

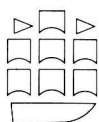
Textile science

An explanation of fibre properties

E. P. G. Gohl and L. D. Vilesky

Textile science

E.P.G. Gohl
L.D. Vilensky



Longman Cheshire

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Foreword

This book is intended to assist senior high school students, technical college students, and all those engaged in the various branches of the textile and clothing industry. It brings together in one volume the explanations which have become generally accepted for the chemical and physical properties, dyeing, printing and chemical finishing of textile fibres. As well, it fills the existing gap between simpler texts and more esoteric texts and learned articles on textile fibres.

It is hoped that the technically and scientifically more sophisticated reader will acknowledge the judicious use of generalisations to which we have had occasionally to resort. These generalisations have kept the book within its intended scope. However, should there be any errors, omissions, or suggestions for improvement of the subject matter presented, we would appreciate hearing of these.

A book of this nature cannot become a reality without the assistance and co-operation of many. For this reason, we would like to express our gratitude to Longman Cheshire Pty Limited for publishing it; to Ms Jane Bohrsman of Longman-Cheshire Pty Ltd for her painstaking interest in what we wrote to ensure that it would be understandable; to Julie Mattick, who typed much of the manuscript, as did Myriam Vilensky; to the many authors of books and scientific papers on textile fibres and related topics which the authors have read over the years and whose accepted theories and postulations are reflected in our explanations; and, finally, to the many firms and organisations, acknowledged elsewhere, who generously and willingly gave their permission to reproduce sundry material.

E.P.G. Gohl
L.D. Vilensky
1979

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Chapter 1 **Introduction to fibre polymers and fibre properties**

The purpose of this chapter is to provide an introduction to polymers, and their effect on the properties of fibres.

One may wonder at the many and varied properties of fibres, yarns and fabrics that have been produced, particularly since the advent of man-made fibres. One may ask what it is that makes a material suitable for use as a textile fibre. Why is it that the properties of textile fibres vary so widely? Examples of fibre properties are strength, elasticity, moisture absorbency, thermal properties, resistance to chemicals, dyeability. To answer these questions, one has to examine closely certain characteristics of the structure of textile fibres.

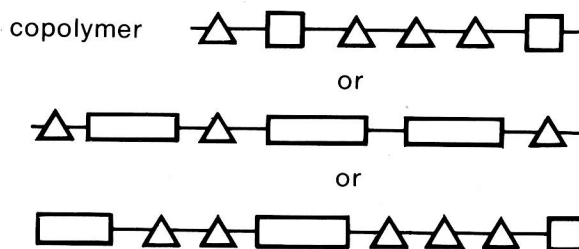
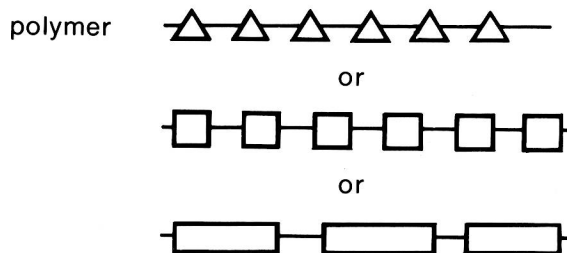
Until the introduction of man-made fibres, we had to rely on fibres from natural sources. However, not all of these fibres were suitable for use as textile fibres because they lacked certain essential properties; that is, they were not long, flexible or strong enough. Natural fibres are affected by soil, feed, and climatic and other environmental conditions. These conditions result in natural fibres having non-uniform properties. Because it is possible to exercise much greater control over the production of man-made fibres, conditions such as these do not affect the properties of man-made fibres. However, even with this greater control, slight variations in the production of man-made fibres can give rise to slight variations in strength, dyeability and some other properties.

The basic unit of the textile fibre and polymerisation

The basic unit of the textile fibre is a molecule or a **monomer** (*mono* = one, *mer* = unit). In natural fibres many of these basic units are connected to form long chains which are called **polymers** (*poly* = many). The process of chemically joining monomers to form polymers is called **polymerisation** and the length of such chains is referred to as the **degree of polymerisation** (DP). The DP of natural fibres is determined by nature. Cotton, for example, has a degree of polymerisation of about 5 000; that is, there is an average of about 5 000 basic units in a chain or polymer of cotton. The DP of all man-made fibres is determined during the production of these fibres. The DP of regenerated cellulosic fibres, such as cuprammonium rayon, is about 250, and for viscose rayon, about 175.

Should the polymer be formed from two or more different monomers, it is called a **copolymer**. There is no definite regularity in the order of monomers which make up a copolymer. As well, in order to improve dye affinity of the fibre for instance, some fibres contain an additional monomer which does not form part of the polymer. It is specially **grafted** onto the polymer chain. The acrylic fibre Zefran is an example of polymer graft-

a monomer \triangle or \square or rectangle



Note. There is no definite regularity in the arrangement of the monomers in copolymers.

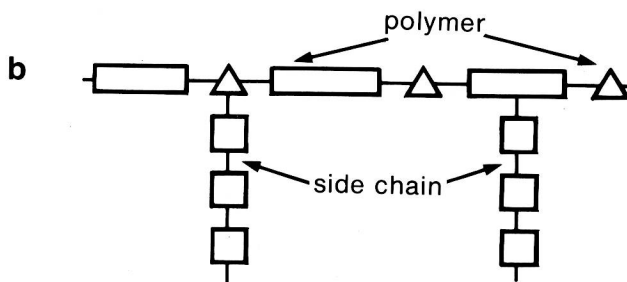


Fig. 1.1

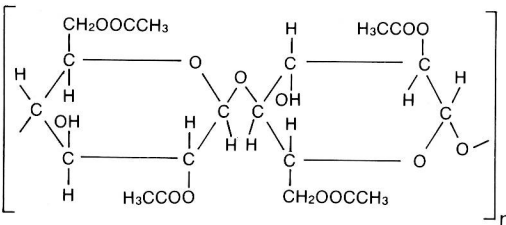
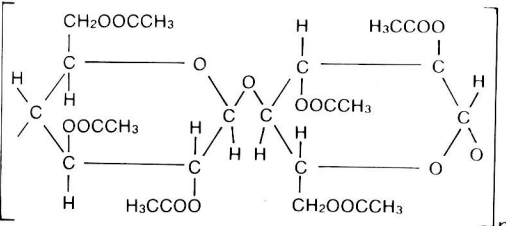
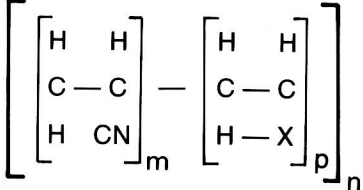
a In this diagram different types of monomers are represented by a triangle, a square and a rectangle. These are then used to represent a polymer and a copolymer. Note that there is no regularity in the arrangement of monomers in a copolymer.

b Side chains, side groups or branches grafted onto a polymer forming a grafted polymer.

ing. Fig. 1.1 shows monomers, polymers, copolymers and a polymer graft. See also Table 1.1

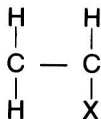
Table 1.1 summarises the chemical composition and structure of the most commonly used textile fibres. Explanations of the chemical terms used can be found in the Glossary and in the text. Should further information be required, refer to E.B. Uvarov, *The Dictionary of Science*, Penguin Books.

Table 1.1 Chemical composition and structure of the most commonly used textile fibres.

Fibre	Basic unit or monomer	Polymer
Acetate	<p>The hydroxyl groups on the cellulose polymer are acetylated to the degree that the <i>acetate or secondary cellulose acetate polymer</i> has less than 92 per cent but at least 74 per cent of its hydroxyl groups acetylated; that is, 2.3 to 2.4 of the OH-groups per glucose unit are acetylated. This is usually shown as 4 acetate groups per cellobiose unit.</p> <p>The <i>triacetate or primary cellulose acetate polymer</i> has at least 92 per cent of its hydroxyl groups acetylated. In general, this is shown as 6 acetate groups per cellobiose unit.</p>	 <p>The <i>acetate or secondary cellulose acetate polymer</i>, which has a degree of polymerisation of about 130 units; that is, $n = 130$.</p>  <p>The <i>triacetate or primary cellulose acetate polymer</i>, which has a degree of polymerisation of about 225 units; that is, $n = 225$.</p>
Acrylic	<p><i>Acrylic</i></p> <p>At least 85 per cent of the mass of the acrylic fibre must be composed of <i>acrylonitrile monomers</i>; that is,</p> $\begin{array}{c} \text{H} & \text{H} \\ & \\ \text{C} & - & \text{C} \\ & \\ \text{H} & \text{CN} \end{array}$	 <p>The <i>acrylic polymer</i>. The values of m and p depend upon the mass of copolymer present; hence, whether it will be an acrylic or a modacrylic polymer fibre. The degree of polymerisation is about 2 000 units; that is, $n = 2\ 000$.</p>

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and no more than 15 per cent is composed of the *copolymer*; that is,

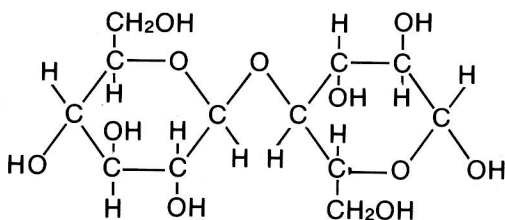


where X is usually an anionic radical.

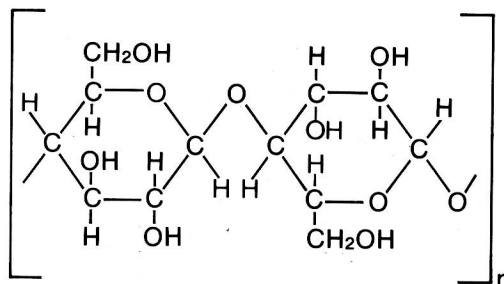
Modacrylic

At least 35 per cent but no more than 85 per cent of the mass of the modacrylic fibre polymer must be composed of *acrylonitrile monomers*, and the remainder is composed of the *copolymer*.

Cotton



Cellobiose, the basic unit of cellulose.



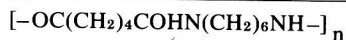
Cellulose, the polymer of cotton, with a degree of polymerisation of about 5 000 cellobiose units; that is, $n = 5\,000$.

Elastomeric The complexity and length of the elastomeric monomers and the repeating units of their polymers makes it impossible to reproduce them satisfactorily within the confines of this table. Refer, therefore, to the section on elastomeric fibres in Chapter 5, 'The Synthetic Fibres' for the two types of elastomeric monomers and polymers; that is, the polyester and polyether types.

Flax Cellobiose — see 'cotton' for chemical formula details.

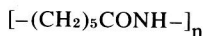
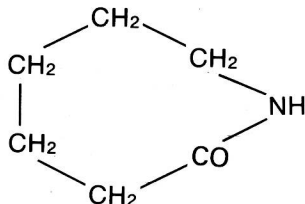
Cellulose is also the polymer of flax, with a degree of polymerisation of 18 000 cellobiose units; that is, $n = 18\,000$. See 'cotton' for chemical formula details.

Nylon For *nylon 6,6* the monomers are *adipic acid*; that is,
 $\text{HOOC}(\text{CH}_2)_4\text{COOH}$
 and *hexamethylene diamine*; that is,
 $\text{H}_2\text{N}(\text{CH}_2)_6\text{NH}_2$.



Polyhexamethylene diamino adipate, the repeating unit of the *nylon 6,6 polymer*, with a degree of polymerisation of 50 to 80 units; that is, $n = 50$ to 80.

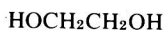
For nylon 6 the monomer is *caprolactam*; that is,



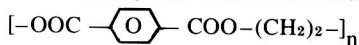
Polycaprolactam, the repeating unit of the *nylon 6 polymer*, with a degree of polymerisation of 200 units; that is, $n = 200$.

Polyester

The monomers of the most common polyester are *ethylene glycol*; that is,



and *terephthalic acid*; that is,



Polyethylene terephthalate, the repeating unit of the *polyester polymer*, with a degree of polymerisation of 115 to 140 units; that is, $n = 115$ to 140.

Rayon

Cellulose is the basic unit of the polymers of *cuprammonium rayon*, *polynosic rayon*, and *viscose rayon*. See 'cotton' for chemical formula details.

Cellulose, in regenerated form, is the polymer for the different rayon fibres, having a degree of polymerisation of about:

250 cellobiose units; that is, $n = 250$, for *cuprammonium rayon*;

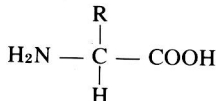
300 cellobiose units, that is, $n = 300$, for *polynosic rayon*;

175 cellobiose units, that is, $n = 175$, for *viscose rayon*.

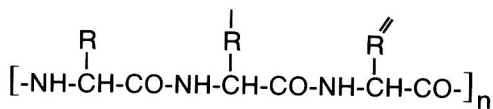
Silk and wool

The *silk fibroin polymer* is composed of 16 different amino acids, whilst the *wool keratin polymer* is composed of 20 different amino acids.

Amino acids have this general formula:



where R = a radical, which is different for each of the 20 known amino acids.



The general formula for the *polypeptide polymer*.

Depending upon the type of radicals, that is, R , R' , R'' , etc. the polypeptide polymer would be identified either as being a *silk fibroin polymer* or a *wool keratin polymer*.

The degrees of polymerisation for silk and wool are not known.

The polymer system

The development of man-made fibres occurred when it was realised that natural fibres consisted of polymers held together by various links or forces, which will be described

later. The development of regenerated fibres was the first step toward producing 'artificial' fibres. They evolved from regenerating or reforming an available natural polymer; for example, cellulose is reformed to produce viscose rayon. The next step was to produce chemicals which had the ability to form links giving rise to polymers.

The chemicals which have this ability can be broadly divided into two categories:

- 1 Those which join with each other to form a polymer, with the loss of a small compound such as water or hydrogen chloride. This process is called **condensation polymerisation**. Fibres formed by this technique are elastomeric, nylon and polyester.
- 2 Those which polymerise with themselves, without any small molecule or substance being removed during polymerisation. This process is called **addition polymerisation**. Fibres formed by this technique are acrylics, polyethylene, polypropylene, polyvinyl alcohol and chlorofibres.

It must be realised that of the multitude of organic chemicals available, only a few have been used in the production of synthetic fibres. What then are the properties required for fibre formation, apart from economic considerations? The properties of polymers necessary for fibre formation are as follows:

- 1 high molecular weight,
- 2 linearity,
- 3 orientation,
- 4 high melting point.

Note: Orientation refers to the arrangement of polymers within the fibre. A crystalline or highly ordered arrangement of polymers is one in which they are parallel to the length of the fibre whereas an amorphous or disordered arrangement of polymers is one in which the polymers lie in a random fashion along the length of the fibre.

High molecular weight

It is essential for a polymer to have a high molecular weight and considerable length (see Table 1.2). A high molecular weight for a polymer indicates that it will also have considerable length. The length of polymers contributes to the strength of the fibre by holding the crystalline regions together; that is, the same polymer may pass through a number of crystalline and amorphous regions as illustrated in Fig. 1.2.

Table 1.2 Certain characteristics of five experimental polyester fibres.

Molecular weight	Average length A° (nm)	Melting point °C	Spinnability, (ability to form fibres)	Durability	Strength
780	60 (6)	67	Nil	Nil	Nil
5 600	440 (44)	73	Short fibres	Nil	Nil
7 300	570 (57)	74	Long fibres	Nil	Weak
9 300	730 (73)	75	Long fibres	Fair	Poor
16 900	1 320 (132)	77	Long fibres	Good	1 250 kg/cm ²

Source: W.H. Carothers and F.T. Van Natta, *Journal of the American Chemical Society*, 1933, **55**, p. 4714.

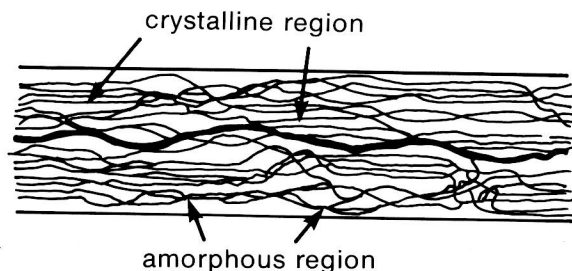
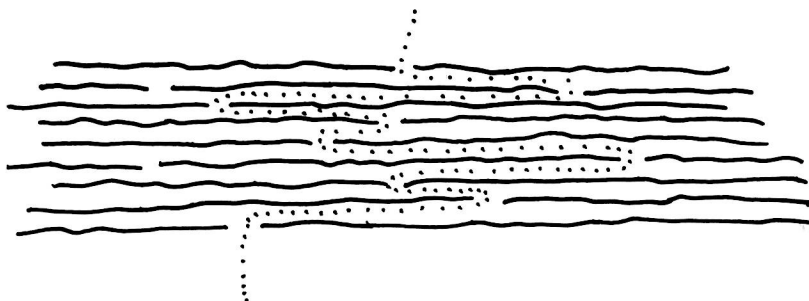


Fig. 1.2 The polymer system of a fibre showing amorphous and crystalline regions and how the length of the polymers holds the two regions together. For emphasis, one polymer is shown as a heavy line.

It has been found that to produce a fibre with adequate strength, a polymer length in the region of 100 nanometers is required (1 nanometer = 10^{-6} mm). The five different molecular weights given in Table 1.2 are for five experimental polyesters. They indicate the inability to form fibres with low molecular weight polymers.

Nylon 6,6 fibres have molecular weights ranging from about 10 000 to 13 000, with a DP of about 50–80 units and a chain length of about 90–140 nm. It can be seen from Table 1.2 that high molecular weight and a polymer length of about 100 nm are essential to produce a fibre with adequate strength. (See Fig. 1.3.)

a



b

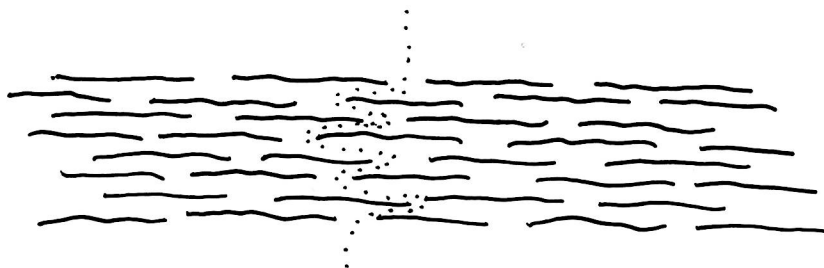


Fig. 1.3

a A strong fibre, as it has polymers of high molecular weight; that is, the polymers are long. This means that 'the path' of the break is long and therefore the fibre is strong.

b A weak fibre, as it has polymers of low molecular weight; that is, the polymers are short. This means that 'the path' of the break is short and therefore the fibre is weak.

Linearity

Fibre polymers must have a linear configuration and should not be branched as shown in Fig. 1.4. Only predominantly linear polymers will form sufficient crystalline regions, permitting an adequate number of interpolymer forces of attraction to occur within the polymer system. This results in a fibre of satisfactory strength and other desirable properties.

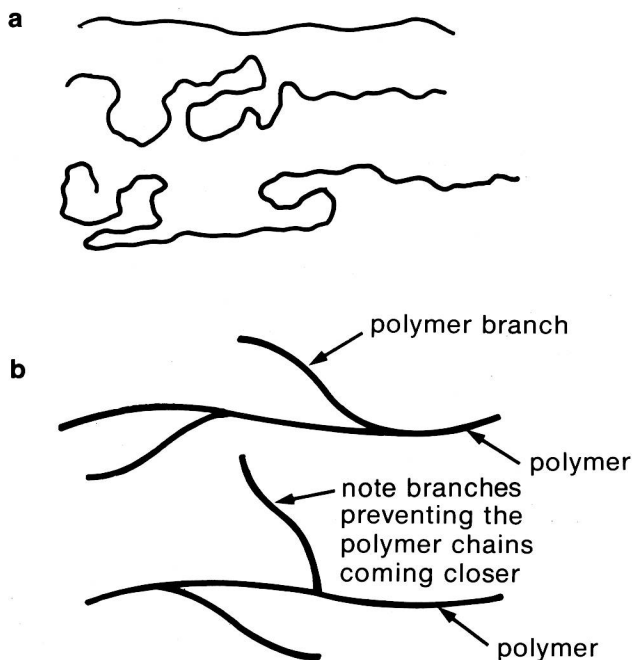


Fig. 1.4

a Linear polymers which can assume various configurations as shown.

b Branched polymers. These also can assume various configurations, but their side groups or branches prevent close packing of polymers; that is, the ready formation of crystalline regions.

Branched polymers, cross-linked polymers, or the type of three dimensionally cross-linked polymer systems as found in the urea-formaldehyde and melamine-formaldehyde resins used for the so called minimum-care finishes are quite unsuitable for the production of textile fibres. Polymers which are bulky and/or branched cannot pack closely enough together, thereby preventing the formation of crystalline regions in the polymer system of the textile fibre. The inability to form crystalline regions prevents the forces of attraction exerting their influence to hold the polymers in an orderly arrangement, thus resulting in a weak fibre. See Figs. 1.1 and 1.3.

Orientation

A fibre consists of a large number of individual polymers arranged in a manner which changes from highly ordered, highly oriented or **crystalline** to random or **amorphous**. It must be appreciated that, within the fibre polymer system:

- 1 the extent of the areas of amorphousness and crystallinity varies;
- 2 the proportions of the areas of amorphousness and crystallinity vary significantly;
- 3 the proportions of the areas of amorphousness and crystallinity in natural fibres are varied by nature; and
- 4 the extent of the areas of amorphousness and crystallinity can be altered during the production of man-made fibres.

After the filament has been extruded and coagulated, it is subjected to a process called drawing. During drawing, the polymers are transformed from a random or amorphous arrangement to one in which the polymers are highly oriented, thus resulting in the formation of crystalline regions. This greatly increases the strength of the fibre.

Note: In some polymer systems the crystalline regions are formed during extrusion and the drawing process merely aligns the crystalline regions parallel to the fibre axis whereas in other systems the polymers formed are amorphous and become crystalline during drawing. Polymer systems in which crystalline regions or crystallites are formed during extrusion may have their crystalline regions increased during drawing but not significantly. There is a limit to the extent that drawing is carried out on textile fibres; for example, a fibre which is extremely crystalline has a hard handle and is abrasive, limiting its use for apparel purposes.

High melting point

The more crystalline a polymer system and the stronger the interpolymer forces of attraction, the greater will be its resistance to heat. Since most textile fibres are subjected to some form of heat treatment, either during the production of textile materials; for example,

- 1 heat-setting of thermoplastic fabrics to produce a more stable fabric, thereby preventing distortion and shrinkage,
- 2 dyeing of textile fabrics,
- 3 certain finishing treatments,

or in the day to day use by the consumer, for example ironing, washing and dry-cleaning, the fibres must have a sufficiently high melting point to withstand the most extreme heat conditions to which they are likely to be subjected.

Inter-polymer forces of attraction

On a number of occasions reference has been made to forces, links or bonds which occur within a textile fibre. These forces will be referred to as forces of attraction and are as follows:

- 1 hydrogen bonds (H-bonds),
- 2 van der Waals' forces,
- 3 covalent bonds,
- 4 ionic bonds.

These forces of attraction may be ranked in decreasing order of strength as follows: covalent bonds, ionic bonds, hydrogen bonds and van der Waals' forces.

Hydrogen bonds

Hydrogen bonds occur between positively charged hydrogen atoms in one polymer and any negatively charged oxygen, nitrogen or chlorine atoms in an adjacent polymer.

Van der Waals' forces

Van der Waals' forces are similar to but weaker than hydrogen bonds. They occur when there is an absence of polar groups, but where the polymers are very closely packed so that attraction can occur between slight charges of opposite character in the polymer chains.

Note: Individually, hydrogen bonds and van der Waals' forces are comparatively weak and depend on the close packing of polymers. The great strength which some textile fibres have is due to the presence of a large number of these forces and the close packing of the polymers.

Covalent bonds

Certain polymers of some fibres, such as wool, are joined together by covalent bonds or **cross-links**; for example, the di-sulphide bond of wool. A covalent bond exists when any two atoms share a pair of electrons. Sharing a pair of electrons results in the strongest and chemically most stable bond between atoms. The greater the number of cross-links or covalent bonds between polymers in a polymer system, the more rigid the fibre becomes. The rigidity of the resins used for minimum-care finishing of textiles is due to their highly three-dimensionally cross-linked polymer system. On the other hand, fibres which possess a low degree of cross-linking, such as wool, or a very low degree of cross-linking, such as elastomeric, possess good to excellent elasticity.

Ionic bonds

These forces of attraction occur between oppositely charged polar groups in polymers and are stronger than hydrogen bonds or van der Waals' forces. They occur principally in wool and polyamide fibres and are also called salt links (as they are the fundamental bond in chemical salts).

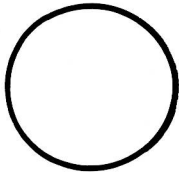
Properties of fibres dependent upon structure

Fibre morphology

The fibre length, fibre surface, internal fibre characteristics and shape of the fibre cross-section of natural fibres are determined by factors such as soil fertility, climatic conditions, quality of nutrients in stock feed, and animal and crop husbandry. On the other hand, textile technologists determine the morphological features of man-made fibres. Thus man-made fibres may be readily produced with different fibre diameters and with varying filament or staple fibre length to suit the specific end-use.

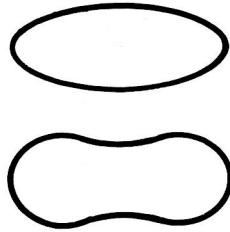
Note: A fibre or staple fibre is a unit of matter which is usually at least 100 times longer than it is thick. Textile fibres are usually over 1 000 times longer than they are thick. Most textile fibres range from 1.5 cm to 15.0 cm in length. A filament is a very long fibre. One 15 denier stocking is knitted from nearly 3 kilometres of multifilament yarn and the filaments this yarn is composed of are as long as the yarn itself.

circular type
cross-section



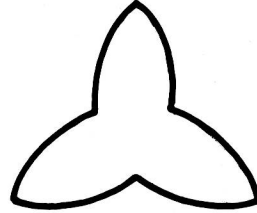
greatest bending
stiffness
often waxy to touch
most rigid
least flexible
least pliant
makes maximum
contact with the skin,
hence, may be
the least comfortable

oval to dog-bone
type cross-section

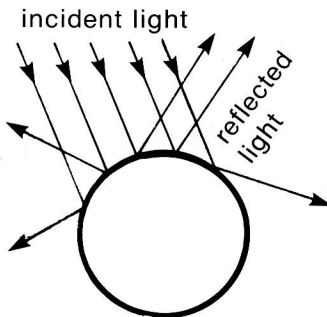


softest
easiest to bend
most flexible
limp, thus may make
too much contact
with the skin and
become uncomfortable

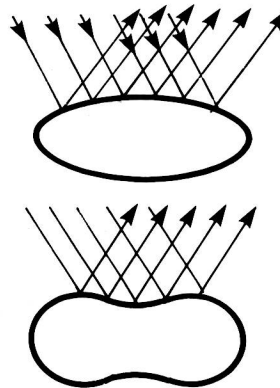
tri-lobal type
cross-section



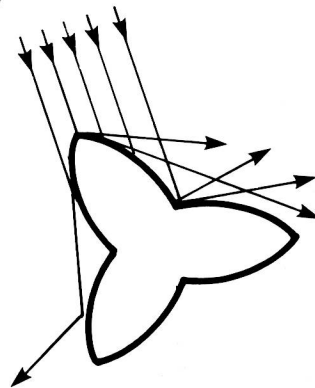
crispest
soft
easy to bend
pliant
flexible
makes only random
contact with the skin,
hence may be
aesthetically the
most pleasant



lustrous, may even
display very harsh
lustre, as the
incident light is
reflected evenly



most lustrous,
particularly if
oval shaped, as the
incident light is
reflected very
evenly



softest lustre, may
display even a sparkling
effect, due to the
very uneven reflection
of the incident light

Fig. 1.5 A generalised comparison of the effect of the shape of the cross-section of the filament upon handle and lustre.