2.1 Introduction

Polyester is the most widely used manufactured fibre today. Polyester and polyester blend fabrics are used in many different consumer and industrial products. It is made by melt spinning and can be produced in a range of sizes, strengths and shapes. Among all synthetic fibres, polyester has exceptional resilience, excellent dimensional stability, crease retention, crease recovery, quick drying etc. making it suitable for easy care fabrics. However, 100% polyester and polyester rich fabrics are not comfortable to wear mainly because of its hydro-phobicity. Aesthetics and Comfort in polyester and polyester blended textiles can be improved by modifications in external form of the fibre. Fibre fineness and cross-sectional shape have a direct influence on the physical properties of fibres e.g. luster [11], friction [12-13] and moisture regain [14], as well as mechanical properties such as bending modulus [15], resiliency [16] and tenacity [17]. Ultimately, these properties will influence the performance of end-use products. These two technical innovations can be considered as the factors that have ignited the technological re-evaluation and recombination leading to the production of novel fabrics. Japanese manufacturers have varied cross-sectional shape and fineness of the polyester fibres to produce fabrics with especially attractive hand and drape. These fabrics, called Shingosen fabrics, are sold in Japan and abroad. The subsequent sections give a detailed review of the work that has been carried out to have an idea about the different variants of fibre form or geometry and subsequently to understand the influence of fibre geometrical features especially the fineness and cross-sectional profile on their mechanical and surface characteristics and ultimately on structure and properties of their yarns and fabrics with the motive to improve the wear comfort of their products.

2.2 Fibre Properties Deciding Body Comfort (In Special Reference to Polyester Fibres)

Comfort, like flavour, is an experience that is caused by the integration in the brain of impulses passed up the nerves from a variety of peripheral receptors. The analysis of the component perceptions which the brain builds up to give a reaction of pleasure, indifference, or displeasure is often beyond us. The causes underlying the comfort or discomfort will be many; probably at least a dozen different physical
properties of the fibre make their contribution to or away from comfort. The better does our knowledge become of the relations between physical properties and comfort, the more possible will it be to set out a specification for really comfortable fibres, and then to make them.

Comfort is not at present capable of absolute definition in quantitative terms, but there undoubtedly exist a number of well-recognised trends and we can use these as a basis for comparison of fibres. Yarn and fabric construction play a large part in the handle, feel and comfort of a garment, but assuming that they are kept suitable and the same, it is still a matter of everyday experience that the fibre itself can cause tremendous differences. Moncrieff [18] has mentioned some fibre properties which can be considered relevant from the point of view of fabric comfort. Following properties of fibres are, amongst others, important in their contribution to comfort.

2.2.1 Stiffness at small stretches or bends

This results in the fibres being soft to a light touch as when a garment is worn. It is measured as the initial modulus and/or bending modulus. Initial modulus is equal to the slope of stress-strain curve at the origin (after the removal of any crimp). It is a measure of the resistance to extension for small extensions. An easily extensible fibre will have a low modulus. Love [20] showed from elasticity theory that a modulus defined as the ratio of bending stress to bending strain is identical with the tensile modulus for a uniform, transversely isotropic beam. Chapman [21] found both the bending stress-strain and tensile stress-strain curves for fibres same. Comparative figures of some of the fibres are given in the Table 2.1.

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Initial Modulus ( KN/mm²)</th>
<th>Bending modulus (KN/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>7.7</td>
<td>---</td>
</tr>
<tr>
<td>Viscose (Fibro)</td>
<td>8.7</td>
<td>10</td>
</tr>
<tr>
<td>Cellulose Acetate</td>
<td>4.2</td>
<td>---</td>
</tr>
<tr>
<td>Wool</td>
<td>5.2</td>
<td>3.9</td>
</tr>
<tr>
<td>Polyester Staple</td>
<td>6.2</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Those fibres that are initially soft to the touch are wool, polyester staple. The soft handle of cellulose acetate has been well recognized.
2.2.2 Compliance

A du Pont study earlier has shown a good correlation between compliance ratio as computed from the stress-strain curve and feel and handle of the fabric, other variables being held the same. In simple terms, compliance ratio indicates the degree of flattening of the stress-strain curve in the region between 5% and 10% extension of the fibre. The greater the degree of such flattening, the fibre is said to have a greater compliance, thus contributing to better feel and handle.

This is the reduction in stiffness for moderate stretches or bends, which enables fibres to stretch say from 5 to 10 per cent without a considerable increase in the load. If the fibre easily, i.e., without the application of much load, adjusts itself to the application of new forces, as it should do when a garment is worn, it is pliable or compliant. A high compliance ratio is desirable; it not only increases comfort of wear, but also confers good draping qualities.

Table 2.2 Compliance ratio of fibres [18]

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Compliance ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscose</td>
<td>0.68</td>
</tr>
<tr>
<td>Cellulose acetate</td>
<td>0.91</td>
</tr>
<tr>
<td>wool</td>
<td>1.0-1.7</td>
</tr>
<tr>
<td>Polyester staple</td>
<td>1.05</td>
</tr>
</tbody>
</table>

It is interesting to note that the manufacturers of polyester staple have deliberately increased the compliance ratio of these fibres in the staple form, where wool-like properties are required.

2.2.3 Frictional coefficient of fibres

Cotton, wool and silk due to their peculiar cross-sections and resulting different frictional coefficients have unique handle. All regular man-made fibres are smooth, but to get varied frictional properties, change in external form of fibres is suggested.

2.2.4 Resilience

This determines the recovery of a garment from distortion; a resilient fibre will prevent baggy stockings, sagging frocks and badly creased garments. A high tendency to recover completely and quickly from deformation is desirable; the garment then keeps its shape. Comparative recovery figures from a brief 1%, 5% and 10% stretch are presented in Table 2.3.
Table 2.3 Recovery properties of different fibres [15]

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Elastic Recovery % from extension (at 65% RH)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1%</td>
</tr>
<tr>
<td>Cotton</td>
<td>91</td>
</tr>
<tr>
<td>Viscose</td>
<td>67</td>
</tr>
<tr>
<td>Cellulose acetate</td>
<td>96</td>
</tr>
<tr>
<td>wool</td>
<td>99</td>
</tr>
<tr>
<td>Polyester staple</td>
<td>98</td>
</tr>
</tbody>
</table>

It is, of course, important that this resiliency should also be present when the fibres are wet; in this polyester have a considerable advantage over the other fibres because of its great resistance to moisture; whilst this is beneficial in respect of retention of resiliency it brings with other qualities detrimental to comfort. Resilience of polyester fibres is excellent.

2.2.5 Loftiness

A fabric should feel full and light, not heavy for its thickness. Two factors determine this; one is permanent crimp, which gives bulkiness, and the other is a low specific gravity of the fibre, which gives lightness. In respect of crimp, wool excels because it has a natural and permanent crimp; Polyester will take permanent crimp and in the staple form they are sold crimped. Viscose staple is usually crimped. Specific gravities can be compared from the values given in the Table 2.4.

Table 2.4 Specific gravity of different fibres [18]

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Specific gravity g/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulosic fibres</td>
<td>1.5</td>
</tr>
<tr>
<td>Proteinic fibres</td>
<td>1.3</td>
</tr>
<tr>
<td>Polyester</td>
<td>1.38</td>
</tr>
</tbody>
</table>

2.2.6 Moisture absorption

A high absorbency is good because it means that perspiration can be taken up easily; in this respect wool excels, and even when it has absorbed some 40 per cent of its own weight of moisture, it still does not feel noticeably damp. Under standard
conditions of temperature and humidity the natural moisture regains of some of the fibres are given in the Table 2.5.

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Regain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(65% r.h., 20°C)</td>
</tr>
<tr>
<td>Cotton</td>
<td>7-8</td>
</tr>
<tr>
<td>Viscose</td>
<td>12-14</td>
</tr>
<tr>
<td>Cellulose acetate</td>
<td>6.9</td>
</tr>
<tr>
<td>Wool</td>
<td>16-18</td>
</tr>
<tr>
<td>Polyester staple</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The moisture regain of the polyester is low only 0.2 to 0.8 per cent. Although polyester is non absorbent, they do have wicking ability. This quality increases polyester's comfort in warm weather, as perspiration is carried to the surface of the fibre and evaporated.

2.2.7 Heat of Wetting

Another factor which contributes to comfort is the “heat of wetting” of a fibre; wool gives out heat when they are wetted and this is thought to help to keep the wearer of a garment warm. Some comparative figures are presented in Table 2.6.

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Heat of wetting (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>46</td>
</tr>
<tr>
<td>Viscose</td>
<td>106</td>
</tr>
<tr>
<td>Acetate</td>
<td>34</td>
</tr>
<tr>
<td>Wool</td>
<td>113</td>
</tr>
<tr>
<td>Polyester</td>
<td>5</td>
</tr>
</tbody>
</table>

Polyester (synthetics in general) seems to be at a considerable disadvantage in this respect.
2.2.8 Thermal conductivity

A fibre is not in itself either “warm” or “cold”, but it slows down to a greater or lesser degree changes of temperature. If the fibre is a very poor conductor of heat then a garment made from it will not transmit the natural warmth of the body to the atmosphere; the body warmth builds up and we feel warm. If we touch a fabric with a low thermal conductivity it does not conduct away the warmth of the finger and we say that it feels warm. There are no records of direct measurement of the thermal conductivity of fibres. However, an estimate of relative values can be obtained by comparing the results of measurements of thermal conductivity of pads of different fibres packed to the same density [22–23]. The traditional warmth of the wool is largely due to its complex surface scale structure which entraps countless little pockets of air which reduce the thermal conductivity and contribute to the warmth of wool.

Table 2.7 gives values for the thermal conductivities of some solid polymers. Polyester has low thermal conductivity and feels warm.

<table>
<thead>
<tr>
<th>Table 2.7 Thermal conductivity of Polymers [15]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>Cellulose acetate</td>
</tr>
<tr>
<td>Nylon</td>
</tr>
<tr>
<td>Polyester</td>
</tr>
<tr>
<td>Polyethylene</td>
</tr>
<tr>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Still air has a thermal conductivity of 25 mW m⁻¹ K⁻¹

2.2.9 Static

Most fibres, even wool, will generate static when dry but they lose this faculty when they are moist because then the electric charges can leak away. Those fibres that have low moisture regains are the most likely to generate static under normal conditions of wear. Nobody wants a garment to crackle as it is put on, or to attract to itself dust and dirt particles, as will those that electrify readily. Their low regain makes the polyester liable to static and cellulose acetate more liable to it than viscose.

Based on above properties which can be moulded through polymerization, spinning and post-spinning processes along with excellent dimensional stability and durability, polyester fabrics are very popular. But they pose problems to wearers remarkably in tropical countries like India only due to their hydrophobicity. To
overcome lower moisture absorbency characteristics, they are commonly used as blended fabrics. It must be added, however, that many people who have worn polyester underclothes say that the lowness of its moisture regain is not disadvantageous, and that the moisture travels through the garment doubtless by wicking and then evaporates. So, it is clear that in the absence of absorbency, moisture management can be effected through enhanced wicking process. Previous research on clothing materials focused mainly on improving the finishing process (application of hydrophilic finish) and incorporating modifications in the external form of polyester. While repeated washing will diminish the effect of the finishing process, modified fibre form (non-circular cross-section, crimps, diameter etc) impart a permanent function of moisture absorption and release adding more comfort to its clothing material. In addition, change in fibre form can bring about a change in fabric handle, feel and drapability.

2.3 Modifications in External Form of Polyester Fibres

Among manufacture fibres polyester dominates the market because of its versatility. It is produced as staple, filament, tow, and fibrefill, which may be made in either filament or crimped staple form.

In order to realize higher levels of performance, various developments and modifications of the form and structure of fibres are required. The fine structure and mechanical performance of natural fibres suggests to us much useful information. Some products developed in imitation of the structure and functions of natural fibres indicate a number of directions taken and yet to be taken by synthetic fibre fabrics. Synthetic fibres such as PET are normally round in cross-section, yet no natural fibre has a perfectly circular cross section. Another, the cross-sectional shapes of man-made fibres are uniform. Some irregularities in shape will occur in natural fibres, but the range of these differences is slight enough that fabric appearance is not much affected. Wool is scaly and irregular, cotton is ‘kidney bean’ shaped, and silk is roughly triangular. Hence, certain desired properties can be built in to polyester fibres during production. Typical characteristics are mentioned in Figure 2.1 which confers on the fibre certain properties which are advantageous in further processing and especially beneficial to the properties of the end product (“fitness in use”). Wada [6] in his paper dealt primarily with polyester fibre fabrics in general, from the view point of the classification of the shape of fibres, which is characterized by the cross-section and surface configuration and secondly with products characterized by the mutual
interactions between the fibre form and the structure of fibre assemblies, such as silk like fabric, spunize fabric, sweat absorption polyester fabric, brilliant colour developing fabrics etc.

The filament cross-sectional shape and form determine many yarn properties, which, in turn, determine the optical, tactile, physiological and technological properties of the final article. There are further opportunities to modify the cross-section and surface shape of fibre during further processing e.g. texturizing, alkalization) in order to change the properties of the final product, but these are less effective than a modification introduced in the production stage.

Some of the modifications in fibre form can be classified as follows:

1) Modified external cross-sections
   i) Cross-sections obtained by modification of the shape of the spinneret
   ii) Cross-section modified by conjugate fibre
   iii) Hollow fibres
   iv) Cross-sections composed of sheath and core

2) Micro-fibres
   Reduction in linear density (less than 1 den)

3) Surface Forms
   i) Voids
   ii) Grooves

4) Variation in longitudinal direction
   i) Thick and thin structure
   ii) Crimp
   iii) Thinned tip

Figure 2.1 Characteristics of polyester fibres built during production [19]
2.3.1 Modified cross-sections

Generally, polyester fibres are produced by melt spinning technology using circular nozzles in the extrusion process [24]. The cross-section of polyester fibre can be easily varied by changing the spinneret-hole shape, and accordingly various effects can be obtained by intentionally changing it. In the early 1970, people began to study the effect of non-circular cross-sectional fibres on yarn and fabric aesthetics, appearance and ‘feel’. Fortunately, melt spinning lends itself quite well of production of Non-circular cross-sectional fibres by varying the shape of the spinneret orifices, provided the melt viscosity is high enough that surface tension effects do not cause the filament to resume a circular shape.

The possible number of cross-sections is so large that it needs a systematic classification. A typical classification of cross-sections is given in Figure 2.2.

![Characteristics of fibre cross-sections](image)

**Figure 2.2 Characteristics of fibre cross-sections [19]**

2.3.2 Microfibres

Fibres of linear density around 1 den can be made by general spinning techniques, but a microfibre of around 0.5 denier is quite difficult to manufacture by conventional methods. In order to obtain a super micro-fibre, conjugate fibre techniques are usually used. A superfine fibre can also be obtained by applying an
alkali treatment to dissolve one component of the fibre. These kind of superfine fibres are used for extremely soft woven or knitted fabrics.

The finest fibres are mostly produced by spinning ‘Islands-in-a-sea’ conjugate fibres. When the sea is dissolved with a certain solvent, the ‘Island’ polymer remains and forms the finest fibres. By using this method, fibres of less than 0.01 den can be obtained and are chiefly used to make artificial leather. Even the category of microfibre, an appropriate linear density must be selected in accordance with the purposes of use.

Microfibres are used in various applications. Examples are high grade woven and knitted fabrics with a soft hand and water-and oil absorbent fabrics, such as towels and typewriter ribbon. Wiping clothes, and clean room garments utilize the large fibre surface. Moisture-permeable, waterproof, and water-repellent high density woven fabric is another use. In these end-uses, a suitable combination of the fibre assembly structure and fibre material is important in realizing excellent performance.

2.3.3 Surface forms

Length and fineness (diameter or linear density) could be considered elements of fibre surface geometry; Length because of surface continuity and fineness because of its effect on the radius of curvature of the fibre surface. However, length and fineness are considered by most technologists to be fibre geometric parameters rather than parameters of fibre surface geometry.

Fibres with structured surfaces can be further subdivided according to morphological fine structure (Figure 2.3). Cross-sectional deformation and/or surface modification can change the yarn properties, and thereby also the properties of the final product.

2.3.3.1 Voids

A common method of making void on the surface of a polyester fibre is to remove micro-particles blended in the polyester polymer by alkali treatment. By applying this method to various polyester fibres, containing different types of particles, fibres with various patterns of voids are obtained on the surface. The micro-voids play a role in increasing the depth of color by the mechanism of decreasing the surface reflection of light. Teijin, a Japanese company, manufactures and sells Wellkey®, a hollow polyester with minute holes in the cross-section that are intended to absorb perspiration.
2.3.3.2 Grooves

Silk fibres have extremely fine longitudinal grooves ranging from 0.1 to 1.0 μm, which give the characteristic hand and luster of the silk. It is assumed that it is necessary to form these fine longitudinal grooves on the fibre surface in order to obtain the silky hand and luster.

![Characteristics of fibre surface constitution](image)

Figure 2.3 Characteristics of fibre surface constitution [19]

2.3.4 Variation in the longitudinal direction

2.3.4.1 Thick and thin structure

An alternating thick and thin structure is thought to be one useful element in forming spunized yarn. There have been many suggestions on the utilization of thick and thin technology in order to make a higher grade spunized yarn, for example, a color-mix effect, creation of natural bulkiness by adding partial shrinkage differences, a finer spunized effect, partial melting and the raggedness-of-scale effect.

2.3.4.2 Crimp

One of the methods used developed to make a spun like yarn is through texturizing process. It imparts bulk and stretch to the yarn.
2.3.4.3 Thinned tip

Animal hair, such as mink and fox, has a tapered tip, which contributes to its fine appearance, and the pleasing hand of fur. Fibres with a tapered tip are used for brushes, painting brushes and so forth in addition to fake fur.

2.4 Modification of Fibre Behaviour by Fibre Cross-Section

The shape of a fibre can be examined both in cross-section and in its longitudinal form. Since cross-section is a practical way in which to view the three-dimensional form of a fibre, cross-sections are often used as a means of comparisons.

2.4.1 Fibre transverse dimension

2.4.1.1 Solid fibres of Circular Cross-section

If $A_0$ is the area of cross-section in cm$^2$, $W$ the linear density in millitex (i.e. g/cm x $10^{-8}$), and $\rho$ the density of the fibre substance in g/cm$^3$, then

$$A_0 = \frac{W}{\rho \times 10^8}$$

(2.1)

And if $P$ = perimeter of fibre section in cm, then,

$$P = 2\pi A_0 = 2\sqrt{\frac{\pi W}{\rho \times 10^8}}$$

(2.2)

Since the surface per cm, neglecting ends, = $P$ cm$^2$ and the volume per cm$^3$ = $A_0$, the specific surface, $S$, is given by

$$S = \frac{P}{A_0} = 2\sqrt{\frac{\pi}{A_0}} = 2\sqrt{\frac{\rho}{W}} \times 10^4 \text{ cm}^2/\text{cm}^3$$

(2.3)

It follows that, other things being equal, the finer the fibre, the greater is the specific surface.
2.4.1.2 Solid fibres with cross sections other than circular

The volume enclosed by a given surface diminishes according to the degree of departure from circularity of section. Hence equation must be rewritten as shown in Equation 2.4.

\[ S = 2K \sqrt{\frac{\pi \rho \times 10^8}{W}} \text{ cm}^2 / \text{cm}^3 \]  
(2.4)

Where \( K \) is a shape factor greater than unity.

Thus the greater the ellipticity of section, as in wool, or the greater the extent of indentation in the sectional shape, as in viscose rayon, the greater is the specific surface for a given linear density.

2.4.2 Fibre deformation behaviour: Bending and Twisting

When a fibre is assembled into a yarn with twist, it lies in a helical path. In this three-dimensional arrangement, the fibre is subject to both bending (flexing) and twisting (torsion). The bending and twisting of fibres influence the behavior of yarns, and the drape and handle of fabrics; and recovery from bending is a factor in creasing.

Twisting and bending both play a part in the arrangement of fibres in a yarn, and transverse compressive forces are involved when tension is applied to a twisted yarn. Bending strength and shear strength may be important in wear.

2.4.2.1 Bending of fibres, flexural rigidity and fibre cross-sectional shape

The flexural rigidity (or stiffness) of a fibre is defined as the couple required to bend the fibre to unit curvature. The flexural rigidity may be calculated in terms of other fibre properties; the problem is similar to that of bending of beams. In order to bend a ruler gripped between both hands, two twisting forces in opposite directions have to be applied at the ends. The twist force is called a couple. In a more scientific way, the effect is measured in terms of flexural rigidity.

\[ \text{Flexural rigidity} = \frac{1}{4\pi} \frac{\eta E T^2}{\rho} \text{ } - - - - - - - - (2.5) \]

\[ \text{Flexural rigidity} = \frac{1}{4\pi} \frac{\text{shape factor} \times \text{modulus} \times \text{tex}^2}{\text{density}} \]
It follows from this relation that the flexibility of a fibre depends on its shape. The shape factor becomes greater, and the rigidity increases, the more distant the material is from the centre. This is illustrated in Figure 2.4. It will be seen that with an asymmetrical shape there may be a difference according to the direction of bending: in practice, the fibres will usually twist so as to bend about the easiest direction. Table 2.8 gives some typical values. Shape factor is a measure of the shape, specifically in relation to bending. A solid circular cross-section gives a higher shape factor than an irregular cross-section.

Hollow sections give higher shape factors and hence greater flexural rigidity than solid cross-sections. A particular example of this are the 'white' kempy wool fibres, associated with Harris Tweed, which have an airspace (medulla) down their centre and so act like a tube. (For rigidity and lightness, metal tables and chairs are made from tubular frameworks).

![Shape factor diagram](image)

**Figure 2.4 Shape factors [15]**

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Flexural rigidity (mN mm²/tex²)</th>
<th>Flexural shape factor (η)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wool</td>
<td>0.20</td>
<td>0.80</td>
</tr>
<tr>
<td>Acetate</td>
<td>0.08</td>
<td>0.67</td>
</tr>
<tr>
<td>Viscose</td>
<td>0.19</td>
<td>0.74</td>
</tr>
<tr>
<td>Silk</td>
<td>0.19</td>
<td>0.59</td>
</tr>
<tr>
<td>Nylon</td>
<td>0.14</td>
<td>0.91</td>
</tr>
<tr>
<td>Glass</td>
<td>0.89</td>
<td>1.0</td>
</tr>
<tr>
<td>Polyester</td>
<td>0.30</td>
<td>1.0</td>
</tr>
</tbody>
</table>
2.4.2.2 Twisting of fibre, torsional rigidity and fibre cross-sectional shape

The resistance to twisting of a fibre is called its *torsional rigidity*. It is defined as the couple (turning force) required to put in unit twist, that is, unit angular deflection between the ends of a specimen of unit length. The torsional rigidity can be obtained in terms of the shear modulus (or modulus of rigidity) in the same way that the flexural rigidity can be obtained in terms of tensile modulus.

The torsional rigidity may be defined either as the torque to produce unit twist in radians per unit length, when it will be equal to

\[ \text{Torsional rigidity} = (\varepsilon \, n \, T^2 / 2\pi \, \rho) \]

or as the torque to produce one turn per unit length, when it will equal

\[ \text{Torsional rigidity} = (\varepsilon \, n \, T^2 / \rho) \]

Essentially then,

\[ \text{Torsional rigidity} = \frac{\text{shape factor} \times \text{specific shear modulus} \times \text{tex}^2}{\text{density}} \]

This expression shows the effect of shape on the torsional rigidity of a fibre in terms of shapr factor. *Shape factor* (\(e\)) for torsional rigidity is equivalent to the quantity used in flexural rigidity but is a different value because it applies to a different three-dimensional direction.

The determination of shape factor has been discussed by Meredith. For simple shapes, the value of the shape factor may be obtained theoretically by integration, no measurement on the fibre being necessary. For slight more complicated shapes, there are expressions for the shape factor that require the substitution of certain parameters of the fibre cross-section, for example, the major and minor axes of elliptic cross-section, or the relative areas of wall and void in hollow fibres. For very complicated shapes, such as that of rayon, an experimental analogy may be used by using soap membrane methodology. Appendix C gives expressions for the shape factor for various cross-sections and shows the values given by Meredith [25]. Table 2.9 shows the values of shape factor for torsion of some fibres given by Meredith.
### Table 2.9 Typical values for specific torsional rigidity and shape factors [15]

<table>
<thead>
<tr>
<th>Fibres</th>
<th>Specific Torsional Rigidity (mN mm(^2) tex(^{-2}))</th>
<th>Torsional Shape Factor ((e))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>0.16</td>
<td>0.71</td>
</tr>
<tr>
<td>Wool</td>
<td>0.12</td>
<td>&gt;0.977</td>
</tr>
<tr>
<td>Triacetate</td>
<td>0.091</td>
<td>0.70</td>
</tr>
<tr>
<td>Silk</td>
<td>0.16</td>
<td>0.84</td>
</tr>
<tr>
<td>Viscose</td>
<td>0.06</td>
<td>0.95</td>
</tr>
<tr>
<td>Nylon</td>
<td>0.05</td>
<td>1.00</td>
</tr>
<tr>
<td>Orlon</td>
<td>0.15</td>
<td>0.57</td>
</tr>
<tr>
<td>Polyester</td>
<td>0.067</td>
<td>1.00</td>
</tr>
</tbody>
</table>

#### 2.4.3 Appearance, feel, bulk and covering

Differences in cross-section are responsible for differences in fibre characteristics such as appearance, hand or feel, surface texture, and body. Lustre and covering power are also affected by cross-sectional shapes. Examples of various cross-sections are shown in Figure 2.5

![Figure 2.5 —Different cross-sections of fibres (a) Round cross-section of polyester fibre (x 1200); (b) trilobal cross-section of polyester fibre (x 1600); (c) pentalobal cross-section of polyester fibre (x1600); (d) hexalobal cross-section (x1000); (e) octalobal cross-section (x1600) [6]](image-url)
Round cross-sectional shaped fibres have a soft, smooth, sometimes slippery feel. Unless a special treatment has been given to the fibre to decrease its luster, the luster of round fibres is high. Covering power is, however, poor. This is because the surface area of round fibres is less than that of any other shape. Also being both round and smooth, the fibre will pack closely together in to a yarn.

Dog-bone shaped and flat cross-section fibres have a harsher, less smooth handle. The covering power of these fibres is excellent. Completely flat cross-sections have a high luster, and some manufacturers have produced flat fibres with a glittering luster, but those with less regular surface, such as cotton, which has a somewhat flat but irregular cross-section, do not have high luster.

One of the earliest cross-sections used was the trilobal section made by extrusion through a T or Y-shaped hole and looking rather like a blunted three-pointed star. The target of this cross-section study was silk. A trilobal cross-section was adopted to make the feel and luster similar to those of silk. Usually, a fibre of a trilobal section shows a highly lustrous and sparkling appearance. As the number of lobes increases (for example quintalobal, octalobal etc.), the luster becomes milder because of the scattering reflection of light. Multilobed cross-sections have quite different yarn appearances. For example, trilobal yarns are glittery as the incident light reflects off the fibre surfaces, while octalobal yarns give an opaque matte effect, since the light is effectively absorbed by multiple reflections from the many faceted angles (Figure 2.6). Many polyester carpet yams are trilobal in section, since this cross-section assists in soil-hiding. It is argued that a cylindrical fibre tends to act as a lens and magnifies the appearance of dirt in the tufts. Sharp edged filaments in textile yarns have the rustle and high frictional characteristics of silk. Where the property is called ‘Scroop’ and is a highly prized feature of pure silken fabrics. Gradually the principles learnt in the early days of NCCS fibre research have been applied to commercial yarns, and many filament yarns for both apparel and BCF carpet yarns and staple for carpet fibre now use non-circular cross section filaments.

Differentiation of the cross-section greatly influences the feel of the fibres, and it is well known that the trilobal form is useful for creating a dry feel. Research on silk like polyester fabrics is now continuing, and studies to improve the cross-section of the fibre are also still in progress. A sharper and more complex cross-section, which is made by modification of the trilobal form as illustrated in Figure 2.7, can give fabrics a very characteristic effect such as a steady luster and a scroopy handle. Fabrics with a dry feel brought about by the hexagonal cross-section of polyester staple fibre and
boa-like high quality fur or blanket made of acrylic fibre with an exceptionally flat cross-section are seen in the market.

One new patented process gives a deeply indented and longitudinally grooved fibre cross-section, spun from a castellated spinneret hole, the so-called 4DG™ (for ‘deep grooves’) fibre process. Such fibres have a very high surface area per unit length in comparison with cylindrical fibres. These odd-shaped fibres have excellent capillary and wicking properties for removing surface moisture and are suggested for many uses such as nappies, sanitary towels, filter media, anti-perspiration shields, shoe liners and medical applications such as wound coverings. Various NCCS yarn cross-sections, including the 4DG™ one are shown in Figure 2.8.

Figure 2.6—Diagrams showing differences in reflection of light in round, trilobal and pentalobal fibres [26]

Figure 2.7—Modification of trilobal cross-section; (A) as used for improvement of scroopy touch of silky fabric; (B) as used for improvement of dry feel [6]
The characteristics of hollow fibres are lightness, a novel appearance, and superior warmth because of the inclusion of air. Hollow fibres are made of a sheath of fibre material and a hollow space at the center. Hollow fibres provide greater bulk with less weight. They are, therefore, often used to make insulated clothing. Hollow polyester fibres are made into fibrefill with good insulating qualities. Compared with ordinary fibres of the same linear density, they are stiffer and more resistant to bending and torsion and have a more opaque appearance, caused by diffused reflection of light. These fibres are generally used for enhancing the lively hand of fabric, wadding, carpet and so on. The typical hollow fibres with a polygonal cross-section are shown in Figure 2.9. It is expected that woven and knitted fabrics made from these materials will have a glistening luster, opaqueness and a dry and rough feel. Some have been put to such specialized uses as filter or as carriers for carbon particles in safety clothing for persons who come into contact with toxic fumes.

In the nutshell, it can rightly be said that the shape of the filament may play a bigger part in the handle and appearance of fabrics than is often realized.

2.4.4 Fibre surface geometry and frictional behaviour

The surface geometry of synthetic fibres is relatively simple in comparison with the surface geometry of natural fibres. This simplicity is a reflection of the uniformity and the quality control in their production. They tend to have little
variation in cross sectional shape and in cross-sectional area along their length, and the microscopic surface roughness normally present is fairly uniform in size and distribution.

Non-circular cross-sectional shapes often have surface geometric profiles with protuberances or projections which are an order of magnitude greater than those of asperities (several micrometers versus a fraction of a micrometer, for example). Furthermore, slight deviation from non-circularity of cross-sectional shape can lead to substantial differences in fibre processing behavior and in the performance characteristics of textile structures. A number of idealized diagrams of cross-sectional shapes of equal cross-sectional area are shown in Figure 2.10. It is pointed out that, while these idealized shapes are representative of the variety possible, commercially produced synthetic fibres would not ordinarily be so perfectly shaped.

It is well known that textile fibres are quite flaccid and, once released from tension, are never found in a perfectly linear configuration, similar to that of a rigid rod for example. Rather, fibres tend to twist, spiral or curl about their own axis. In fibres with a smooth, circular cross-sectional shape, as represented by Figure 2.10a, the effect of this tendency to twist or spiral is minimal. In fibres with non-smooth, non-circular cross-sectional shapes, however, a spiraling edge is generated (similar to that of a screw) thereby restricting the potential for inter-fibre contact and for high fibre packing density. The less circular the cross-sectional shape of the fibre, the larger the restriction.

An indication of the restrictive tendency is shown by the circles around each cross-sectional shape in Figure 2.10. The potential area of contact with contiguous fibres over a very short segment of fibre length can be approximated by the arcs of fibre surface parameter that are congruent with the circle circumscribing the idealized cross-sectional shape. Thus, if a fibre with a smooth, circular cross-sectional shape (Figure 2.10a) had a potential for inter-fibre contact of 100%, the potentials for the other shapes shown in Figure 2.10 would vary, approximately, as follows: 2.10b (rough, circular) 30%, 2.10c (tetrakelion) 27%, 2.10d (trilobal) 16%, 2.10e (elliptical) 11%, and 2.10f (triangular) 2%. Once again, Figure 2.10b suggests the dramatic effect of asperities on the surface of a fibre with a circular cross-section. It is pointed out, however, that when, asperities are superimposed onto a non-circular cross-section, the effect of the asperities is masked by the dominant non-circular profile.
Fibre surface roughness and crimp are also considered the components of fibre surface geometry. Agglomerates of delustrant particles located near the surface of synthetic fibres cause asperities. Crimp is necessary for the efficient manipulation of fibre in the early stages of mechanical processing, especially on opening and carding equipment. But under greater tension (sufficient for removal of crimp), the fibre becomes quite linear and the projections of the crimp nodules are substantially less prominent. It is to be expected that the role of these components of fibre surface geometry during textile processing should be substantially different. Moreover, it should be expected that the prominence of the role of each component might vary according to the stage of processing or to the structure of the fibre assembly.

The surface properties significantly influence the technological processing of fibres. In particular, fibres in contact are often made to move relative to one another, creating frictional forces that are of great importance [29–30]. Some fibres have smooth, even surface contours when examined longitudinally, others are rough and uneven. Horizontal lines or other markings may appear in the length of some man-made fibres as a result of irregularities in the cross-sectional shape of the fibre. The valleys between the lobes of multi-lobal fibres cause shadows, which under the
microscope appear as dark lines and are known as striations. Superimposed on this topography are the crimp and overall fibre size. All of these surface factors, as well as those associated with the internal structure, determine the frictional behaviour of fibres [31-36]. This combination of characteristics is often determined by some type of frictional measurement. In most situations, the “Force of Friction” or simply “Friction” is measured and is defined as the resistance to the motion that is developed when one body slides over the surface of another. The frictional behavior is dominated by the properties of the small regions of contact; therefore, there appear to be at least three mechanisms responsible for friction viz. surface roughness, adhesion and plowing [37]. The strength of twist yarns varies between 15 and 75% of the tensile strength of the fibres in the cross-section. This large variation in transfer of fibre strength to yarn strength illustrates the importance in the clinging power of single fibres and the cohesive forces between fibres apart from fibre configuration. Clinging power is recognized to be a function of coefficient of friction.

Gupta and El Mogahzy [1, 38] divided the factors affecting the fibre friction into two main groups, namely, factors affecting morphology of contact, and factors affecting mechanical properties of junctions. The first group includes the nature of the surface, such as cross-sectional shape, crimp, surface roughness (convolutions, scale etc) and contact mode during testing (point contact, line contact and area contact). The second group includes the chemical and physical structure of the fibre, such as functional groups, molecular orientation and crystallinity, bulk specific shear strength of junctions and visco-elastic properties of junctions in compression.

El Mogahzy and Gupta [1] investigated the effects of fibre structural factors such as fibre cross-sectional shape, molecular orientation, annealing and fibre type on fibre friction. They reported that circular cross-sectional fibres have higher coefficients of friction ($\mu$) than non-circular cross-sectional fibres (i.e. triangular and trilobal fibres). The non circular cross-sectional fibres had surface geometric profiles with protuberances that are inherently stiffer and thus more resistant to compression than the bulk material of the fibre. This may be because the molecules in the lobes of triangular or trilobal fibres are more highly oriented and packed than the molecules in the bulk of the material. Due to the greater stiffness and resistance to compression of a fibre with non-circular cross-section, it may have a smaller contact area and a lower friction than a fibre with circular cross-section.

The coefficient of friction increases as molecular orientation increases, probably due to the increase in area of contact [35-36]. This was attributed to the fact
that a fibre with a higher molecular orientation is more easily deformable under 
compression (lower K), has a smoother fibre surface (higher m), and is more plastic in 
nature under transverse pressure (higher n) [1]. These results have been analyzed in 
terms of the structural parameters in the structural model of friction which is shown in 
Equation 2.8

\[ F = S \cdot C_m \left( \frac{1}{K} \right)^n m^{1-n} N^n \text{ (2.8)} \]

The model provided a theoretical base for the empirical equation \( F = a \cdot N^n \), which has been fitted successfully to experimental data. As per this equation, the factors that affect friction in fibres fall in to two groups: first is the morphology of contact given by the number of asperities \( m \) over which the contact is maintained and the nature of the stress distribution on the contact region described by the model constant \( C_m \). Second is the mechanical behavior of the junctions given by the values of the contacts \( K \) and \( \alpha \) in the pressure area relationship \( P = K \cdot A^\alpha \) and the value of the specific shear strength of the junctions \( S \) (Here \( K \) represents the stiffness or hardness of the material).

Attention has been given to the influence of fibre geometry on the mechanical properties of assemblies during processing [39]. Relative to the effect of fibre cross-sectional shape, it was found that fibres of circular cross-section produce greater cohesion in webs and slivers than do trilobal fibres. The explanation for this tendency is that a circular cross-section provides a greater area of contact between adjacent fibres than does a trilobal cross-section; because, with twist in the fibres, the trilobal will be in contact only where adjacent ridges cross one another, whereas on the circular fibres, there are no such twisting ridges. This situation is somewhat analogous to the differences in friction between a twist-less multifilament yarn and the same yarn with twist. It is well known that the twisted multifilament yarn makes much less contact with a contiguous frictional surface because of the spiraling filament ridges in the yarn structure caused by the helical twist geometry.

As a summary it can be said that in the early stages of staple fibre processing, crimp is most essential for processability and plays a dominant role over surface roughness and cross-sectional shape. This relatively important role of crimp is also observed in the mechanical properties of loose staple-fibre assemblies. In the latter stages of processing when fibres are much more liberalized and in more intimate
contact with one another, the role of surface roughness and cross-sectional shape becomes quite prominent and the role of crimp subsides. In tightly twisted textile structures, the effects of fibre surface geometry are masked. However the fibre-fibre and fibre-machine interaction that occur during processing, exclusively through fibre surface contact, are reflected in the qualities and performance characteristics of the textile structures.

2.5 Modification of Fibre Behaviour by Fibre Fineness

It is widely accepted that for textile raw materials in general, the transverse fibre dimensions are of the utmost technical importance, not only in one respect but in many contexts.

2.5.1 Bending rigidity and fibre fineness

The equation of fibre flexural rigidity derived in Appendix A is shown in Equation A-6. Since the fineness comes in as a squared term, and in view of the range of values occurring in practice—from 0.1 tex for a fine man-made fibre to 1 tex for a coarse wool and higher for some hair fibres and man-made monofil. it will be the most important factor in determining the flexural rigidity and a change in fineness has a more significant effect on the flexural rigidity than the other factors. If the fineness is reduced by a factor of 2 then the flexural rigidity is reduced by a factor of 4. A practical example of this factor is that, in order to produce glass fibre which is sufficiently flexible for conventional processing, it is extruded with much finer filaments to compensate for the higher modulus value.

It is convenient to introduce a quantity that is independent of the fineness of the specimen that is nothing but the specific flexural rigidity, $R_f$; it is equal to the flexural rigidity of a filament of unit tex. It will be given by:

$$R_f = \frac{1}{4\pi} \frac{\eta E}{\rho}$$

i.e.

$Specific\ flexural\ rigidity = \frac{Couple/\ Curvature}{(Linear\ density)^2}$

Values of $R_f$ obtained by using values of the modulus obtained in tensile tests are given in Table 2.8.
2.5.2 Torsional rigidity and fibre fineness

As fineness varies and other things are equal, resistance to torsion, too, increases more rapidly than fibre weight per unit length. Hence fineness plays an important part in determining the ease with which fibres can be twisted together during yarn formation.

Considering the situation from another angle, it can be shown that the torque generated in a yarn of given count by a given amount of twist increases as the linear density of the fibres increases. Thus internal stresses capable of producing kinks and snarls in a yarn are greater when the constituent fibres are coarse than when they are fine.

The expression given in Equation (2.7) shows the effect of fineness on the torsional rigidity of a fibre (to produce one turn per unit length). As in bending, since fineness comes in as a squared term, it is the most important factor. Hence, Finer fibres are supposed to be more easily twisted.

The torsional rigidity of a specimen of unit linear density (in tex), independent of the fineness of the particular specimen, and this may be called the specific torsional rigidity, $R_t$. It is given by:

$$R_t = \frac{\varepsilon n/\rho}{- - - - - - - - - -} \quad (2.10)$$

The values of specific torsional rigidities of some of the fibres are shown in Table 2.9.

2.5.3 Reflection of light and fibre fineness

The finer the fibres incorporated in a fabric, the greater is the number of individual reflecting surfaces per unit area of the fabric. Fibre fineness therefore affects the character of the luster of the fabric. In descriptive terms, fine fibres produce a soft sheen, whereas coarse fibres give rise to a hard glitter.

Practically all textile materials are, however, translucent in a greater or less degree. A substantial part of the light reflected from a fabric is therefore reflected from internal surfaces, and in dyed fabrics the intensity of the light so reflected- i.e. the apparent depth of shade- depends on the mean path length of the light rays through the coloured substance. This in turn depends on the number of fibre surfaces- both internal and external- per unit depth of the structure. Hence, other things being equal, the finer the fibre, the lighter is the apparent shade [40-41].
2.5.4 Absorption of liquids and fibre fineness

The rate at which dyes are absorbed into a fibre obviously depends on how much surface is accessible to the dye liquor for a given volume of the fibre substance, i.e. it depends on the specific surface [42-43]. It therefore follows that the time required to exhaust a dye bath is shorter for fine fibres than for coarse fibres and for fibres with strongly indented cross sections than for those which are smoothly cylindrical.

2.5.5 Role of fibre fineness in yarn tenacity

Fibre fineness is one of the important factors influencing the tensile properties of yarn. Consider a fibre, with radius “a”, in a given field of tensile and transverse stress as shown in Figure 2.11. The tension on the fibre will be proportional to the area of cross-section, and thus to \( a^2 \). However, the frictional resistance to slip, coming from a particular element of given length, will be proportional to the total normal load on the element, which, in turn, is proportional to the surface area of the element, and thus to the circumference and to the radius “a”. Consequently the tension tending to cause slip increases as \( a^2 \), while the frictional resistance increases only as \( a \). Thus the greater the fibre radius, in other words the coarser the fibre, the greater will be the tendency for the fibre tension to overcome the frictional forces resisting slippage. So the finer the fibre, the stronger will be the yarn.

\[ \text{Figure 2.11—Dependence of fibre tension and frictional drag on fibre radius, under given tensile and transverse stresses [15]} \]
The dependency of fibre radius on the coefficient of friction has been theoretically estimated in terms of the adhesion theory of friction and of pressure area relationships determined by the power law [1]. The resulting equation is:

\[
\frac{\mu_1}{\mu_2} = \left(\frac{r_1}{r_2}\right)^2 (1-n) \quad (2.11)
\]

where \(\mu_1\) and \(\mu_2\) are the coefficients of friction of fibres with radius of \(r_1\) and \(r_2\), and \(n\) is the friction index, implies that the coefficient of friction increases with the radius of fibre. The coefficient of friction of nylon 66 fibres increased with increasing fibre denier, in a range of 7 to 20 denier [44].

### 2.5.6 Stiffness, handle, and drape of fabrics and fibre fineness

For cylindrical rods or wires of homogeneous and isotropic materials, the resistance to bending varies as the square of cross-sectional area. Textile fibres are rarely homogeneous, never isotropic, and only in certain cases circular in cross-section. Even so, it still remains true that, as fineness varies and other things are equal, resistance to bending increases more rapidly than does fibre weight per unit length.

From this it follows that, for a yarn of given count or a fabric of given weight per unit area, made from a given type of raw material, the resistance to bending diminishes as the fineness of the fibre increases. Fibre fineness is thus an important factor in determining the stiffness of a fabric or, alternatively, its softness of handle and its draping quality.

### 2.6 Relationships of Fibre Fineness and Cross-sectional Shapes with Spun Yarn Structure and Properties

Processing and performance behaviour of staple fibre in yarn production is dependent on three groups of properties, firstly fibre mechanical properties eg tensile, flexural & torsional stress/strain relationship, secondly tribo-physical properties eg. Surface morphology, lubricity and crimp and lastly the fibre assembly structure eg. degree of fibre entanglement. Fibre fineness and fibre cross section have a direct relationship with these properties and definitely deciding the yarn properties. Peirce [45-46] recognized the need and importance of separating inherent fibre properties from the effects of the imposition of the geometric form in the development of textile end structures, as the complex interaction of these two major parameters as they exist in and affect the behavior of the final product. Fibre geometrical features like cross-sectional shapes and linear density may be considered as the important geometrical
forms which can have tremendous impact. It has been mentioned that slight deviations from circularity of cross sectional shape can lead to substantial differences in fibre processing behaviour and in the performance characteristics of textile structures [47-48]. The detailed account of diversified effects of fibre cross-sectional shape and diameter have been very well documented [49] emphasizing the creation of various effects like “New Silky”, “New Worsted”, “Peach Skin” and “dry Touch” etc. In fact, fabric handle is considered to rely on and be determined by the cross-sectional shape of the fibres [48, 50]. Not only handle, other comfort related properties like warmth retention, water transport, and luster are also modified [6].

With the advancement of polymer technology and fibre spinning techniques, strength and elongation of yarns made of manmade fibres and their blends has no longer been a major concern in the highly competitive, quality conscious consumer market. The demand for quality is mostly in terms of all visual aspects of uniformity of yarns like regularity in mass, diameter, twist and yarn faults and imperfections. In this context it is a general observation [51-53] that very few of insights gained from research on cotton can be used for improving the control on quality of manmade fibres and their blends processing. Although the technological considerations involved at each stage of processing are principally the same.

Most synthetic fibres are produced with a circular cross-sectional shape by extrusion through round holes. However, variety of cross-sectional shapes can also be produced by changing the spinneret profile. These non-circular cross-sectional shapes often have surface geometric profiles with protuberances or projections. Furthermore, slight deviation from circularity of cross-sectional shape can lead to substantial differences in fibre processing behavior and in the performance characteristics of textile structures [1, 47, 49, 54-58]. Fibre cross-sectional shape affects the cohesion and bulkiness (volumetric packing density) of fibre assemblies [28]. Also, the relative luster and stiffness (bending modulus) of a fibre are affected [6, 49]. It is a well acknowledged engineering fact that bend and twist stiffness are greatly affected by variation in fibre size, shape and density. In fact, variation in fibre cross-sectional shape in a particular type of fibre of same linear density, influence the manner in which inherent bend and twist moduli (an inherent fibre characteristic) contribute to bend and twist stiffness.

The fibre-fibre and fibre machine interaction that occur during processing, exclusively through fibre surface contact, are reflected in the qualities and performance characteristics of the textile structures. Fibre cross-sectional shapes is
one of the important surface geometrical parameter affecting not only the early stages of mechanical staple fibre processing but plays prominent role in the latter stages also even in the yarn form when fibres are much more linearized and in more intimate contact with one another. Fineness of fibres because of its effect on the radius of curvature of the fibre surface can be considered an another element of surface geometry.

Some exhaustive work [45, 59-66] has been carried out concerning internal structure and mechanisms of twisted yarns by theoretical modeling. As an outcome of this extensive research, it has become well established that the yarn structural features that have a major influence on the yarn properties and performance are volumetric density (fibre packing density), fibre segment length between points of entanglement (fibre modular length) which is related to twist geometry and mobility of fibre segments between points of entanglements (dimensional stability). Over and above these structural features, there is another aspect of fibre assembly which can be considered not less important in any sense and which influence the performance of the yarn in the downstream process and in end use; is the uniformity of arrangement of fibre mass along the yarn length and the imperfections.

Scardino and Lyons [67-68] reviewed, in general terms, the recognized important influence that fibre properties have on the behavior of linear assemblies in staple yarn manufacturing systems. It was found that fibres having geometrically smoother surfaces produced greater cohesion (drafting tenacity) in slivers and rovings, in the worsted, cotton and woolen systems, and that roughness generally appeared to influence the evenness achieved in the linear assemblies during drafting. Tygi et al [69] showed that bulk is considerably higher for yarns spun with trilobal polyester fibre and it increases as the polyester content is increased in polyester/cotton blend.

Yarn diameter and dye uptake were studied for ring process by Kaushik et al [70]. They found that the use of trilobal fibres brings about a large yarn diameter owing to the higher rigidity of these fibres. The coarse or more rigid fibres resist more to bending while twisted into yarns, leading to a longer radius of curvature, which, in turn, is caused by the movement of the fibres away from the axis. In this investigation, the assessment of the response of polyester fibre yarns towards disperse dye was made in terms of absorbency. It was observed that the yarns spun from fibres of finer denier absorb more dye owing to the large specific surface of these fibres in comparison to that of the coarse denier fibres. Also, the polyester yarns spun from
trilobal fibres absorb more dye than the yarns spun from fibres of round cross-section and dyed under identical conditions. Such a trend was attributed to the higher absorbency of the constituent components and the lower packing density of the yarn which favors its accessibility to chemical reagents.

In respect of yarn evenness and imperfections, Kaushik et al [70] observed that yarns spun from trilobal fibre are slightly more irregular and have more imperfections than the yarns spun from a circular fibre. This observed trend was explained on the basis of higher level of inter-fibre cohesion in trilobal fibres. Yarns with trilobal fibres also showed slightly higher number of neps. The same results were observed in case of rotor yarns by Tyagi [71].

The drafting force during roller drafting and the drafting behavior have been widely studied [72-73]. In addition, earlier experimental work had also investigated the correlation between drafting force and yarn quality to determine the optimum spinning-drafting conditions for improving yarn quality. The force required to draft a roving depends upon the frictional properties of its constituent fibres that may be influenced by the factors such as fineness, cross-section and spin finishing. The magnitude of the inter-fibre frictional force will be proportional to the overall geometric area of contact. Su and Fang [74] showed that the cross-shaped surface is rougher than the regular polyester fibre and thus the non-circular polyester fibres has smaller inter-fibre frictional force resulting in lower inter-fibre cohesive force of the profiled polyester fibres. Further he demonstrated a strong relationship between coefficient of variation (CV %) of drafting force and yarn unevenness. For blended fibre, a greater variation in fibre length will lead to an increase in the number of floating fibres and greater product irregularity. Since cotton fibre is variable in length, so yarn quality of spun polyester was less uneven than that of cotton and P/C blended yarns, which were spun under optimum spinning conditions.

Korkmaz [75] explained the effects of fibre fineness on dynamic cohesion force at different delivery speeds. In order to monitor the effect of fineness, he produced polyethylene terephthalate (PET) fibres and slivers which were almost identical except for fineness, of 0.88, 1.11 and 1.33 dtex. In this study, the dynamic cohesion force of a single card sliver at different roller speeds (15, 30 and 60 m/min) were measured by using a Rothschild Cohesion Meter. The cohesion force of 1.11 and 1.33 dtex card slivers increased with increasing delivery speed, while the cohesion force of microfibres had a decreasing trend at the same delivery speeds. Sliver irregularity was positively correlated with variation in cohesion, while a negative
correlation was detected between sliver irregularity and cohesion force and between sliver irregularity and fineness. Therefore, he showed that the slightest change in fibre fineness can cause dramatic changes in the drafting process and sliver irregularity.

Tyagi et al. [76] studied the influence of process parameters and annealing treatment on structural parameters, tensile properties, flexural rigidity and abrasion resistance of polyester dref-3 yarns. They found that annealing leads to a marked increase in helix angle and helix diameter, and a decrease in mean fibre extent. The results showed significant improvement in breaking extension, work of rupture and abrasion resistance, and an appreciable decrease in tenacity, hairiness and flexural rigidity on annealing. The degree of change in these characteristics is more marked in the yarns made from a circular polyester fibre and the coarse fibre denier, thicker core and higher production speed facilitate it. Compared to the yarns made from a trilobal fibre, the yarns spun from a circular fibre exhibit higher thermal shrinkage which further increases with the increase in spinning speed.

Under most conditions of fibre processing and fabric tactile evaluation, fibre strains are of a low order of magnitude in varying combinations i.e. stretch, bend and twist. The role of single fibre deformations in deciding their fabric properties such as flexibility, drape, handle, crease retention and wrinkle recovery has been emphasized [77-79].

Designing of a textile product with a specific end use is possible by selecting a suitable fibre and product structure. This possibility is realized depending on the way how the translation of fibre properties in to the product takes place. A lot of work has been reported on this contribution of fibre characteristics and role of process parameters in deciding the structure and properties of yarn. But the literature available [56-58, 70, 80] regarding fibre behavior (especially fibre denier and fibre profile) affecting the yarn performance at low stresses and strains is scanty and needs further investigations. Since they govern the tactile/ handle characteristics of the ultimate product.

The strain applied in most of the post spinning operations is of low magnitude with the result that the low strain behavior of yarn assumes considerable importance. Hearle [61] showed by a theoretical analysis on multifilament yarn that the ratio of tensile moduli of yarn to fibre reduces with increase in twist angle. But later on it was modified to incorporate the discontinuities of the staple fibres establishing that initially with increase of twist yarn modulus increases due to coherence effect but after a certain limit (optimum twist) it goes on reducing owing to obliquity effect.
Similarly some theoretical contribution [81-84] regarding bending characteristics has been made establishing that yarn structure and nature of finishing modify the translation of bending characteristics of the constituent fibres into yarn properties. Some extensive experimentation [85-86] has also been carried out to establish the effect of twist, setting conditions and fibre parameters on the bending behavior of continuous and staple fibre yarns.

Tyagi and Sharma [87] found out the influence of annealing treatment on the performance characteristics of polyester DREF 3 yarns in relation to fiber profile and spinning speed. Annealing resulted in a marked decrease in initial modulus, which was caused by loosening of the yarn structure. The yarns spun from a fine denier were found to exhibit the highest initial modulus, low compressional energy, and higher compressional resilience.

Another structural feature which is having a direct correlation with the touch feeling of textile products is the presence of surface hairs. It is well established that yarn hairiness affects not only the efficiency of its conversion into the fabrics but also the apparel characteristics such as the handle, thermal insulation and appeal characteristics. A detailed account of occurrence of hairiness in the yarns has been compiled by Barella [88-90] emphasizing on the importance of fibres and process variables in altering greatly the hairiness of these structures. Barella [89-90] identified the three forms of projections comprising the yarn hairiness i.e. fibre ends projected from the yarn core, fibre loops and wild fibres. Pillay [91-92] while working on cotton identified the torsional rigidity, flexural rigidity; fibre length and fibre weight the fibre properties in order of importance in the incidence of hairiness.

The handle and mechanical properties of the fabrics woven from polyester multifilament yarns with different cross-sectional shapes have been documented in various publications [48-49]. The contribution of yarn structure to the aesthetic and tactile qualities of apparel fabrics is transmitted through the linear density and surface geometry of the constituent fibres. Some researchers have studied the influence of fibre type and twist on yarn flexural rigidity. But the role of fibre profile does not get clear. Kaushik et al. [56-57] through their study, elucidated that trilobal fibres exhibit a slightly higher flexural rigidity than the yarn spun from circular fibres and this was held true both in ring as well as in rotor spun yarns. There was general decreasing trend of flexural rigidity due to the addition of cotton in the fibre mix.

In their experimental investigation Tyagi et al. [69] found that the yarns spun with trilobal polyester fibres exhibit fewer hairs and more unevenness due to higher
inter-fibre cohesion, which interferes with the drafting process and leads to inadequate dispersion of fibre components in the strand. In yet another research work Kaushik et al. [70] proved that circular fibres exhibit more hairiness than their trilobal counterparts owing to the lower bending resistance of circular fibres. Further, hairiness appeared to be appreciably low in yarns spun from coarse fibres owing to the greater weight of the fibres.

A lot of information is available about the blends of circular polyester fibres with other natural and regenerated fibres [56, 93-97]. The effects of various types of polyesters, differing in inherent characteristics, in blends have been studied [98-100]. But the information regarding processing performance and product characteristics of non-circular polyester fibres especially in blends [56-58] is limited. A study was planned by Scardino and Lyons [101] to know how the parameters of fibre geometry affect the mechanical properties of fibre assemblies i.e. card web and draw frame slivers. It was observed that the fibres of circular cross-section, in general, produce greater cohesion in webs than do the trilobal fibres. In this connection, it may be supposed that a circular cross-section provides a greater area of contact between adjacent fibres than does a trilobal section; because with twist in the fibres, the trilobal will be in contact only where adjacent ridges cross one another, whereas on the circular fibres there are no much twisting ridges. Whether greater cohesion in webs is correlated with greater contact area between the component fibres was, however, brought in to question when the cohesion forces of webs composed of smooth and rough fibres, other parameters being the same, were compared. It was seen that, on the average, the cohesion of samples with the rough fibres was the higher. Thus the role played by contact area was left unclear by these results.

Influence of fibre cross-sectional shapes on the structure and properties of both rotor and ring spun yarns were reported for polyester and acrylic fibres by Sengupta et al. [54]. It was observed that the fibre cross-sectional shapes greatly influence the tensile behaviors of rotor spun yarns while in case of ring spun yarns the effect is marginal. Packing coefficient of ring yarns did not vary much between yarns with fibres of different cross-sectional shapes. Therefore in case of ring yarns the yarn tenacity values followed the same trends as that of the respective fibre tenacity. In contrast to ring yarns, rotor yarns showed quite different trend, where, in case of polyester fibres, trilobal having the lowest tenacity showed the highest yarn strength followed by circular and hollow fibres. Since, rotor yarn failure is greatly influenced by the fibre slippage and the stress distribution which is mainly dictated by inter-fibre
friction and initial packing of the yarn. Trilobal fibres were found to have more cohesive force and higher yarn packing coefficient than circular and hollow fibres.

The results on yarn breaking strength and extension corresponding to different fibre cross-sections quoted by Kaushik et al. [70] are opposite. Here, yarns spun from a trilobal fibre have been found to possess a lower strength than the yarns spun from a circular fibre. This observation was attributed to the lower breaking strength and lower packing density of the trilobal fibres. Whereas, higher breaking extension were explained on the basis of lower tenacity, higher extension and lower toughness of trilobal fibres as compared to their equivalent circular fibres.

2.7 Pore Characteristics between the Fibres and Effect of Fibre Cross-Section and Fineness

Textile fibre assemblies are to a great extent mechanically resistant and at the same time soft, porous and drapeable. These unique characteristics determine a textile’s use in clothing and for some special technical and medical applications. Textile porosity and other related properties have special significance [102]. In fact, all textiles are discontinuous materials in that they are produced from macroscopic sub-elements (finite length fibres or continuous filaments). The discreet nature of textile materials means that they have void spaces or pores that contribute directly to some of the key properties of the textiles, for example thermal insulating characteristics, liquid absorption characteristics, and softness and other tactile characteristics [103].

The most frequently used property for characterizing pores between fibres is porosity, which expresses the relative amount of air or fluid found in the gaps between fibres. But porosity is an insufficient parameter for describing fibre assembly characteristics. Besides porosity, pore sizes and the shape of air gaps i.e. sizes of peepholes, slits and channels between fibres, are very important parameters for describing pore characteristics [102]. The space between fibres may be concentrated in few big gaps or in huge number of possibly small, different slits, slots or channels. Therefore, pore size and shape are the significant parameters that determine textile behaviour. Also tortuosity phenomena of pore space influence the transport of water, solutes, and gases in textile structures. Sectional and longitudinal shapes of pores, and pore constrictions are also reflected in the tortuosity factor.

Apart from compression (compactness like yarns and fabric constructional parameters) and orientation, pore size and shape resulting from fibre arrangements in
the textile structure depends on fibre parameters like cross-section, linear density etc. Pore size and shape in a real textile structure are generally random. Therefore, in practice, it is unusual to describe textile characteristics by pore parameters. But a lot of these characteristics, for example, pore diameter, can be easily established from available fibre assembly variables. By introducing the expression “fictive pore borders” Neckar and Ibrahim [102] were able to find possible alternative theoretical definitions describing pores of any shape and type.

Even for a fibrous material made of identical fibres, i.e. the same geometrical shapes and dimensions and physical properties, the pores formed inside the material will exhibit huge complexities in terms of sizes and shapes so as to form the capillary geometry for transporting functions. The pores will even changes as the material interacts with fluids or heat during the transport process; fibres swell and the material deforms due to the weight of the liquid absorbed.

Various analytical attempts have been made to characterize the internal structures of the fibrous materials. A detailed work in this aspect was carried out by Komori and his colleagues. Komori and Makishima [104] and Komori and Itoh [105] predicted the mean number of fibre contact points and the mean fibre lengths between contacts; Komori and Itoh [106] the fibre orientations and Komori and Makishima [107] the pore size distributions of the fibre assemblies. Establishing the size and shape of pores experimentally is not an easy job. Some direct (based on evaluations of microscopic sections of the fibre assembly with image analysis) and indirect (based on the principles of capillary and fluid flow and Carman-Kozeny equation) experimental methods are available. An experimental method based on aerosol filtration of solid particles is an ISO standard [102]. Here pore size can be evaluated indirectly from the size of particle passing through the porous material.

2.8 Relationship of Fibre Properties to their Fabric Comfort Characteristics

2.8.1 Clothing comfort

Comfort is the most important aspect of clothing [108-109]. Clothing comfort can be classified into following three groups, namely, Psychological, Tactile and Thermo-physiological.

Psychological comfort bears little relation to the fabric properties and mainly related to the fashion trend prevailing in the society. Tactile comfort essentially is a result of how much stress is generated in the fabric and how it is distributed over the
skin and therefore has a strong relationship with the both mechanical and surface properties of fabric. Tactile comfort is directly related to fabric handle.

Thermal comfort is related to the fabric's ability to maintain the skin temperature and allow transfer of perspiration produced from the body. Four properties are suggested as critical for thermal comfort of a body: thermal resistance, air permeability, water vapor permeability and liquor water permeability. Thermo-physiological comfort [109-110] means the ambient body temperature of ~37°C is maintained. Whatever the heat human body produces must flow out through the clothing via the body surface. Thermal comfort doesn’t involve psychological factors. Therefore cultural background doesn’t affect the fabric preference from the thermal comfort point of view.

Saville [110] distinguished two aspect of wear comfort of clothing; firstly, Thermo-physiological wear comfort which concerns the heat and moisture transport of the clothing and the way that clothing helps to maintain the heat balance of the body during various level of activity and secondly, skin sensational wear comfort which is concerns the mechanical contact of the fabric with skin.

There are some key parameters that cause the person to feel comfort and discomfort [111]. These variables are grouped under following three separate categories:

a) Physical variables such as environment, level of activity and fibre/fabric/garment properties

b) Psycho-physiological parameter such as state of being, end uses and occasion of wear, tactile and visual aesthetic, fit etc

c) ‘Stored modifiers’ or ‘filters’ consisting of elements of all our past fantasies, experience and expectations

Thus comfort is a term that is also used loosely in describing human sensory perceptions. In short, comfort is the psychological feeling or judgement of a wearer, under certain combinations of physical activities and environmental conditions. The generation of such feeling or judgement, however, involves a number of complex processes, as shown in Figure 2.12.

Figure 2.12 shows that the overall feeling, or judgement on comfort of clothing, is derived from multidimensional sensations generated from a large number of stimuli from clothing and external environment, communicated to the brain through multichannel of sensory responses.
2.8.2 Influence of fibre parameters on thermo-physiological Comfort

Energy balance between human body and environment needed for physiological comfort is modified favorably by conscious selection of clothing material and construction parameters emphasizing the fact that functions of clothing are essential to man in all environments especially extreme weather conditions. Wear comfort of fabrics defined in terms of thermal or moisture effects [113-115] can be categorized as the thermo-physiological comfort. The heat and moisture transport properties of fabrics are so constituted that they provide a “microclimate” around the body which gives a comfortable feeling.

Woven fabrics, as a porous material, enable the transmission of energy in the form of heat as well as of substances, such as liquids (perspiration), gases (air) and therefore is suitable for different applications e.g. as summer or winter wears, depending on the level of these transmission. The extensive review on textile comfort [111] makes it clear that fibre content, yarn and fabric structure, specific fabric finish have the strongly influencing effects on heat and moisture transportation. Best-gordon [179] attempts to relate fibre type and fabric construction to comfort, but his discussion is presented only in the most general terms.
Nowadays polyester is most widely and popularly used fibres because of its some favorable characteristics namely high strength, dimensional stability, easy-care and wrinkle free characteristics but 100% polyester and polyester rich fabrics are not comfortable to wear because of its hydro-phobicity. Some attempts have been made world-wide to overcome this limitation of polyester by introducing a change in external form of the fibres. In this context, fibre fineness and fibre cross-sectional shapes as essential influencing factor in wear comfort has been the subject matter of research investigations of fabric designers [6]. Many new types of fabrics with novel features, called “Shingosen” fabrics, made from polyester fibres, have been developed in Japan by proper selection of these fibre parameters [49], as they influence physiological comfort level through thermal resistance/ transmission, moisture vapor permeability, water resistance etc apart from modifying the handle properties.

Matsudaira and Kondo [7] proved that the retention of warmth by polyester fibre is increased by making a grooved and/or hollow in fibres because of reduction of thermal conductivity of polyester fibres. In other important experimental investigation [116-117], relationship between heat conducting properties of fabrics and fibre, yarn and fabric structure and blend composition has been established. Results of wear trials showed that fibre fineness represents an essential and significant influencing factor on the wear comfort of a textile [10]. Thermal properties are essentially influenced by air permeability. An open, bulky fabric like brushed knitted fabrics may be very efficient for warmth under still-air conditions but when exposed to high wind these material lose their insulation. Whereas a denser, more wind resistance fabrics would not loose so much from its still-air condition insulation. Hence fibre geometry is of considerable importance as they govern available fibre drag surface and pore size distribution. The lower dtex of micro fibres proved to be physiologically advantageous especially in wear situations where heavy sweating occurs. In sweating conditions, wetting and wicking is the most effective process to maintain a feel of comfort. In the case of clothing with high wicking properties, moisture coming from the skin is spread throughout the fabric offering a dry feeling and the spreading of the liquid enables moisture to evaporate easily. Some research investigations [118-119] have established the relationship of fibre content, fibre geometrical features to such serviceability criteria as wicking, wettablility, and speed of capillary migration.

Peirce et al. [120] highlighting the importance of water vapor permeability stated that Since perspiration acts as a safety valve for the removal of excess heat
from the body, it is important that clothing offer a min. impedance to its evaporation. Information on the water-vapor permeability of fabrics is therefore necessary in designing efficient clothing. Among fabrics of close texture, there appears to be no correlation between air and water-vapor permeability. Apart from the doped fabrics with very high resistance, there is correlation between the resistance of a fabric and its thickness. All fabrics tested had greater resistance than still air of the same thickness. The equiv. air thickness of a nylon fabric was approx. 10 times the fabric thickness; of a cotton fabric, roughly 3 times; of the wool fabrics, roughly 1.5 times; while for an impregnated cloth (imitation leather), the ratio was more than 9000.

Some recent studies [69, 121] have also established the significance of fibre cross-sectional shapes in modifying the thermo-physiological comfort properties of fabrics.

In brief, thermo-physiological comfort is essentially dealing with all transport properties of the fabrics. Fibre properties especially fibre linear density and cross-sectional shapes affect this thermal transport by bringing a change in fabric structure. It has been observed by Yoon and Buckley [122] that thermal insulation, air permeability, and water vapor transmission rate are dependent mainly on the fabric geometrical parameters, namely, thickness, porosity and tortuosity. Porosity includes, shape, size and numbers of the pores existing in the fabrics. Conversely, liquid water transport is strongly dependent on the constituent fibres. Geometrical factors do however play a major role in this mechanism also. Following brief discussion makes clear the role of fibre geometrical parameters on various transport properties.

2.8.2.1 Wicking/ capillary flow

The behaviour of a given textile during its contact with water (or with the liquid generally) is one of the important properties of textiles. Wetting of fibre materials can critically affect many manufacturing processes as well as the end use performance of materials. The flow of liquid moisture through textiles is caused by fibre-liquid molecular attraction at the surface of the fibre materials, which is mainly determined by the surface tension and the effective capillary pore distribution and pathways [123]. Liquid transfer through a porous structure involves two sequential processes – wetting and wicking. Wetting is the initial process involved in fluid spreading. In this process the fibre-air interface is replaced with a fibre-liquid interface as shown in Figure 2.13(a). The forces in equilibrium at a solid-liquid boundary are commonly described by the Young-Dupre equation, as given by Kissa [124] is shown in Equation (2.12).
\[ \gamma_{sv} - \gamma_{sl} = \gamma_{lv} \cos \theta \]  

here, \( \gamma \) represents the tension at the interface between the various combinations of solid (S), liquid (L) and vapour (V), and \( \theta \) is the contact angle between the liquid drop and the surface of the solid to be wetted as shown in Figure 2.13 (b).

The contact angle is a direct measurement of the fabric wettability. A low contact angle between the fibre and the liquid means high wettability [131]. With an increase in surface roughness, the spreading of water along the surface becomes faster due to the troughs offered by rough surfaces as the apparent wetting angle is decreased. The wettability of the material also changes with the chemical nature of the surface and so with an increase in hydrophilicity, the contact angle is reduced (Table 2.10), thus increasing the surface wettability [125].

Another parameter quantifying what we call degree of wetting- is the net attraction between solid and liquid, usually called the work of adhesion, \( W_{sl} \) [32] is also shown in Table 2.10. This too is dependent on part on the nature of the solid surface. As the roundness and the diameter of the fibres are reduced, the cosine values of the advancing angle increase, thus increasing the surface wettability.

![Figure 2.13(a): Equilibrium state of a liquid drop on a solid surface [127]](image)
An alternative experimental approach, based on Wilhelmy balance principle and was first described by Collins [129], introduced a term Wetting force \( F_w \), which can be defined as the pull exerted on a vertical rod (i.e. filament or fibre) when it is inserted into a liquid.

\[
F_w = P \ Y_{lv} \ \cos \theta
\]  

(2.13)

Where, \( P \) is the perimeter of the solid along the three phase boundary line. This pull can be downward when the liquid rises up the solid or it can be a push upward when the meniscus is depressed at the inter-phase boundary. Normalizing for the length of contact between filament and liquid, we can describe a characteristic specific wetting force ‘\( w \)’ as shown in Equation (2.14).

\[
w = \frac{\text{Force per filament}}{\text{Perimeter of filament}} = \frac{F_w}{P} = Y_{lv} \ \cos \theta
\]  

(2.14)

Figure 2.14 illustrates this concept in terms of forces acting on the fibre before and after contact. In addition to wetting force, any significant immersion of the fibre in the liquid will induce a buoyancy force \( F_b \). The measurement of wetting force will be influenced by the shape of the fibre end i.e. fibre cross-section. Since Wilhelmy wetting force is the weight of the liquid clinging to the filament which is proportional to the surface area of the filament.
In sweating conditions, wicking is the most effective process to maintain a feel of comfort. In the case of clothing with high wicking properties, moisture coming from the skin is spread throughout the fabric offering a dry feeling and the spreading of the liquid enables moisture to evaporate easily. When the liquid wets the fibres, it reaches the spaces between the fibres and produces a capillary pressure. The liquid is forced by this pressure and is dragged along the capillary due to the curvature of the meniscus in the narrow confines of the pores as shown in the Figure 2.15. The ability to sustain the capillary flow is known as wickability [130].

The magnitude of the capillary pressure [127] is given by the Laplace Equation 2.15.

\[ \Delta P = \frac{2\gamma_{lv} \cos \theta}{r} \]  

(2.15)
Where $\Delta P$ is the capillary pressure developed in a capillary tube of radius $r$. A difference in the capillary pressure in the pores causes the fluid to spread in the media. Accordingly, the smaller the pore size, the greater is the pressure within the capillary, and so the smallest fill first. During draining of the capillary under external pressure, the smaller pores drain last.

The transport of liquid into a fibrous assembly, such as a yarn or fabric, may be caused by capillary forces only. The capillary forces drive the liquid into the capillary spaces. The capillary spaces in yarns and fabrics are not uniform. Further, fibrous materials encounter roughness on the surfaces and walls of the pores. A liquid may spread along grooves or rugosities on a surface, even if it does not spread on a smooth surface of the same solid. The driving force for such surface wicking depends on the geometry of the grooves, surface tension of the liquid and free energies of the solid-gas and solid-liquid interfaces [127].

For theoretical treatment of capillary flow in fabrics, the fibrous assemblies are usually considered to consist of a number of parallel capillaries. The movement of the liquid in a non-homogeneous capillary system, such as a fibrous assembly, is discontinuous. The wetting front advances into the capillary system in small jumps because the irregular capillary spaces have various dimensions. Most textile processes are time limited, and the rate of wicking is therefore important. However, the wicking rate is not solely governed by interfacial tensions and the wettability of the fibres, but by other factors as well. The wicking rate depends on the capillary dimensions of the substrate which depends on fibre form and geometry.

The mass rate ($M$) at which a liquid moves through a porous channel is related to the pressure difference ($p$) across the channel by Poiseuille’s law [127] as

$$M = \pi \rho \eta r^4 / 8 \eta h$$

If the pressure difference $p$ is due to capillary forces, then

$$M = \pi \rho r^3 \gamma_w \cos \theta / 4 \eta h$$

The volume rate ($V$) is

$$V = \pi r^3 \gamma_v \cos \theta / 4 \eta h$$
Linear rate of flow (u) is

\[ u = \frac{dh}{dt} = r \gamma \cos \theta / 4 \eta h \]

Where h is the height of the liquid rise in the capillary channel.

The distance travelled by a liquid flowing under capillary pressure, in horizontal capillaries, is approximately given by the Washburn-Lukas equation [131]:

\[ L = \left( \frac{r \gamma \cos \theta}{2 \tau^2 \eta} \right) t^{1/2} \]

(2.16)

Where, L is the capillary rise of the liquid in time t and η is the viscosity of the liquid and τ being the tortuosity factor. The amount of water that wicks through the channel is directly proportional to the pressure gradient. The capillary pressure increases as both the surface tension in the solid-liquid interface and the capillary radius decrease.

A textile material consists of open capillaries, formed by the fibres walls [132]. From the Lukas-Washburn equation, it is expected that capillary rise at a specific time will be faster in a medium with larger pore size. However, Miller [133], using a comparative wicking study, showed that this is not always the case. He found that higher initial wicking through the capillaries with bigger diameter has been overtaken with time by the capillaries with smaller diameter. A larger amount of liquid mass can be retained in larger pores but the distance of liquid advancement is limited. This may be explained by the Laplace equation, as the radius of the capillary decreases, the pressure generated in the capillary will be higher, causing faster flow through the capillary. The model developed by Rajagopalan and Aneja [134] also predicts that at a constant void area, increasing the perimeter of the filaments increases the maximum height attained by the liquid. Conversely, increasing the void area at a constant perimeter decreases the final height attained, but increases the initial rate of liquid penetration. With the increase in the packing coefficient of the yarn, the fibres come closer to each other introducing a greater number of capillaries with smaller diameter likely to promote liquid flow. In any system where capillarity causes relative motion between a solid and a liquid, the shape of the solid surfaces is an important factor, which governs the rate and direction of liquid flow [135]. The shape of the fibres in an assembly changes the size and geometry of the capillary spaces between the fibres and consequently the wicking rate. With an increase in the non-roundness of a fibre,
the specific area increases, thus increasing the proportion of capillary wall that drags the liquid.

The tortuosity [136] of the pores has a great influence on the wicking process. It depends on the alignment of the fibres as well as on irregularities in the fibre diameter or shape along the pores. With an increase in the tortuosity of the pores, its wicking potential is reduced [137-139]. For instance, yarns spun with natural fibres have very irregular capillaries due to various factors such as fibre roughness, cross-sectional shape and limited length, which interrupt the flow along the length of the yarn [139]. In the case of textured filament yarns, as the number of loops in the yarn increases, the continuity of the capillaries formed by the filaments decreases as the filament arrangement becomes more random. Under these conditions wicking is reduced. The same explanation is also applicable to the slower wicking found in twisted yarns. During the spinning process, at higher twist levels, slow migration of fibres takes place along the yarn structure, changing the packing density and resulting in disruption of the continuity, length and orientation of the capillaries. The twist direction has no significant effect on the yarn wicking performance. The presence of a wrapper filament also retards wicking as the volume of liquid in the capillaries is reduced [140]. The density and geometry of fabric pores, which can be varied according to woven fabric structure, has a significant influence on the liquid flow pattern, both in the interstices and downstream [136, 141].

Darcy’s law [127] is used to describe a linear and slow steady state flow through a porous media, and is given by Equation (2.16). The rate of flow (Q) changes directly with the pressure head (∆P) and is inversely proportional to the length of the sample (L₀) in the direction of flow:

\[ Q = -K \frac{\Delta P}{L_0} \quad (2.17) \]

K is the proportionality constant, known as the flow conductivity of the porous medium with respect to the fluid. K is dependent on the properties of the fluid and on the pore structure of the medium [142]. Hydraulic conductivity can be written more specifically in terms of permeability and the properties of the fluids as shown in Equation (2.18).
Where, \( k \) is the permeability of the porous medium and is normally a function of the pore structure \([66, 143]\) and \( \eta \) is the viscosity of the liquid. Capillary pressure and permeability are the two fundamental properties used to predict the overall wicking performance of a fabric \([133]\). The capillary pressure decreases with an increase in the saturation as the pores fill with liquid and decreases to zero for a completely saturated media. The permeability of the media increases with an increase in the saturation, due to the higher cross sectional area of the absorbed water film to flow \([125]\). At low saturation level, smaller pores in the media fill up first than larger pores. According to Adler \([144]\) wicking cannot begin until the moisture content is very high. Fast liquid spreading in fibrous materials facilitated by small, uniformly distributed and interconnected pores. On the other hand, high liquid retention can be achieved by having a large number of pores or a high total pore volume \([130, 145]\).

The dynamic surface wetness of fabrics, as described by Scheurell et al. \([146]\), is an important parameter influencing the skin contact comfort in actual wear, as it is influenced by both the collection and the passage of moisture along the fabric. The dynamic surface wetness of fabrics has been found to correlate with the skin contact comfort in wear for a variety of types of fabrics, suggesting that the mobility of thin films of condensed moisture is an important element of wearing comfort. In the case of a cotton fabric, even though the moisture uptake from the skin is high due to high wettability, the dynamic surface wetness is not very good, as due to low capillarity, the passage of moisture is not spontaneous. It collects moisture in spite of flowing it out. As a result, it creates a clammy feeling in high sweating condition.

In the case of normal polyester fibre fabrics, even though capillarity is good, due to poor wettability they are not comfortable to wear. In the case of polyester microdenier fibre fabrics, the water uptake is high and due to the high number of capillaries a large amount of moisture can pass very quickly through them to the atmosphere, thus providing a dry and comfortable feeling to the wearer.

Wicking behavior of the fibrous structures is a critical aspect of the performance of the products such as sports clothes, hygiene disposable materials and medical items. Immersion, capillary sorption, adhesion and spreading are the primary processes involved in wetting of fibrous material. Transport of a liquid into a fibrous assembly may be caused by external forces or by capillary forces only.
Capillary penetration of a liquid can occur from an infinite (unlimited) or limited (finite) reservoir. Wicking processes from an infinite reservoir are immersion, tranplaner wicking and longitudinal wicking. Wicking from a limited reservoir is exemplified by a drop placed onto the fabric surface. The pores within the structure are responsible for the liquid flow through a material and the size and connectivity of the pores in the fabric influence how fast and how much liquid is transported through the material. Hsieh through his observations [147-148] reported that, in the case of woven, non-woven and knitted fabrics, a distribution of pore sizes along any planer directions is expected. Hsieh [149] has also shown that with poor wetting, many pores in fabrics are not filled by water due to the effect of reduced \( \cos \theta \) in driving the water into the pores, e.g. with polyester fabrics. When liquid moves into a fibre assembly, the smaller pores are completely filled and liquid then move to the larger pores. The sizes and shapes of fibres as well as their alignment will influence the geometric configurations and topology of the pores, which are channels with widely varying shape and size distribution and may or may not be interconnected [148-151].

The shape of fibres in an assembly affects the size and geometry of the capillary spaces between fibres and consequently the wicking rates. The flow in capillary spaces may stop when geometric irregularities allow the meniscus to reach an edge and flatten [124]. The distance of liquid advancement is greater in a smaller pore because of the higher capillary pressure, but the mass of the liquid retained in such a pore is small. A larger amount of liquid mass can be retained in larger pores but the distance of liquid advancement is limited. Therefore, fast liquid spreading in fibrous materials is facilitated by small, uniformly distributed and interconnected pores, whereas, high liquid retension can be achieved by having a greater number of large pores or a high total pore volume [149].

Wicking is affected by the morphology of the fibre surface, and may be affected by the shape of the fibres as well. Fibre shape does not affect the wetting of single fibre. However, the shape of the fibres in a yarn and fabric affect the size and geometry of the capillary spaces between the fibres, and consequently, the rate of wicking. Randomness of the arrangement of the fibres in the yarns considerably influences the amount of water and transport rate of the fabrics. Wicking fabrics are modern technical fabrics which draw moisture away from the body. They are made of high-tech polyester, which, unlike cotton, absorbs very little water. Cotton will absorb 7% of its weight in water, polyester only 0.4%. Cotton will therefore hang onto your sweat, making your garment heavy and unpleasantly clammy. Wicking polyester has
a special cross-section and a large surface area, which picks up moisture and carries it away from your body, spreading it out, to evaporate easily on the outside of the fabric. So you stay cool and dry.

Classical capillary theory, based on equivalent capillary tubes, is readily applied for yarns and woven fabrics, because they are compact with a porosity in the range of 0.6-0.8 and have better defined fibre alignment. Further, wicking in woven fabrics is mainly concerned with liquid movement in between the fibres in the yarn [152] and the larger pores that exist between the yarns are therefore less important [153].

On the basis of his experimental data Steinlin [154] proved that the amount of dye necessary to obtain a definite depth of shade varies whenever the fibre fineness changes and the shape of the fibre cross-section remains the same. He also pointed out that the amount of dye to be applied must be corrected in inverse proportion to the square root of the fibre fineness. He further postulated that when the fibre fineness remains unchanged and the shape changes, there is a clear mathematical relationship between the dimensionless shape index and depth of colour produced by mass dyeing pigments. His discussion was centered on the interaction of the two factors of fibre fineness and filament profile. He stated that in changing from a round-section to a trilobal-section, for example, a 40-90% increase in pigment added is needed to maintain the shade. The shape index factor is useful in quality control of the fibre.

2.8.2.2 Thermal resistance, moisture diffusion and air permeability

The clothing system plays an important role in human thermal responses because it determines how much of the heat generated in the human body can be exchanged with the environment. The heat and moisture vapor transport processes are not only of diffusion type but are also enhanced by the ventilating motion of air through the fabric, initiated by the relative motion of the human with respect to the environment.

As a multiphase system, all the thermal transfer processes become possible, depending on the construction and environmental conditions. Theoretically, thermal conduction always happens as long as a temperature gradient is present between a material system and the environment. When that temperature gradient is small, heat transfer via radiation can be ignored. Furthermore, if the fibre volume fraction is high enough, convection is suppressed by the tiny pores between fibres. Consequently thermal conduction turns out to be the only or the most dominant heat transfer mechanism.
For a given material properties, the classical three dimensional conduction equation for constant pressure processes is obtained [103] as:

\[
\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \Phi + \frac{\Phi}{\rho c_p} \tag{2.19}
\]

\[
\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\Phi}{\rho c_p} \tag{2.20}
\]

Where 
\(k\) = thermal conductivity, material property
\(\alpha\) = thermal diffusivity, a combined material property
\(\Phi\) = heat generating rate in the material
\(\rho\) = density
\(c_p\) = specific heat

Systems with fibres are generally heterogeneous. For example textile fabrics are a mixture of fibres and air. Internal structure, properties of each component and interactions among components, will determine the behaviors of the whole heterogeneous material. The effective thermal conductivity depends not only on the properties of each component, but also on the way those components are assembled into the whole system, i.e. the internal structure and the interactions among the individual components. The structure of fibre assemblies is decided by single fibre structure including longitudinal and transverse length, and ratio between them, geometry of cross-sections, crimp of fibres, and so on. After that, distribution of fibres and connection between them.

The perceived warmth through contacting, results from our tactile sense and is a reflection of contact transient, is actually related to the so called effusivity \(\varepsilon = \sqrt{kpc_p}\) of material, where \(k\) is the thermal conductivity (W/m K), \(\rho\) is the density (kg/m\(^3\)) and \(c_p\) is the specific heat capacity (J/kg K) of the material. A surface with a higher effusivity value feels cooler. In fact, effusivity deals with the heat exchange between substances through interfaces, whereas conductivity describes the ability of that substance to transfer heat. Obviously the narrow range of the thermal conductivities \(k\) of various textile fibres (0.1-0.3 W/m K) cannot account for the vast scope of the cooling sensation received by touching different fabrics. It is the material density \(\rho\) and the specific heat capacity \(c_p\) that are responsible. Since both are either determined by, or are heavily dependent upon, the structural details of the fabric, this explains why fabrics made of the same fibre often exhibit entirely different skin contact sensations.
Moisture diffusion is the process during which water molecules migrate through given materials. For homogeneous material, the results of certain thermal conduction problems can be readily transcribed into solutions of the corresponding mass diffusion process by changing parameters and variables. For multi-component systems such as fibrous materials, the system diffusion behavior is determined by the resultant of each, often different, behavior of the multi-components. For instance, in a fibrous material, moisture diffusivity in the solid fibre is much smaller than in air, and the system behavior is not equal to that of either fibre or air. The migration of liquid water in fabrics is determined by other mechanisms and will not be analyzed in the context of the diffusion process. On the other hand, the governing equations for thermal conduction and moisture diffusion processes are built on a requirement for balance, thermal conduction is based on energy conservation and moisture diffusion requires mass conservation, although the mass diffusivity of moisture in air is much larger than it is in the fibre, whereas the thermal conductivity of fibres is larger than that of air. Textile fabrics are composed of fibres and air in voids. Under certain concentration gradients, the main contribution to moisture flux is from the diffusion process through the air voids. But it has been shown that adsorption of moisture by fibres will also affect the response of fabrics to the moisture gradient [155]. Hence there is some difference between the diffusion process in non-hygroscopic and hygroscopic fibres. But it has been observed by some researchers [111, 120, 156] that the water vapour transport under steady state generally takes place through the air spaces in the fabric and that moisture sorptive capacity of the fabrics does not play any significant role.

Non-hygroscopic fibres can be treated as an inert phase during the moisture diffusion process. That implies this mass transfer process can be approximated as one happening in a single phase system such that a simple representation is widely applied for porous media with an inert solid phase,

$$D_{eff} = \varepsilon D_a / \tau$$  \hspace{1cm} \text{(2.21)}$$

Where $D_a$ is the moisture diffusivity in bulk air; $\varepsilon$ and $\tau$ are porosity and tortuosity, respectively. Intuitively, this simple equation is established by treating $\varepsilon$ and $\tau$ as correction terms, accounting for reduced diffusion area and blockage of diffusion path. Tortuosity is a dimensionless parameter that characterizes the deviation of the diffusion path from a straight one.
However, many commonly used fibres, e.g. cotton, viscose and wool, are hygroscopic and the responses of hygroscopic fabric under moisture gradients is much more complex due to interactions between moisture and fibres [155]. After the initial wetting process, so that the system is in a steady state, fibres are saturated and diffusion through the air void becomes a dominating process, except that swollen fibres lead to a smaller free space.

The fabric transport property most sensitive to fabric structure is air permeability, defined as the volume flow rate per unit area of a fabric when there is a specified pressure differential across two faces of the fabric. Goodings [157] developed an expression relating air permeability to the fabric structure by assuming that air flows predominantly through inter-yarn pores and inter-yarn pores can be viewed as cylindrical holes perpendicular to fabric surfaces. When the pressure drop (Δp) across the fabric surface is low, the expression can be written as

\[
\frac{Q}{\Delta p} = \frac{1}{8 - \mu NL} \beta^2
\]

Where \( Q \) = air flow rate per unit fabric area , 
\( L \) = fabric thickness 
\( N \) = number of pores per unit area  
\( \mu \) = air viscosity

Goodings’ treatment clearly shows that air permeability is related only to the fabric geometrical parameters.

In their investigation, Tyagi et al. [69] have found out that the Non-circular polyester fiber produces fabrics with higher air-permeability, higher water-vapor transmission, higher absorbency, higher thermal insulation and higher wickability. Nevertheless, polyester-viscose fabrics are superior to polyester-cotton fabrics in respect of all these characteristics except thermal insulation.

2.8.3 Influence of fibre cross-sectional shapes and fineness on sensorial comfort

Fabric Hand and Tailorability characteristics are of immense assistance to fabric designers who are looking for a specific product for a particular end use. Textiles differ from other technical structures in that it must have sufficient strength and at the same time it has to be flexible, elastic and easy to pleat and shape. Very important criterion when you evaluate textiles in traditional apparel use is that the
fabric and the garment are comfortable in aesthetic and in physiological sense. The phenomenon of appearance, comfort sensation (handle) during wear and handling of fabrics during garment manufacturing is accompanied by two types of deformations (low magnitude or low stress) i.e. in-plane deformations (The 2-D deformations along with the cloth surface plane in warp, weft and shear) and Out-of-Plane deformations (bending deformations; the 3-D surface curvature for warp and weft). Considerable work\textsuperscript{194-201} has been reported on the study of these deformations of the woven fabrics emphasizing their mechanisms, influence of constructional parameters and establishing their association with subjective assessment of touch feeling. Lindberg et al. \textsuperscript{[158]} and Gibson et al. \textsuperscript{[159]} recorded the bending and shear behavior of a wide range of commercially produced fabrics forming a “Fabric Map” so that they can be positioned on the map relating to its tailorability.

Recent development in the objective evaluation of fabric handle has indicated clearly the importance of the low load deformation properties. Earlier Schwartz \textsuperscript{[160]} and Brand \textsuperscript{[161]} considered fabric hand as a subjective property. In the direction of evaluating fabric hand objectively, pioneering work of Peirce \textsuperscript{[162]} has been a breakthrough which quantified the relationship between measurable fabric properties and hand. Later on Kitazawa and Susami \textsuperscript{[163]}, Mahar T J et al. \textsuperscript{[164]}, Howorth W S et al. \textsuperscript{[165]} and Kawabata \textsuperscript{[166-167]} analysed hand of a fabric into its mechanical property components from objective measurements of constituent physical characteristics under the conditions (low stress conditions) appropriate for the assessment of aesthetic characteristics Later on correlation equations were developed to predict the potential performance of the fabrics in garment manufacturing, garment appearance in wear, subjective hand values using these properties.

There are various elements like fibre characteristics, yarn types, fabric constructions, method and type of dyeing and finishing processes, affecting fabric hand. A manifestation of this possibility has been the Shingosen fabrics introduced by Japanese producers. The fascinating handle of these fabrics have been investigated and shown that they resembled with ordinary polyester fibre, natural silk, cotton and wool fabrics \textsuperscript{[168-173]} by using the objective evaluation method of fabric handle developed by Kawabata \textsuperscript{[166, 174]}.

In the quest of obtaining the novel handle features, it was proposed and practically demonstrated by various fibre manufacturers that keeping all construction parameters of yarn and woven fabrics at some fixed level, it is the fibre form that can effect a remarkable change. fibre length, cross-section, surface structure, fineness,
density and resulting yarn uniformity all have an important effect on the suitability of textile products to their applications.

The effect of fibre parameters especially fineness and cross-sectional shapes have been prominently highlighted [6, 48, 180]. In his investigation, Matsudaira [48, 180] established that the silky touch was brought out by mainly by the technique of irregular shapes of fibre cross-sections and Peach-face effect by using ultra-fine fibres.

The way in which new special fibres influence the handle and tailorability is of special interest. Some studies [48, 58, 180], have demonstrated this fact with supporting data. Micro Fibres possess soft handle, silky appearance, good air permeability and exceptional drape [10]. In order to clarify the effects of different fibre cross-sectional shapes on fabric mechanical properties and handle; Polyester “Shingosen” fabrics of different fibre cross-sections were investigated using the KES-FB system [48].

2.9 Developments in Polyester Fibre Technology

Polyester fibre appeared significantly on the market in the first half of the 1960 and its steady expansion has been much due to the continuous efforts to meet the general demand for good natural fibres. As early as the 1960s, there were quite a few attempts to mimic natural silk. A trilobal cross-section was adopted to make the feel and luster of synthetic fibre similar to those of silk [6]. In 1977 and 1978, alkali-weight-reduction technology was introduced to provide a natural silk like drape. The polyester-fibre georgette however was unable to reproduce the softness and fullness of natural silk sufficiently to satisfy consumers. During 1980s, the Japanese synthetic-fibre industry started concentrating on the development of high-value added products. The fibre and textile technology was refined to allow synthetic fibres to possess not only a texture and hand similar to those of silk, wool or cotton but also other favorable characteristics specific to synthetic fibres. The characteristics of the new polyester-fibre fabrics are very distinct from those of conventional polyester-fibre fabrics, even surpassing silk or wool to some extent with respect to hand, drape and shape stability. These new fabrics are termed as Shingosen, which is a group of products of novel fabric characteristics developed with the concepts summarized in Table 2.11.
Table 2.11 Shingosen and its characteristics [49]

<table>
<thead>
<tr>
<th>Sr No.</th>
<th>Concept Class</th>
<th>Characteristics</th>
<th>Technology Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Super-soft Material</td>
<td>Peach-skin appearance and touch, micro-powder touch</td>
<td>Ultra-fine filament, microwave structure by self-shrinkage</td>
</tr>
<tr>
<td>2</td>
<td>Super-bulky material</td>
<td>Silk-like characteristics with more voluminous hand and drapability, dry scooping feeling characteristics</td>
<td>Alkali weight reduction, blended yarn of different shrinkage, non-circular cross-section</td>
</tr>
<tr>
<td>3</td>
<td>Worsted-type material</td>
<td>Wool-like characteristics and hand feel with crispness and stiffness</td>
<td>False twisting after air jet entanglement of yarns of different characteristics</td>
</tr>
<tr>
<td>4</td>
<td>Super-drape material</td>
<td>Rayon-like dry touch and heavy drape</td>
<td>High density and dry touch by adding inorganic microparticles</td>
</tr>
</tbody>
</table>

It can be easily seen that shingosen technology is based on existing technologies and covers the technologies in each step from the production of polymer materials to dyeing and processing. Thus it is clear that a new fabric could be developed with a pre-fixed concept. Up to the 1980s, the concept was to imitate natural fibres with fibres often referred to as ‘Silk-like’, ‘wool-like’, and ‘cotton-like’. Shingosen resulted from the paradigm shift from -like to super-. Shingosen has a distinct hand, different from that of any natural fibre, and this paradigm shift removed the conventional barrier restricting the concept of the desirable characteristics of synthetic-fibre fabrics.

This evolutionary development of polyester fibre technology gives the impression that among so many developments, two technical innovations have been the factors that ignited the technological revolution and recombination leading to the production of novel fabrics. One is the ultra-fine polyester fibre of less than 0.6 denier (0.67 dtex), and another is the fibre possessing a non-circular cross-section.

2.10 Summary

The functions and uses contributed by different fibre forms are innumerable. The fibre form has a strong influence on the physical properties, aesthetics and comfort of fabrics. The wide range of sizes, and shapes in which it can be produced, as well as its competitive price, ensure its continued versatility and consumer acceptance. At the same time, effective textile and structural design should be followed so that the new materials can fully perform their function capacity. So there is vast potentiality and
scope to gather the information on various fibre forms, which can be helpful in designing textile products suitable for different end uses.