacture of fancy yarns often involves plying and cabling together different yarns of varying counts and twists. The density (tpi) and direction of twist (S/Z) are often manipulated during plying and cabling so as to create particular effects. Differences in individual yarn fineness is employed to make corkscrew and spiral yarns. If the direction of twist in the component yarns is kept different, the plying operation will produce an unbalanced twisted spiral yarn.

One of the most popular and well-known fancy yarns is slub yarn which has been used in various types of apparel such as suits and shirts. Corkscrew, spiral, chenille, gimp, loop, snarl and boucle have all found acceptance in apparels and for the production of furnishings and upholstery. Cotton melange yarn has been highly successful in enhancing the appeal of knitted garments such as T-shirts, etc.

1.11 Physical properties of woven fabrics

Fabric cover, mass, specific volume and thickness are important physical properties and can be determined based on yarn count, thread spacing and yarn crimp.⁸

1.11.1 Fabric cover

In fabric, ‘cover’ is measured as the fraction of total fabric area covered by the component yarns. For a circular cross-section yarn, the cover factor is given as:

$$\frac{d}{p} = \frac{E\sqrt{T}}{280.2\sqrt{\square\square_f}} = \frac{K}{28.02\sqrt{\square\square_f}} \quad [1.4]$$

$$K = E\sqrt{T} \square 10^{-1} \quad [1.5]$$

where T is yarn tex, d is yarn diameter, E is the number of threads per cm = $1/p$, K is the cover factor, and ϕ is the packing coefficient.

For $d/p = 1$, cover factor is maximum and given by:

$$K_{\max} = 28.02\sqrt{\square\square_f} \quad [1.6]$$

Fractional fabric cover is given by:

$$\frac{d_1}{p_1} + \frac{d_2}{p_2} - \frac{d_1 d_2}{p_1 p_2} = \frac{1}{28.02} \left[K_1 + K_2 - \frac{K_1 K_2}{28.02} \right]$$

Multiplying by 28.02 we get a fabric cover factor:

$$\text{Fabric cover factor} = K_1 + K_2 - \frac{K_1 K_2}{28} \quad [1.7]$$

1.11.2 Fabric mass

Fabric mass (expressed as grams per square meter (gsm)) is a very commonly used parameter, and is given⁹ by:

$$\text{gsm} = [T_1 E_1 (1 + c_1) + T_2 E_2 (1 + c_2)] \square 10^{-1} \quad [1.8]$$

$$\text{gsm} = \sqrt{T_1 [(1 + c_1) K_1 + (1 + c_2) K_2 \beta]} \quad [1.9]$$

where E_1 , E_2 are ends and picks per cm; T_1 , T_2 are warp and weft yarn tex; K_1 and K_2 are the warp and weft cover factors, c is the fractional crimp and $d_2/d_1 = \beta$. In practice, comparison between different fabrics is usually made in terms of GSM. A fabric engineer tries to optimize the fabric parameters for a given GSM.

1.11.3 Specific volume

The apparent specific volume of fabric, v_F , is calculated using the following formula:

$$v_F = \frac{\text{fabric thickness (cm)}}{\text{fabric mass (g/cm}^2\text{)}} \quad [1.10]$$

where fabric mass (g/cm²) = 10⁻⁴ \square GSM
and

$$\text{Fabric packing factor, } \square = \frac{v_f}{v_F} \quad [1.11]$$

where v_f and v_F are, respectively, fibre and fabric specific volume. A knowledge of fabric specific volume helps in calculating the packing of fibres in the fabric. Such studies are useful in evaluating fabric properties such as warmth, permeability to air or liquid.

1.11.4 Thickness

Fabric thickness for a circular yarn cross-section is given by: $h_1 + d_1$ or $h_2 + d_2$, whichever is greater:

$$h_1 = \frac{4}{3} p_2 \sqrt{c_1} \quad [1.12]$$

$$h_2 = \frac{4}{3} p_1 \sqrt{c_2} \quad [1.13]$$

When the two threads project equally, then $h_1 + d_1 = h_2 + d_2$ and, in that case, the fabric's *minimum thickness* is given by:

$$\text{Minimum thickness} = 1/2(h_1 + d_1 + h_2 + d_2) = D; \quad h_1 = D - d_1$$

Such a fabric produces a smooth surface and ensures uniform abrasive wear. In a fabric with a coarse thread in one direction and a fine thread in the other, maximum crimp is obtained for the coarse thread by stretching the fine thread straight. In this case the fabric's *maximum thickness* is given by:

$$\text{Maximum thickness} = D + d_{\text{coarse}}, \text{ since } h_{\text{coarse}} = D$$

1.11.5 Packing of yarns in fabric

The maximum number⁹ of warp and weft yarns in a fabric depends on the weave and yarn count. For plain weave, the maximum number of threads which can be packed in a fabric depends on the following equation:

$$\sqrt{1 - \left[\frac{p_1}{D}\right]^2} + \sqrt{1 - \left[\frac{p_2}{D}\right]^2} = 1 \quad [1.14]$$

where p_1 and p_2 are the spacing between the neighbouring warp and weft yarns, respectively, and D is the sum of the yarn diameters.

1.12 Mechanical properties of woven fabrics

Woven fabrics are subjected to a combination of in-plane extension/tension, shear, compression, bending in a perpendicular plane and out-of-plane buckling deformations.¹⁰ The tensile properties of woven fabrics depend on the yarn and the fabric structure, that is the yarn twist, yarn strength, weave, crimp and cover. The degree of yarn twist affects fabric elongation. A reduction in twist improves cover and reduces air permeability.

An increase in picks/cm and twist density within a normal limit significantly improves both tensile strength and surface durability, but a reduction in pick density improves the tear strength in the filling direction. The breaking strength of a textile fabric is enhanced by an increase in the strength of its component yarns and the number of yarns per unit width. Fabrics made from ring spun yarns give a higher breaking load than those made from open-end yarns, though the effect of scouring and bleaching in increasing the breaking load is more pronounced with the former.

Cloth strength is affected by the degree of binding of cross threads which aid inter-fibre frictional force and contribute to tensile strength. The degree of binding is dependent on the density of weave and cloth setting. The elongation

at break increases with the increase in these variables. The tensile strength of a fabric decreases with an increase in fabric cover. Crimp decreases the strength of the yarn and fabric. The initial modulus of the fabric decreases with an increase in crimp. The straightening of longitudinal threads during tension applies compressive forces at the points of contact with the cross-yarn. If the cross-yarn jams before crimp exchange is complete, then a reduction in fabric strength and extension occurs.

The buckling, bending and drape characteristics of woven fabric influence its performance during the making-up process and in the actual use of the garment. These properties are important, particularly when the fabric is limp, resulting in large-scale deformation even when a small force is applied. The engineering concept of buckling helps to explain the behaviour of fabric during garment manufacturing as well as during its use as a garment. The folding of a garment, bending of sleeves, bending of trouser legs, cutting and sewing operations, etc., all involve buckling phenomena. In bending, a woven fabric exhibits initial non-linearity due to frictional restraint, followed by the linear deformation-recovery behaviour of the material. The puckering tendency of a cloth during stitching shows similar behaviour as does formability, a measure of the ability of a fabric to absorb compression in its own plane without buckling. The formability value is used as a direct indicator of the likelihood of seam pucker occurring during the sewing of a garment.

Fabrics are subjected to bending deformations in most uses. Bending is a very common phenomenon during the use of garment fabrics. Additionally, it has some influence on the drape of upholstery, furnishings and curtain fabrics. Creasing and wrinkling of fabrics and garments is also associated with bending deformation. Bending resistance is made up of the bending resistance of threads lying in the direction of bending, frictional restraint and interaction between the threads. The four main factors directly influencing minimum bending rigidity G_{\min} are fibre tensile modulus, fibre linear density, yarn linear density, and the number of threads per unit cloth width.¹¹

Inter-fibre adhesion can increase elastic fabric stiffness considerably. Textile yarns, being visco-elastic, exhibit time-dependent effects such as stress relaxation. This causes decay in the inter-yarn force at the cross-over point and results in setting. In addition, fabrics can be set by finishing treatments to relax internal stresses in the fabric and lower its internal energy level.

1.13 Effects of fibre and yarn properties on the use and application of woven fabrics

The physical and mechanical properties of a fibre, as the unit cell of a textile material, clearly contribute to a fabric's mechanical properties. However, according to the spinning system used, the yarn structure and properties can

be varied considerably to alter packing, surface and mechanical properties. The fabric itself imposes another set of variables, such as sett and weave, to further diversify the overall list of fabric properties.

The use of textiles for apparel, home furnishing and industrial/technical applications depends on a unique combination of required properties. Fabrics for apparel, for example, require comfort, hand, drape, breathability, easy care, durability/abrasion, aesthetics, dyeability and, of course, tailorability. The requirements of fabrics for home textiles (such as curtains and upholstery, for example) are drape, aesthetics/colour/design and resistance to stain/soiling and degradation from light. Fabrics for industrial and technical applications require specific characteristics which usually include strength and durability. This section reviews some of these properties and how they are influenced by fibre and yarn properties.

In general, spun yarns of either single or blended fibres are the major building materials in woven fabrics. Continuous filament yarns are used either as textured or as core spun yarns. There needs to be maximum packing of yarn in fabric for several applications. The properties of a textile which govern its conformation to a technical specification are the function of the yarn network (interlacement, diameter, spacing), thickness and mass. A large group of fabric properties are more dependent on pore structure than on yarn network, for example, resistance to the flow of liquids, gas and light.

Woven fabrics are made from interlaced yarns which are flexible. The yarns are made by twisting together long, thin, flexible and strong fibres. The properties of yarn and fabric depend largely on the properties of the constituent fibres. Textiles are low-density materials and contain a large proportion of air within their total structure and thus the characteristic textile properties arise from two basic fabric elements: fibre and air. Another set of attributes rely on interchange in yarn and interstices geometry: tear resistance, fabric drape and sewability. Fabric strength and extension is a function of crimp and yarn twist. It is very important to have an in-depth knowledge of the principles involved in the selection of raw materials and their conversion to desired yarns and fabric structures, followed by dyeing and finishing. Additionally, knowledge of polymers and coating helps when designing technical fabrics for different applications.

1.13.1 Creasing and wrinkling properties

In practical use, textile fabrics are subjected to a wide range of complex deformations such as bending, folding, creasing and wrinkling which may be added deliberately during manufacturing or produced by body movement during use. Of these, wrinkling and creasing can affect the aesthetic characteristic of a fabric. The ability of a fabric to resist creasing or wrinkling and to recover from such deformations is determined by many factors, the most

important being the mechanical properties of its fibres, such as their tensile strength, bending and torsion, the geometrical and constructional parameters of the yarn and fabric, and the presence or absence of finishing agents on or within the fibre.

Resistance and recovery from creasing is largely influenced by the type of fibre, yarn and fabric structure. Bending elasticity plays an important role in the creasing phenomenon of a fabric. Among the commonly used textile fibres, linen exhibits creases easily due to a very high degree of orientation of cellulose in the fibre. Cellulosic materials are highly susceptible to creasing. The materials which resist creasing also resist deformation and therefore they behave as a rigid material. Ideally a fabric which is deformed should recover from its deformation rapidly. Wool is well known for its very good elastic recovery and therefore has the ability to resist and recover from creasing.

1.13.2 Shear properties

Shear behaviour is one of the most important characteristics contributing to the performance and appearance of woven fabrics. Shear properties influence drapeability, pliability and hand behaviour of apparel fabrics. The study of shear behaviour of fabrics has special significance, particularly for mass-produced apparel. This is mainly because cloth is deformed in all directions during handling on machines, as well as in actual use. In fact, the ability of a fabric to be deformed by shearing distinguishes it from other flat flexible materials such as paper and polymer thin films. Shear angle is one of the main criteria for characterizing the formability of fabrics. This property enables a 2D fabric to undergo complex deformations and helps a 3D garment to conform to body contours, imparting the desired mechanical comfort.

1.13.3 Compression properties

Compression is defined as a decrease in intrinsic thickness with an increase in pressure – intrinsic thickness being the thickness of the space occupied by a fabric subjected to barely perceptible pressure. Compression of fabrics is an inevitable phenomenon during fabric handling and processing. Compressive properties are concerned with the surface smoothness, softness and fullness of a fabric. The compressive properties of textile materials have direct relevance to bulk and handle of fabrics. In a woven construction, warp and weft yarns are compressed due to inter-yarn pressure. The softness of a fabric is determined by its compressibility which depends on the compressibility of the yarn and the fabric construction. Compressibility of fabric is an integral component of fabric hand.

Tailorability of cloth significantly depends on fabric compressional behaviour. Compressibility of fabrics significantly influences drapeability.

When a fabric is draped on the edges of a contour, there is compressional deformation at the point of bending. Fabrics with higher compressional energy give a higher drape coefficient. A highly compressible fabric has high compressional energy and can absorb or withstand compressive forces to a greater extent at the deforming points. This prevents folding at the deforming points and a higher drape coefficient results.

1.13.4 Abrasion properties

Abrasion is a kind of wear in which rubbing away of component fibres and yarns of the fabric takes place. During abrasion, a series of repeated applications of stress takes place. Therefore abrasion resistance is the capacity to absorb energy. The abrasion resistance of a fabric is dependent upon many factors including fibre properties, yarn structure and size, fabric mass and geometry as well as fabric finish (including lubricating and sizing agents used). For hydrophilic fibres, the amount of moisture present also affects abrasion resistance.

1.13.5 Fabric comfort

The subjective feeling of fabric comfort is a complex result of psychological and physiological responses of the human body and the physical properties of the fabric. Comfort¹² has two attributes: mechanical (evaluated by visual and tactile means) and thermal (assessed by the permeability of a fabric to air, water and heat). Comfort is evaluated in part by fabric hand – a traditionally subjective evaluation made by judging the feel of a fabric between the fingers. The fabric hand is expressed by an index – total hand value (THV) – based on a combination of mechanical properties derived from tensile strength, shear, bending, compression, surface friction and the surface deformation recovery of fabric at low stress. These fabric properties are also useful for tailorability and formability, that is, the forming and sewing of flat fabric pieces into 3D-shaped garments. Thermal comfort is evaluated in terms of air permeability, thermal insulation capacity, water repellency and water vapour transmission.

Fabric characteristics such as fibre type, yarn linear density, thread (yarn) density, weave type and yarn twist affect fabric hand, since these constructional parameters determine fabric surface characteristics, which significantly contributes to the perceived touch of a fabric. Surface properties also help to judge the smoothness and crispness of a fabric. Geometrical roughness is another important factor affecting perceived softness of a fabric. For a given fabric construction, the denier, cross-sectional shape and crimp of the fibres influence the softness of the final product. Very fine filaments are effective for good draping, anti-crease properties and softness of handle,

but these yarns are more susceptible to abrasion than coarse-filament yarns. The desired softness of handle can also be achieved through modified fibre cross-section.

1.14 Effects of fibre and yarn properties on woven textiles: apparel and sports textiles

In the apparel market, polyester in staple or filament form has a clear advantage because of its easy-care qualities and low cost. Although 100% polyester has limited appeal because of its less desirable handle, it is extremely popular in blends with cotton. Filament yarns are used for outdoor clothing applications or where a fur-like or silky appearance is desired. Fibres with enhanced or modified properties are in great demand. Yarn bulk is enhanced by using bicomponent or biconstituent fibres. Pilling is reduced by producing fibres that are more brittle, whilst a yarn with exceptionally soft handle is produced by using fine-denier fibres or fibres treated with special friction-reducing finishes. Abrasion resistance is enhanced by modifying the spinning conditions to produce a denser filament microstructure.

Sports textiles are textiles used in sports goods and in sportswear. Sportswear is clothing, including footwear, which is worn for sport or exercise. It includes shorts, tracksuits, T-shirts, polo shirts and trainers. Sportswear is also often worn as casual fashion clothing. For most sports, athletes wear a combination of different items of clothing. These should have protective properties against variable atmospheric conditions during use as well as for protection against physical damage. In addition, they require a high tear strength, resistance to abrasion, shape stability and colour fastness. Almost every piece of sports clothing is designed to be lightweight so the athlete is not encumbered by its weight. The best athletic wear for some forms of exercise, for example cycling, should not create drag or be too bulky. On the other hand, it should be loose enough so as not to restrict movement. Various physically dangerous sports require protective gear, e.g. for fencing, American football or ice hockey.

Garments should allow the wearer to stay cool in hot weather and warm in cold weather. In cold climates the best athletic wear should not only provide warmth but also transfer sweat away from the skin. For activities such as skiing and mountain climbing, this is achieved by using layering. Moisture transferring materials must be worn next to the skin, followed by an insulating layer and wind and water resistant shell garments. Waterproof fabric prevents the penetration and absorption of liquid water. The term 'breathable' implies that the fabric is actively ventilated. Breathable fabrics passively allow water vapour to diffuse through them yet prevent the penetration of liquid water. Water-resistant and moisture-permeable materials may be divided into three main categories: high density fabrics, resin-coated

materials and film-laminated materials. These are selected according to the finished garment requirements in casual, athletics, ski or outdoor apparel.

Densely woven waterproof breathable fabrics consist of cotton or synthetic micro-filament yarns with compacted weave structure. One of the most famous waterproof breathable fabrics, known as Ventile, was manufactured by using long staple cotton with minimal space between the fibres. Usually combed yarns are woven parallel to each other with no pores for water to penetrate, and Oxford weave is preferred. When the fabric surface is wetted, the cotton fibres swell transversely, reducing the size of pores in the fabric and requiring very high pressure to cause penetration. Therefore, waterproofing is provided without the application of any water repellent finishing treatment.

Densely woven fabrics can also be produced from microdenier synthetic filament yarns. The individual filaments in these yarns are less than 10 micrometers in diameter, so that fabrics with very small pores can be engineered. The use of superfine or microfibre yarns makes the production of dense fabrics possible enabling capillary action which gives the best wicking properties. The wicking behaviour of a fabric is dependent mainly on the base fibre's moisture properties. While most fabrics, both natural and synthetic, have the ability to wick moisture away from the skin, not all of them are fast-drying and air permeable (two factors which have a direct influence on cooling and perceived comfort). High-tech synthetic fabrics are lightweight and capable of transporting moisture efficiently and dry relatively quickly. It is generally agreed that fabrics with moisture wicking properties can regulate body temperature, improve muscle performance and delay exhaustion. While natural fibres such as cotton may be suitable for clothing worn for low levels of activity, synthetic fabrics made of nylon or polyester are better suited for high levels of activity. They absorb much less water than cotton, but can still wick moisture rapidly through the fabric. No single fibre or blend of different fibres provides an ideal sportswear fabric: the right type of fibre should be in the right place. A two-layer structure is better, with a synthetic fibre layer close to the skin with high wicking properties (e.g. a microdenier polyester, which is ideal for wicking perspiration away from the skin) and an outer layer usually of cotton or rayon which absorbs and evaporates.

1.15 Future trends

Electronic-textile (e-textile) technology holds out the promise of truly wearable computers as well as inexpensive large-scale computational devices. New fibres are being created for inclusion in e-textiles, including battery, conductive and mechanically active fibres. Methods are being developed to attach discrete components to e-textiles, including processors, microphones and speakers. In the category of wearable computing, a garment providing the user with precise location information within a building is being developed.

Virtually all woven e-textiles are expected to use the new fibre batteries and solar cells that have been developed.

Conductive woven fabrics are being made by utilizing metallic conducting wires as flexible wearable electrical circuits; the properties of these nanotube-based yarns can be leveraged to produce more robust systems far lighter and more flexible than metallic wires. As a step in the direction towards the creation of nanotube-based electronic components for fabric applications, super-capacitors have also been woven into a textile fabric. The capacitors have capacitances and life cycles comparable to commercially available super-capacitors. Since nanotubes are also known to have effects similar to piezoelectric materials, such materials can be integrated into structures to produce sensors that monitor stresses. Chemo-, piezo- and thermo-resistive fibres are now available in textile compatible form and their integration into fabrics and garments is being actively pursued.

1.16 Sources of further information and advice

The best source of information is the internet. The following list of links to fibre producers, machinery manufacturers and technical textiles producers gives plenty of innovative information, of interest to both academics and industry:

- <http://www.ibena.de/techtex/english/fabric/fabric.html>
- <http://www.innovationintextiles.com/>
- <http://ec.europa.eu/enterprise/sectors/textiles/research-innovation/technical-textiles/>
- <http://www.technicaltextilesguide.com/>
- http://www.huntsman.com/textile_effects/eng/Technical_Textiles/Technical_textiles/index.cfm?PageID=629
- <http://www.technical-textiles.net/htm/j20050119.557671.htm>
- <http://www.aramid.com/>
- <http://www.highbeam.com/doc/1P3-618128741.html>
- <http://www.ascendnif.com/>
- <http://www.universalfibres.net/industrialFibres.php>
- <http://www.ifai.com/>
- <http://www.sagezander.com/>
- <http://www.torayusa.com/tomac/products/synthetic.htm>

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