FIBER PRODUCTION

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1. Introduction

1.1. History of Fiber Production and Usage

Ten thousand or more years ago, mankind found fibers growing on wild plants, twisted them into strands, and made ropes and nets. For clothing, the fibers attached to animal skins gave warmth. Spinning and weaving developed in prehistoric times. Plants and animals were domesticated for fiber production in addition to food. By the time of the ancient civilizations, many types of natural fibers were being produced in different parts of the world, although it was not until about 1500 that they all became a substantial part of global trade. Until 1890, only natural fibers were available to the textile industry. The advance of chemistry led to ways of dissolving natural cellulose, extruding the solution and forming artificial fibers, which came on the commercial market in the 1890s. Forty years later, synthetic polymer fibers were made. The first regenerated polymer fiber to attain continued, large-scale commercial production was viscose rayon, starting with a factory opened by Courtaulds in Coventry, UK, in 1905. Nylon was the first synthetic polymer fiber to be a real commercial success; the first factory was built by Du Pont in Seaford, Delaware, US, in 1939. Polyester, which is now the most-produced synthetic fiber, followed 10 years later. A second generation of high-performance synthetic polymer fibers became available in the last quarter of the twentieth century.

The largest usage of fibers is in flexible fabrics, in which, apart from small quantities of finishes, the fibers are the sole component. The spaces between the fibers play an important role in fabric performance. In addition to woven, knitted, and nonwoven fabrics, there is a limited usage in cordage, which is a one-dimensional form. The industry, for which these fibers are the raw material, is the textile industry. Although often thought of as a single industry, it is diverse in its manufacturing methods and produces the most varied range of products of any industry. Consumer products are the best known: clothing ranges from high fashion to cheap commodity products, and household uses from cleaning cloths to carpets. Technical uses, which go back over the centuries but are a growing market, link to many other industries. For example, the automotive industry is a large user of textiles, and polyester ropes, with strengths of 1000 tons or more, are being used to moor oil-rigs in deep water.

There is also usage of fibers in composite materials. Fabrics may be coated to provide an impermeable barrier or a special surface, though the fabric itself remains an open structure. Of greater interest is the use of fibers to reinforce a matrix in solid composites. In flexible composites with an elastomeric matrix, as used for example in tires, cotton was the first fiber to be used, but has been replaced by rayon, nylon, polyester, and, for special uses, newer, high-performance fibers. Rigid composites with a thermoset matrix, now also with other types of matrix, were introduced early in the twentieth century. Again cotton was first used, followed by nylon, glass, carbon fibers, high-performance polymer fibers, and ceramic fibers. For environmental reasons, there is current interest in the use of stiffer plant fibers, such as flax and hemp, which are a renewable resource. Other plant fibers, such as jute and sisal, are grown in less developed countries, but are losing markets, and some are by-products of food crops.

However, even with low fiber costs, the cost/benefit balance may not be favorable.

Allowing for uncertainty in some of the statistics, the current world demand, production, or capacity (in thousand tons) of some of the fibers to be covered in this article is approximately: cotton, 20 000; polyester, 20 000; nylon, 5000; olefin, 5000; other plant fibers, 5000; regenerated cellulose, 2500; glass, 2500; wool, 1000; other synthetic polymer fibers, 400; silk, 100; carbon 15; rock wool 100 and small amounts of other ceramic fibers. Two groups of commercial fibers are excluded from this article. The first dates back for centuries: wood-pulp fibers are used in papermaking, but are too short for textiles. The second consists of fibers with special properties developed in the last years of the twentieth century. Examples are optical fibers, fibers for medical uses, fibers with particular chemical, thermal, electrical, or magnetic properties. The production methods for these fibers are variants of those described for more widely used fibers.

1.2. Fiber Dimensions, Properties, and Units

Fibers are defined as units of matter characterized by flexibility, fineness, and a high ratio of length to thickness, but this could cover a wide range of sizes. The fineness of a fiber is best described by its linear density (mass/length), based on the unit *tex* (g km^{-1}). The submultiple decitex (dtex) is commonly quoted, because it is close to the older unit, *denier* (gram per 9000 m). The textile fibers described in this article will be in the range of 1 dtex to 20 dtex, which gives diameters of 5 μm to 50 μm. Coarser forms are known as monolfilaments. *Microfibers* down to 0.1 dtex have been introduced. *Nanofibers* down to 10^{-7} dtex have been made in the laboratory by extrusion of polymer solutions or melts in high electric fields. Mechanical properties are best expressed on a weight basis in specific quantities, namely force/linear density. The appropriate SI unit is *N tex*$^{-1,}$, which equals stress in GPa / density in g cm^{-3}, but gram/denier, which equals 0.088 N tex^{-1}, is widely quoted.

It is not the purpose of this article to provide a comprehensive account of fiber properties and the way in which, even for given types, they vary appreciably with production conditions. However, some typical values, including ranges for some fibers, are given in Table 1. Where the ranges are attributable to differences in molecular orientation, high strength and modulus will be associated with low break extension, but where differences are attributable to improved structures or elimination of defects, high strength and high break extension will go together. The mechanical properties of polymeric fibers change appreciably with temperature and, for those which absorb water, with humidity; the values in Table 1 are at the standard atmosphere of 65% rh, 20 °C.

Fiber	**Density**	**Tenacity**	**Strength**	**Break extension**	**Initial modulus**	
	(g/cm^3)	**(N/tex)**	**GPa**	**%**	**N/tex**	**GPa**
Cotton	1.52	0.19–0.45	0.29–0.68	5.6–6.8	3.9–7.3	5.9–11
Viscose rayon	1.49	0.18–0.41	0.27–0.61	12–27	4.8-8.8	7.2–13
Acetate (sec'y)	1.32	0.13	0.17	24	3.6	4.7

Wool	1.30	0.14	0.18	43	2.1	2.7
Silk	1.34	0.38	0.51	23	7.3	9.8
Nylon 6 / 66	1.14	0.29–0.84	0.33–0.96	20–46	0.6–9	0.68–10
PET (polyester)	1.39	0.47–0.82	0.65–1.14	13–37	8.8–17	12–24
Acrylic	1.19	0.27	0.32	25	6.2	7.4
Polypropylene	0.91	0.65	0.59	17	7.1	6.5
Para-aramid	1.44	1.6–2.1	2.3–3.0	2.5–4.4	51–98	73–141
HMPE	0.97	2.6–3.5	2.5–3.4	2.7–3.8	90–170	87–165
Glass	2.5	1.4–1.8	3.5–4.6	4.8–5.4	29–35	72–87
Carbon	1.8	1.3–2.1	2.5–3.7	0.7–1.7	128–218	230–405
Alumina-based	3.2–4.2	0.31–0.73	1.2–2.2	0.29–1.12	56–106	152–414
Silicon-based	2.3–2.74	0.71–1.37	1.7–3.5	1–1.7	75–100	180–263

Table 1. Typical fiber properties (from Morton and Hearle, 1993, Bunsell and Berger, 1999, and manufacturers' data)

2. Plant Fibers

2.2. Cellulose

The figures above show that the production of cellulose in plants account for nearly half of the world's textile fibers (much more than half if wood-pulp is included). The starting materials are carbon dioxide and water; the necessary energy comes from sunlight; the chemical reactions and the deposition of the cellulose are genetically controlled. Photosynthesis converts CO_2 and H_2O into glucose, $C_6(H_2O)_6$, and O_2. Within the protoplasm of living plant cells, enzyme complexes condense the glucose molecules, with the elimination of one molecule of H_2O, into long chains of cellulose molecules with the chemical formula shown in Figure 1.

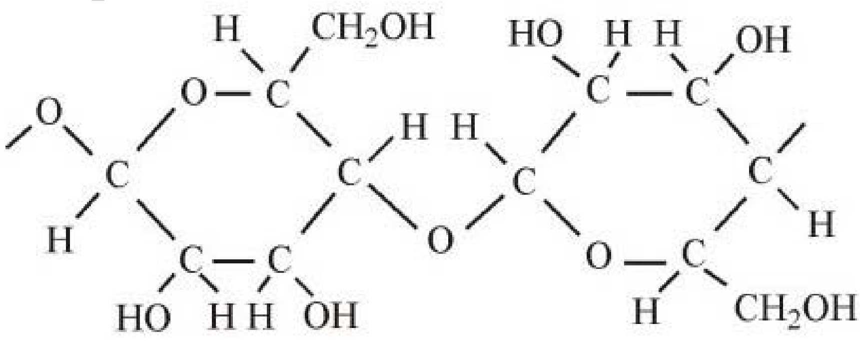

Figure 1. Repeat unit of cellulose

This mode of production of the polymer has two important consequences. First, the chains, which are directional (O to $CH(CH_2OH)$ in the rings), are lined up in the same direction. Second, about 30 chains are formed together at each enzyme complex and are able to crystallize in fibrils. The fibrils are then laid down on the cell walls in geometries that are characteristic of the particular plant. In some plants, there are also appreciable amounts of lignin and hemi-celluloses, but others have fibers of almost pure cellulose. For the latter, measures of degree of crystallinity, from X-ray diffraction, moisture absorption, and other techniques, are about 66%, but the disorder can be attributed to the packing of fine, almost perfectly crystalline fibrils.

Cellulose is also produced by some bacteria, which is of research interest that could become a means of commercial production in the future.

2.2. Cotton

Cotton is produced in many parts of the world in temperate and tropical climates from California, Greece, and China in the North to Argentina and Australia in the South. Growth takes about six months from seed-time to harvest. About three months after planting, the plant flowers, is fertilized, and forms seeds. From the surface of the seeds, the fibers develop. All this happens within the closed cotton boll, which contains many seeds. When fiber formation is complete, or earlier if frost or other sources of damage occur, the bolls open. Much harvesting is still by hand, but mechanical pickers are used in more industrialized countries. The cotton goes to gins, which may be regarded as the last stage of cotton production or the first stage of textile processing, where, if necessary, it is dried, but the main function is to separate the fibers from the seed and to remove dirt, pieces of leaf, and other contamination. The cotton is then baled for transport to local spinning mills or for export.

The formation of a cotton fiber takes place in two stages. First, the cell grows as a thin hollow tube with a primary wall to its final external dimensions. Then a secondary wall is laid down inside the primary wall, with fibrils at an angle of about 21^o, to form the major part of the fiber thickness. When growth is complete, a small, circular lumen remains in the center of the fiber. On drying, the lumen collapses and causes the fiber to take the form of a convoluted ribbon.

Modern cotton plants derive from several species of the genus *Gossypium*, which were probably domesticated independently in Asia and in the Americas. Selective breeding, which is now enhanced by genetic engineering, has led to improvements in fiber quality, productivity, and suitability for different regions. Agricultural methods vary. In the Central Valley of California, which has a consistent climate, growth of a single variety in large ranches with controlled irrigation is similar to industrial production, and gives a closely standardized product. In other places, more traditional agricultural practice is followed. The longest and finest fibers command the highest prices, but the bulk of world production is now of medium-quality cottons of varieties developed in the US. Grading was originally by the subjective assessment of skilled cotton classers, but is now by objective tests of length, fineness, maturity, cleanliness, and color.

2.3. Other Plant Fibers

The number of plants that have yielded fibers for use in textiles is enormous, but much is small-scale local use. Some are by-products of plants grown for food or natural oils. Only those which have entered world trade in significant quantities will be mentioned here. There are two other seed fibers: coir, from the husks of coconuts, is a coarse fiber used in brushes and matting; kapok, which is grown in the tropics, is a hollow fiber used as a stuffing, particularly in lifebelts because of its buoyancy. The other plant fibers for real textile usage are the stiffening elements in stems (bast fibers) or leaves. After harvesting, either mechanical action alone or retting, which was traditionally carried out in ponds but may now be chemical, followed by mechanical action, enables the other plant tissues to be removed, leaving the long, natural fiber strands. These are multicellular, and the ultimates are very small. The commercial fiber dimensions depend on the severity of the preparatory processes. Generally, the fibrils are more nearly parallel to the fiber axis than in cotton, so that the fibers are stronger but less extensible.

Jute, at about 3000 thousand tons p.a., is the most extensively produced bast fiber. It is grown in the Indian subcontinent as a herbaceous annual, which reaches about 5 m in height. Jute was formerly exported for use in sacking and similar coarse textiles, but this export market has been lost to polypropylene. Finer grades can be used in furnishings and cheap clothing. Sunn hemp, with a production less than 100 thousand tons p.a., is a crop similar to jute, grown in India and Bangladesh. Flax, at about 600 thousand tons p.a., is the next largest bast fiber in production, but probably exceeds jute in value. It is used for higher-quality linen fabrics. Hemp is a word that has been used for many types of fiber. The bast fiber, true (soft) hemp, *Cannabis Sativa*, was the most widely used fiber in cool regions before cotton became dominant in world trade, but current production is only about 25 thousand tons p.a.. It provided somewhat coarse clothing, such as traditional jeans, and is now being promoted as an ecologically advantageous product, though production is banned in the US because of its association with other varieties of cannabis, which are rich in narcotics. Both flax and hemp are grown from seed as annuals in cool climates. The plants grow to about 1 m high and, after harvesting the fibers are extracted from the stems. Another high-quality plant fiber, ramie, which is produced in small quantities mainly in China, is grown from cuttings.

The leaf fibers are also known as hard fibers and are used mainly in cordage. Sisal, *Agave sisalana*, and henequen, *Agave fourcroyudes*, with production of about 300 thousand tons p.a., are the most important types and are grown in tropical regions of East Africa, and Central and South America. The plants, which have large spiky leaves growing out in a rosette from a short trunk, last for six or seven years before flowering, producing small buds that develop into new plants, and dying. The leaves are cut from the age of about three years until the plant dies.

Other plant fibers, which include kenaf and nettle among the bast fibers and istle and Manila hemp among the hard fibers, together with many others, account for another 300 thousand tons p.a.

3. Animal Fibers

3.1. Proteins

The natural fibers from animal sources are based on proteins, which have the basic formula shown in Figure 2.

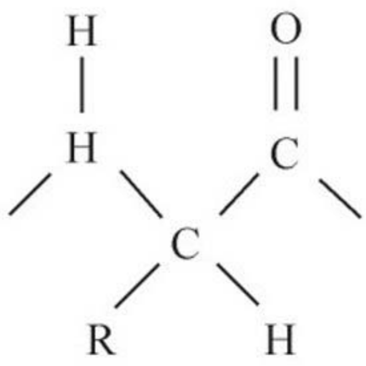

Figure 2. Basic repeat unit in proteins

There are 20 different side-groups, R, and their sequence determines the function of the particular protein. The side-groups comprise inert (-H and hydrocarbons), acidic, basic, hydroxyl-containing, and more complex forms. Of particular importance are two anomalous types. Proline is a ring structure, which joins on to the main-chain carbon in place of -H and distorts chain geometry. Cysteine is formed as $-CH_2.S.H$, but can be oxidized to cystine, $-CH_2.S.S.CH_2-$, which forms cross-links within or between chains.

3.2. Wool

Wild sheep were domesticated in ancient times, and have been improved by selective breeding. Some breeds, such as the cross-bred sheep of New Zealand, have been optimized for meat production; others, such as mountain or desert breeds, have been optimized for harsh environments. The wool from these sheep is a secondary product and is usually a coarser type. Merinos, which originated in Spain and dominate the Australian industry, are bred primarily for their fine wool. Sheep are raised on farms at a density that depends on the quality of pasture. They are shorn annually, usually in the spring. In Western Australia there is some autumn shearing to avoid thin places, which occur in the dry season of late summer, giving weakness in the middle of spring-shorn fiber. As with cotton, subjective grading is giving way to objective testing and sale by specification. There is considerable variability in the wool quality, and the marketing aspects of wool production are important in directing the right blends to the right use. Wool as grown contains a substantial amount of grease, so that scouring is the link between production and textile processing.

Wool and related hair fibers have the most complex structures of any fiber at many levels from chemical, since they contain a mixture of proteins, to the whole, multicellular fiber. Cell division takes place at the base of follicles on the skin, and the cells of the central cortex grow into spindle shapes with scale cells in the surface cuticle. Inter-cellular material, rich in lipids, also forms. As each portion of the growing circular fiber moves up the follicle, α-keratins are laid down within the cortical cells in a parallel assembly of intermediate filaments (IFs), also known as microfibrils, which are about 7 nm in diameter. Specific sequences of side-groups, with little cysteine, enables the chains to crystallize in slightly distorted α-helices in the IFs. The α-keratins have terminal zones (tails), which are rich in cysteine. These project from the IFs and space their centers about 10 nm apart. Further up the follicle, globular keratin-associated proteins (KAPs), which are also rich in cysteine, are laid down. As the fiber continues to move up the follicle, the chemical reaction of keratinization cross-links the KAPs and the IF tails as cysteine converts to cystine. The resulting fine structure is a composite of helically crystalline microfibrils, which under tension have a transition to an extended β-crystal lattice, in a cross-linked, amorphous rubbery matrix. This composite structure leads to the high elastic extensibility of wool and hair. Finally, before emerging from the follicle, the sebaceous gland applies a coating of grease to the fiber.

One other aspect of the genetic control of growth should be mentioned. The cortex has a bicomponent structure, with a different mixture of proteins in para- and ortho-segments. There is also a difference in fine structure. In the para-cortex, the microfibrils are parallel to the fiber axis; in the ortho-cortex, they are twisted together in macrofibrillar whorls. In wool, the ortho and para twist round on opposite sides of the fiber, and differential contraction on drying causes the fibers to crimp, which is another valuable feature of wool. Hairs with a symmetrical arrangement of ortho and para are straight.

3.3. Other Hair Fibers

As with plant fibers, hair from many other animals has been used. For example, coarse horse-hair was a common stuffing material. The hairs in commercial use are effectively variants of wool and are mostly more expensive fibers with desirable qualities. Examples are: camel hair; mohair, cashmere, and other goats; alpaca, llama, and vicuna from South America; and rabbit fur used in felts. Some of these animals are shorn annually like sheep, but the fibers may be collected in other ways. Camel hair is shed naturally and cashmere is combed.

3.4. Silk

Silk production is small, but it is an important luxury fiber, which was first cultivated in China about 5000 years ago and started to spread West about 1500 years ago. The silk moth *Bombyx mori* lays eggs; caterpillars (silkworms) hatch out; after 35 days of eating large quantities of mulberry leaves, the silkworms extrude silk as twin filaments through channels in their heads to form a cocoon, within which the caterpillar changes to a chrysalis. A few are allowed to emerge as moths to lay more eggs, but the majority is killed to obtain undamaged silk. The cocoons are soaked in hot water and the silk is unreeled to provide 800 m lengths of continuous filaments, which are twisted (thrown) into yarns.

Silk differs from other natural fibers in that, like manufactured fibers, it is extruded (spun) and not formed from living cells. Genetic control is limited to the chemistry of the spinning solution and the geometry and rate of extrusion. The protein is a block copolymer. Simple crystallizable sequences alternate with more complicated sequences, which form amorphous regions.

In addition to silk from *Bombyx mori*, there is some use of wild silks, such as tussah. There is considerable interest in spider silks, which include extremely strong fibers, though this is mainly in terms of possible artificial production of similar fibers.

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Biographical Sketch

John W S Hearle read Natural Sciences at Cambridge University, 1943-5 and 1948-9, graduating with First-Class Honours in physics. He was a Research Officer at the British Cotton Industry Research Association from 1946 to 1948. In 1949, he was appointed an Assistant Lecturer in the Department of Textile Industries in the Manchester College of Technology and the Faculty of Technology, University of Manchester, being awarded a PhD in 1952. He became a Lecturer, Senior Lecturer, Reader, and from 1974 to 1985, Professor of Textile Technology and Head of Department of Textiles in the University of Manchester Institute of Science and Technology (UMIST).

Dr Hearle was a Smith-Mundt Fellow at Clemson University, South Carolina, in 1953, in 1963-4 a Visiting Associate Professor of Mechanical Engineering at MIT. and in 1986-1990 spent periods as a Distinguished Visiting Professor of Mechanical Engineering at the University of Delaware and then as Professor of Materials Science and Visiting Scientist at DuPont Experimental Station.

Dr Hearle was awarded the degree of ScD by Cambridge University in 1973. He is a Fellow of the Institute of Physics. He is an Honorary Fellow and Honorary Life Member of The Textile Institute, and has been a Vice-President and Chairman of Council. He is an Honorary Member of Fiber Society (USA).

Dr Hearle's research interests are in the structural mechanics of fibres and fibre assemblies. He has published many research papers and general articles. He is an author of: Physical Properties of Textile Fibres; Structural Mechanics of Fibers, Yarns and Fabrics; Polymers and their Properties; An Atlas of Fibre Fracture and Damage to Textiles; Textured Yarn Technology; Handbook of Fibre Rope Technology. He has edited and contributed to many other books. He has consulted extensively with industrial companies, and from 1986-1995 was Chairman of Tension Technology International, now Senior Consultant.