Fibers

8

8.1 Introduction

In Chapter 7, a textile fiber was categorized as a polymeric material that has a unique linear structure, which is created naturally or man-made. Natural fibers can be of cellulosic sources including cotton, flax, and jute or of protein sources including wool and silk. They can also be of mineral sources including asbestos. Man-made fibers can be subdivided into two categories: regenerated fibers such as rayon, lyocell, cellulose acetate, and triacetate and synthetic fibers such as polyester, polyamide, and polyacrylic. Fibers can also be of inorganic sources including glass and metallic fibers. The availability of many types of fibers provides product designers with a wide range of structural features resulting in many physical and chemical properties that contribute to the performances of numerous end products.

In 2017, fiber production was at a record high of 103 million metric tons [1]. This is an increase of over 900% since 1950 when global fiber production was less than 10 million metric tons. Since the early 2000s, polyester fiber has overtaken cotton fiber and dominated the fiber market. In 2017, the market share of synthetic fibers reached 60%, with polyester fiber alone at 51% of the total global fiber production (more than 53 million metric tons); nylon fiber was about 5.5%, and other synthetic fibers were about 5.5%. Cotton fiber was second in total market share reaching 25% (about 26 million metric tons); wool fiber was about 1 million metric tons or 1% market share; long-vegetable fibers including jute, linen, and hemp were at about 5%; and silk and down had market shares of less than 1%. Cellulosic-based man-made fibers had a market share of 7% (about 6.5 million metric tons). These are the common choices of fiber types in today's product development projects in the textile and garment industry.

The largest use of textile fibers is in the apparel and clothing sector, which was more than 75% in 2017. About 10% of the market share is in household products, and about 12% is in the growing technical textile market. Globally, the value of basic fibrous products (yarns and fabrics) produced by textile mills is estimated to reach the trillion-dollar mark before 2020. The apparel market is also estimated to reach the trillion-dollar mark by the same year leading to an apparel retail market of over $1.6 trillion. On the other hand, the technical textile market is estimated to reach over $220 billion by 2020. The importance of textile fibers can also be realized from the nearly 70 million people working in this industry around the globe.

The expansion of the technical textile market will only mean unlimited potentials for the growth of fiber production worldwide. In this market, fibers are blended or integrated in nonfibrous structures. They are used as temporary binding elements in medical sutures, which must biodegrade instead of being removed and wasted; they are used as carrier for other materials such as electronics in smart fashion; they are incorporated into composite structures in which metals or other polymeric matrixes

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are used; they are used in construction products partnering with cement and other construction materials; they are used in the human body as artificial organs; they are used to reinforce soil and embankments as geotextiles; and they are used as filtration means in different filters handling numerous types of other materials.

In the context of product design, it is important that engineers of all fields understand the differences between textile fibers and other materials. In this chapter, the key differences between fibers and other materials will be discussed. In addition, an overview of different types of fibers will be presented. By no means, the coverage of textile fibers in this book is intended to be comprehensive or inclusive. Readers interested in learning more detail about textile fibers can refer to many published books on the subject [2–6].

8.2 Basic differences between fibers and other materials

Most fibers are essentially polymeric-based materials, and they largely share many of the inherent characteristics of polymers. For example, the Cambridge charts [7] shown in Fig. 7.2 of Chapter 7 indicated that polymeric materials exhibit bulk density ranging from about 900 to 2800 kg/m^3 (0.9–2.8 g/cm^3). As shown in Fig. 8.1, most conventional fibers fall in the range from 0.9 to 1.6 g/cm^3. Some specialty fibers such as carbon and glass fibers have density in the range from 1.75 to 2.6 g/cm^3. The uniqueness of a textile fiber will typically stem from three basic attributes: linearity, flexibility, and light weight. These attributes make fibers easily manipulatable in numerous products and constructions. In the following sections, a review of some of the unique characteristics will be presented. These will include fiber structure, deformation behavior, strength parameters, thermal conductivity, aspect ratio, and surface characteristics.

8.2.1 Fiber structure

The internal structure of a polymeric fiber consists of small molecules or monomers joined together to form a long molecular chain. As shown in Fig. 8.2, this structure can be described by three basic parameters [8, 9]: (1) the degree of polymerization, (2) the degree of order, and (3) the degree of orientation. The length of the molecular chain depends on the number of molecules connected in a chain, which is generally known as the "degree of polymerization." This is typically determined by the ratio between the molecular weight at a certain point of time during polymerization and the molecular weight of one monomeric unit. Molecular chains may be arranged in a dominantly random order, commonly known as amorphous structure, or in a dominantly organized order, commonly known as crystalline structure. Most fibers exhibit structures that are partially crystalline and partially amorphous. This is commonly known as the degree of order, with highly crystalline fibers being of high molecular order. In addition, fibers can be made at different levels of molecular orientation by stretching the molecular chains to different levels of draw ratio; this is known as the degree of orientation.

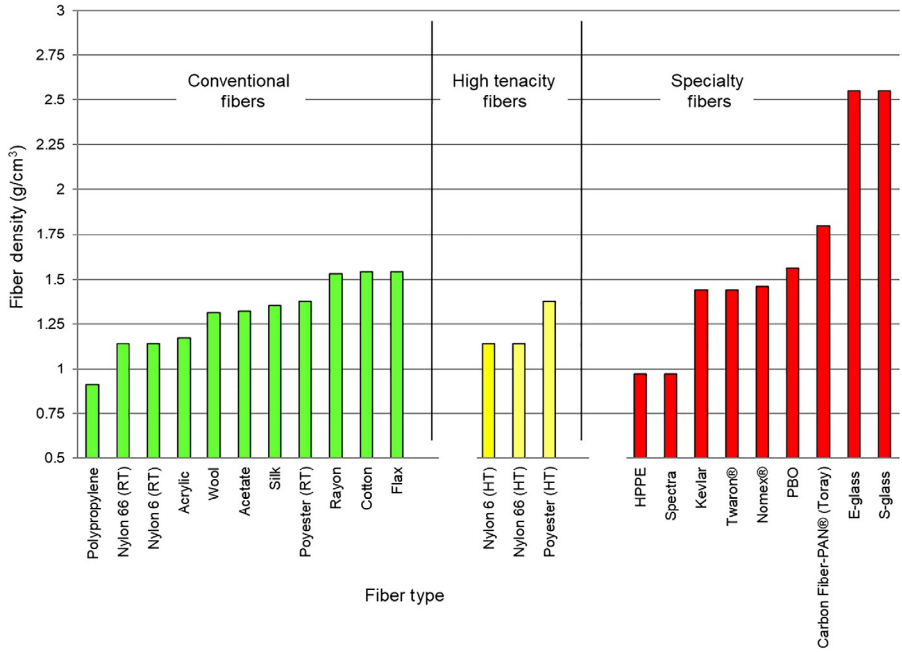

Fig. 8.1 Typical values of density of different fiber types.
Graph developed from data J. Gordon Cook, Handbook of Textile Fibers: Vol. II: Man-Made Fibers, Woodhead Publishing Limited, Cambridge, 2009 (Reprinted 1993, 2001, 2002); J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; B. Lomas, J.W.S. Hearle, W.D. Cooke, Atlas of Fiber Fracture and Damage to Textiles, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 1998; R.R. Franck, Bast and Other Plant Fibers, The Textile Institute, Woodhead Publishing Limited, England, 2005; Cambridge Material Charts, Department of Mechanics, Materials, Design, United Kingdom, 2002. http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts; W.S. Morton, J.W.S. Hearle, Physical Properties of Textile Fibers, The Textile Institute-Butterworths, Manchester and London, 1962.

8.2.2 Fiber deformation behavior

To understand the unique strength characteristics of fibers, it is important to provide few comments on the nature of their mechanical behavior in comparison with other materials [10–12]. In general, crystalline metals and ceramics will typically deform by a very small amount (often unnoticeable) at small levels of applied stresses. Typically, small loads will result in small displacement of the metal atoms, less than 10% of their interatomic distances. Fibers being a polymeric material will respond easily to external loading even at very small levels. Within elastic limits, polymer molecules recoil almost immediately from the load, but some polymers may exhibit a slight delay in the elastic recoil [10, 11]. When the applied stress exceeds the elastic limit, polymeric materials undergo the phenomenon of polymer yielding, which is the

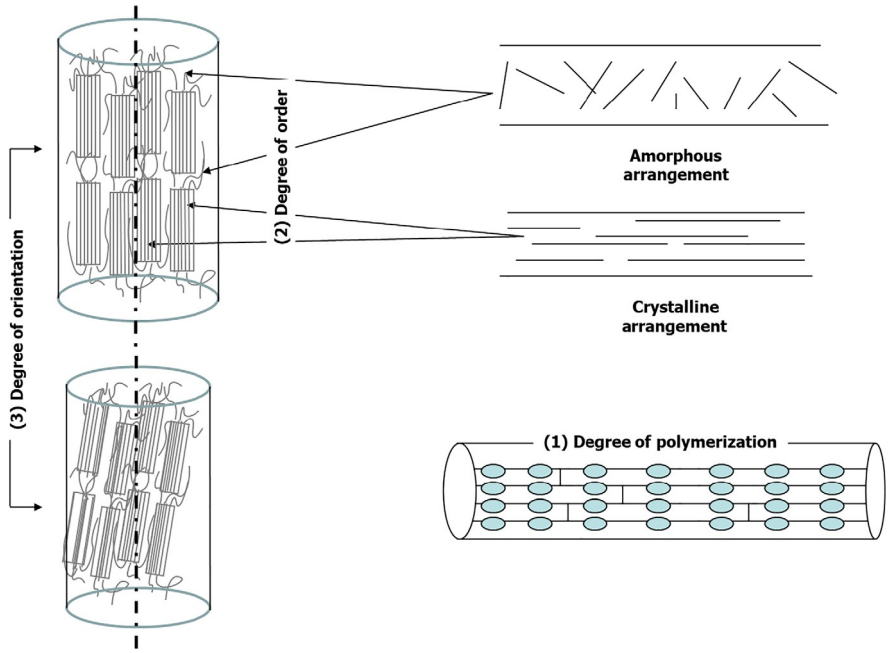

Fig. 8.2 Basic structural features of fibers.

onset of a permanent or irreversible deformation. For noncrystalline (or amorphous) polymeric materials, yielding will result from molecular uncoiling, leading to a neck forming at the yield point, which is followed by an overall drop in stress. At the neck region, the folded chains become aligned. The microscopic thinning down in cross section results in a local increase in the stress, and any deformation occurs preferentially there. This helps the neck propagate crosswise under a steady load, in a process known as cold drawing. Any deformation produced beyond the yield point is not recoverable. In a crystalline polymer, the unfolding of chains begins in the amorphous regions between the lamellae of the crystals. This is followed by breaking up and alignment of crystals.

When time is a factor in rationalizing the mechanical behavior, one will find that metals and ceramics behave differently from fibrous materials. Typically, crystalline metals and ceramics deform plastically by dislocation motion, which is in step time wise with the applied stress. Fibers, after passing the elastic region, also deform plastically under stress by sliding of long-chain molecules past one another via the breaking of the weak secondary intermolecular bonds. The difference is that plastic deformation can increase with time without an increase in stress. Another difference is that the deformation is not purely plastic particularly at the initial stage; it is a mix of plastic and elastic deformation. With further time, deformation can be purely plastic. This overall deformational behavior of fibers is uniquely described as a viscoelastic behavior, implying a combined behavior of fluid and solid [8, 12].

Theoretically, the viscoelastic behavior of fibers and polymeric materials has been simulated by conceptual models such as the so-called Maxwell and Voigt models, which consist of a series of springs and dashpots [8, 12]. In this regard, two common time-dependent phenomena should be realized: creep and stress relaxation. In simple terms, creep occurs when a constant force is continuously applied on a component, causing it to deform gradually with time. As a result, it is a strain-time relationship with an increasing strain over time. The extent of creep will largely depend on the constant force applied. For thermoplastic polymers, creep will also depend on the temperature with the increase in temperature leading to faster deformation. A classical model of the creep behavior of a material has three stages of strain versus time. The first stage consists of the initial elastic and plastic effects of loading and an initially high but rapidly decaying creep rate. This is followed by steady-state creep in stage two where the rate is linear with time and concludes with tertiary creep where the creep rate rapidly accelerates and ends in failure. Stress relaxation is almost exclusively a characteristic of polymeric materials under constant strain over time. It is typically manifested by a reduction in the force (stress) required to maintain a constant deformation. In classic polymer relaxation theory, the time-dependent behavior is governed by highly developed equations often based on Maxwell or Voigt models and governed by a spectrum of relaxation times for the material.

The effect of temperature on the deformational behavior of fibers is also well documented [4, 8, 13, 14]. Fibers may be subject to high temperatures during processing and during chemical or thermal finishing. A polymeric fiber that melts, softens, or deteriorates under detergent treatments or hot water would make an unacceptable fabric. Fibers made from thermoplastic polymers can be manipulated during processing by raising their temperature above the softening or glass transition temperature (T_g), texturizing or deforming them, and cooling them again below the T_g to set the intended textured structure. Nonthermoplastic fibers can be treated using chemical cross-linking to reduce the loss of energy of deformation and provide better dimensional stability and shape recovery after deformation. For cotton fibers, this type of treatment is commonly known as permanent-press finish, and it functions by forming cross-links between adjacent cellulose polymer chains. These give cotton some elastic and resiliency properties.

8.2.3 Fiber strength parameters

Although most fibers belong to the category of polymer material, their molecular structure and deformational behavior provide them with unique values of strength parameters. In this regard, it will be useful to divide fibers into two main categories: conventional fibers and specialty fibers. The first category represents fibers that are commonly used for traditional fibrous products. These include natural fibers and common synthetic fibers (e.g., nylon, polyester, polypropylene, and acrylic fibers). The second category represents fibers that are commonly used for technical fibrous products (e.g., aramid fibers, carbon fibers, and glass fibers). Values of strength-related parameters of conventional fibers are listed in Tables 8.1–8.3, and those of specialty fibers are listed in Table 8.4. The units used in these tables are those used commonly

Table 8.1 Values of some strength parameters of natural fibers [3, 6, 7].

Fiber type	Tenacity (g_f/denier)		Breaking elongation (%)	Flexural rigidity (g_f/denier)	Elastic recovery (%) at 1%	Elastic recovery (%) at 3%
	Dry	Wet				
Cotton	2.7–4.0	3.5–5.5	4–6	60–70	50	35
Wool	1.8–2.0	1.3–1.4	25–45	4–6	60	
Flax	6–7	7–9	1.5–3.5	160–180	80	65
Silk	4–5	3–4	20–25	50–120	45	40

among fiber and polymer engineers. Values in these tables are also demonstrated in Figs. 8.3–8.5. Examination of these values reveals the following important points:

- As shown in Fig. 8.3, tenacity values of conventional fibers range from about 140 to 850 MPa (0.1 N/tex to about 0.65 N/tex). Some high-tenacity fibers can reach up to about 1200 MPa (0.9 N/tex). Note that synthetic fibers such as nylon and polyester can be produced in a wide range of tenacity depending on the intended applications.
- As shown in Fig. 8.4, some specialty fibers exhibit very high-tenacity values that easily fit within the range of metals and ceramic materials. The level of tenacity of this category of fiber will depend on the emphasis of application. For example, Nomex fiber being essentially a flame-retardant meta-aramid has a tenacity of 0.7 GPa. Kevlar fiber being a strength-oriented product can have a tenacity of about 3 GPa.
- As shown in Fig. 8.5, most conventional fibers, except cotton and flax, have high breaking elongation values (exceeding 15%). Specialty fibers, on the other hand, exhibit low breaking elongation.
- As indicated earlier, the most unique characteristic of fibers is flexibility. This is the characteristic that yields the comfort and fit of traditional fibrous products and the easy assembly and shape manipulation of technical fibrous products. The most common measure of flexibility is the initial modulus, known as Young's modulus. Fig. 8.6 shows another one of Cambridge material charts [7] in which values of Young's modulus for polymers range from about 0.08 to 10 GPa. These values are clearly below those of metals, ceramics, and composite materials. Most conventional fibers exhibit values within this range as shown in Fig. 8.7. Only flax fibers can exceed this range.
- Specialty fibers exhibit Young's modulus values approaching those of metals and ceramic materials. This is clearly illustrated in Fig. 8.8.

8.2.4 Fiber thermal conductivity

Another parameter that distinguishes fibers from many other materials is thermal conductivity. This is the ability of material to conduct heat. The general expression of thermal conductivity is as follows [8–12]:

$$k = \frac{\Delta Q}{A \times \Delta t} \times \frac{x}{\Delta T}$$

Table 8.2 Values of tenacity and elongation of man-made fibers in dry and wet conditions [2–6, 8, 9, 13, 14].

Fiber type	Tenacity (g_f/denier)				Breaking elongation (%)			
	Dry		Wet		Dry		Wet	
	RT	HT	RT	HT	RT	HT	RT	HT
Polyester (filament)	2.8–5.6	6.8–9.2	2.8–5.6	6.8–9.2	24–42	10–25	24–42	10–25
Polyester (staple)	2.4–7.0	5.7–6.9	2.4–7.0	5.7–6.9	12–55	20–34	12–55	20–34
Polyester (partially oriented)	2.0–3.0		2.0–3.0		120–170		120–170	
Nylon 6 (filament)	4.0–7.2	6.5–9.0	3.7–6.2	5.8–8.2	17–45	16–24	20–47	19–33
Nylon 6 (staple)	3.5–7.2				30–90		42–100	
Nylon 6,6 (filament)	2.3–6.0	5.9–9.8	2.0–5.5	5.1–8.0	25–65	15–28	30–70	18–32
Nylon 6,6 (staple)	2.9–7.2		2.5–6.1		16–75		18–78	
Lyocell (Tencel)		4.8–5.0		3.8–4.2		14–16		16–18
Rayon (Fibro) (filament and staple)	2.3	3.0	1.1	1.5	18–22		18–22	
Acetate (filament and staple)	1.2–1.4		0.8–1.0		25–45		35–50	
Acrylic (Acrilan) (staple)	2.2–2.3		1.8–2.4		40–55		40–60	
Olefin (Spectra)		30–35		30–35		2.7–3.6		2.7–3.6
Olefin-polypropylene (filament)	2.5–5.5		2.5–5.5		30–100		30–100	
Olefin-polypropylene (staple)	2.5–5.5		2.5–5.5		30–150		30–150	
Spandex (Lycra)	0.8–1.0				400–800			

Table 8.3 Values of stiffness, toughness, and elastic recovery of man-made fibers [2–6, 8, 9, 13, 14].

Fiber type	Stiffness (g_f/denier)		Toughness (g_f cm)		Elastic recovery (%)		Specific gravity	
	RT	HT	RT	HT	RT	HT	RT	HT
Polyester (filament)	10–30	30	0.4–1.1	0.5–0.7	76/3	88/3	1.38	1.39
Polyester (staple)	12–17		0.2–1.1		81/3		1.38	
Polyester (partially oriented)			1.3–1.8				1.34	
Nylon 6 (filament)	18–23	29–48	0.67–0.90	0.75–0.84	98–100/1–10	99–100/1–8	1.14	
Nylon 6 (staple)	17–20		0.64–0.78		100/2		1.14	
Nylon 6,6 (filament)	5–24	21–58	0.8–1.25	0.8–1.28	88/3	89/3	1.14	1.14
Nylon 6,6 (staple)	10–45		0.58–1.37		82/3		1.14	
Lyocell (Tencel)		30		0.34				1.56
Rayon (Fibro) (filament and staple)							1.53	
Acetate (filament and staple)	3.5–5.5		0.17–0.30		48–65/4		1.32	
Acrylic (Acrilan)(staple)	5–7		0.4–0.5		99/2		1.17	
					89/5			
Olefin-polypropylene (filament)	12–25		0.75–3.0		95/5			
					85/10			
Olefin-polypropylene (staple)					93/5		0.91	
					85/10			
Spandex (Lycra)					97/50 to 99/200		1.2	

Table 8.4 Values of strength parameters of some specialty fibers [3, 15].

Fiber type	Specific gravity (g/cc)	Tenacity (N/tex)	Initial modulus (N/tex)	Breaking elongation (%)
Kevlar29	1.44	2.030	49	3.6
Kevlar49	1.44	2.080	78	2.4
Kevlar149	1.44	1.680	115	1.3
Twaron	1.44	2.100	60	3.6
Nomex	1.46	0.485	7.5	35
HPPE(Dyneema SK60)-1 dpf	0.97	2.800	91	3.5
HPPE(Dyneema SK65)-1 dpf	0.97	3.100	97	3.6
HPPE(Dyneema SK71)-1 dpf	0.97	3.500	122	3.7
Spectra 900-10 dpf	0.97	2.600	75	3.6
Spectra 2000-3.5 dpf	0.97	3.400	120	2.9
PBO poly(*p*-phenylene benzobisoxazole)	1.56	2.54	177	
Carbon Fiber-PAN (Toray)	1.80	2.0–6.0	180–450	0.7–2.0
E-glass	2.55	1.5–2.5	54	1.8–3.2
S-glass	2.50	2.0–3.0	62	4.0
Steel wire	7.85	0.18	26	1.5

where $\frac{\Delta Q}{\Delta t}$ is the rate of heat flow, A is the total surface area of conducting surface, ΔT is temperature difference, and x is the thickness of conducting surface separating two temperature levels.

The earlier expression indicates that thermal conductivity is a direct function of the quantity of heat, ΔQ, transmitted during time Δt through a thickness x, in a direction normal to a surface of area A, due to a temperature difference ΔT, under steady-state conditions and when the heat transfer is dependent only on the temperature gradient. In SI units, thermal conductivity is therefore expressed in W/(m K).

Fig. 8.9 shows typical values of thermal conductivity of some conventional and specialty fibers. Fig. 8.10 shows thermal conductivity values for other common materials. Values in both figures should be taken only for general comparative purposes. Fig. 8.11 shows values of thermal conductivity of highly conductive materials. In general, most fibers exhibit low thermal conductivity, which makes them useful in many heat insulation applications. Specialty fibers such as carbon and glass fibers can have exceptionally high thermal conductivity.

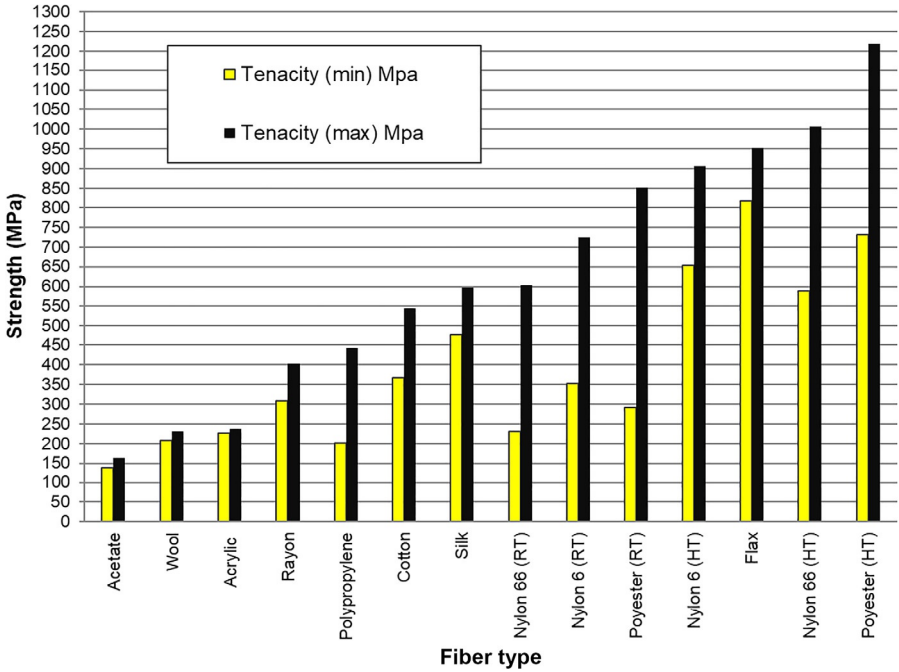

Fig. 8.3 Typical values of strength of different conventional fiber types (*RT*, regular tenacity; *HT*, high tenacity).
Graph developed from data J. Gordon Cook, Handbook of Textile Fibers: Vol. II: Man-Made Fibers, Woodhead Publishing Limited, Cambridge, 2009 (Reprinted 1993, 2001, 2002); J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; J.W.S. Hearle, R.H. Peters, Fiber Structure, The Textile Institute, Butterworths, 1963; B. Lomas, J.W.S. Hearle, W.D. Cooke, Atlas of Fiber Fracture and Damage to Textiles, The Textile Institute, Woodhead Publishing Limited Cambridge, England, 1998; R.R. Franck, Bast and Other Plant Fibers, The Textile Institute, Woodhead Publishing Limited, England, 2005; W.S. Morton, J.W.S. Hearle, Physical Properties of Textile Fibers, The Textile Institute-Butterworths, Manchester and London, 1962; Y. Elmogahzy, Engineering textiles, in: Integrating the Design and Manufacture of Textile Products, first ed., Woodhead Publishing (Elsevier), UK, 2009; I. Block, Manufactured Fiber, AccessScience@McGraw-Hill, 2002, doi:10.1036/1097-8542.404050, http://www.accessscience.com, last modified: May 6; W. Klein, Man-Made Fibers and Their Processing, The Textile Institute, Manchester, 1994.

8.2.5 Fiber aspect ratio

A key characteristic that makes fibers uniquely distinguished from other materials is the high aspect ratio (length/diameter ratio). Typical values of aspect ratio for fibers may range from 200 to several thousands. From a design viewpoint, fibers of high aspect ratio should result in stronger yarns than those of low aspect ratio by virtue of the long interfiber contact and the possibility of placing more fibers in the yarn cross section [16]. More importantly, high aspect ratio can result in a significant

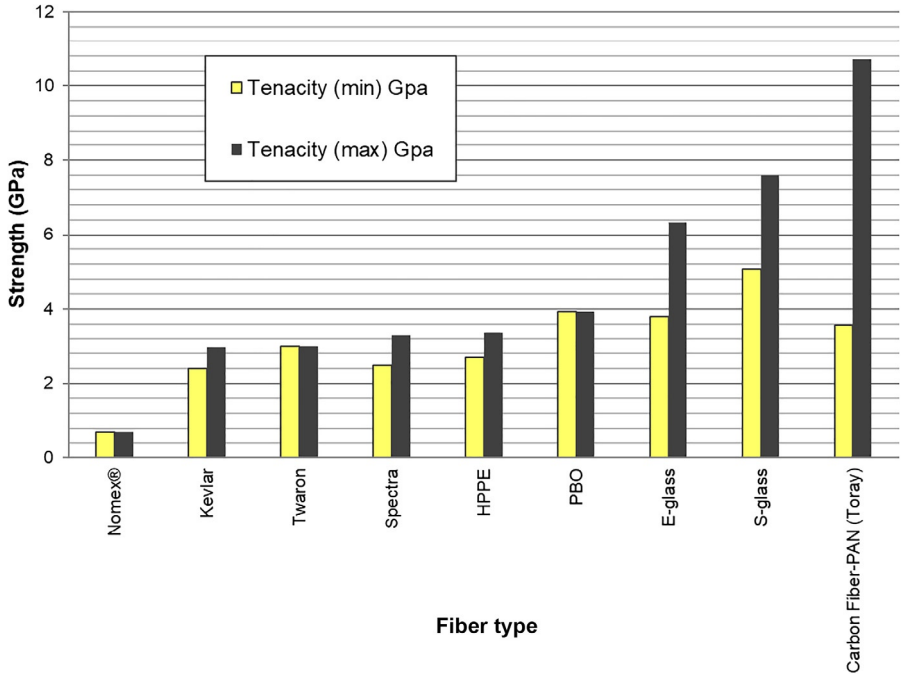

Fig. 8.4 Typical values of strength of different specialty fibers.
Graph developed from data J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; T. Hongu, G.O. Phillips, New Fibers, second ed., Woodhead Publishing Limited, 1997.

improvement in fiber flexibility by virtue of the fact that the bending rigidity of fiber is proportional to the fourth power of dimeter (d^4), where d is the fiber diameter.

As discussed in Chapter 7, entertaining material options should be made in view of the design problem statement and both the performance and the manufacturing criteria associated with the material. When flexibility is the main performance criteria, a design engineer can have multiple options to produce high flexibility as shown in Fig. 8.12. At the fiber level, high flexibility in fibers should result in high flexibility in end products provided that the methods to bind the fibers together into a yarn or fabric can preserve this flexibility or at least minimize its inevitable reduction. In this regard, the material choices will be an inherently flexible fiber, natural staple fibers of high aspect ratios or continuous filaments cut to various lengths, each associated with different aspect ratio. At the yarn level, fiber flexibility can be transferred into yarn flexibility using appropriate spinning method or low twist levels in the yarn. Similarly, fabrics of open constructions using flexible yarns can produce flexible end products [16]. When manufacturing criteria are considered, fiber flexibility has to be of optimum values to avoid manufacturing problems as explained in Chapter 7 using the example of microdenier fibers.

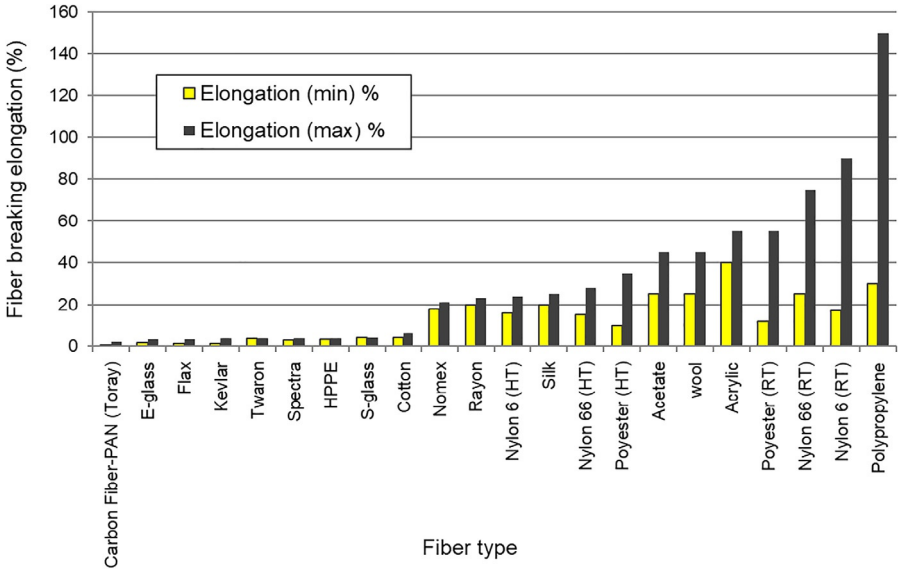

Fig. 8.5 Typical values of elongation of different fiber types.
Graph developed from data J. Gordon Cook, Handbook of Textile Fibers: Vol. II: Man-Made Fibers, Woodhead Publishing Limited, Cambridge, 2009 (Reprinted 1993, 2001, 2002); J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; J.W.S. Hearle, R.H. Peters, Fiber Structure, The Textile Institute, Butterworths, 1963; B. Lomas, J.W.S. Hearle, W.D. Cooke, Atlas of Fiber Fracture and Damage to Textiles, The Textile Institute, Woodhead Publishing Limited Cambridge, England, 1998; R.R. Franck, Bast and Other Plant Fibers, The Textile Institute, Woodhead Publishing Limited, England, 2005; W.S. Morton, J.W.S. Hearle, Physical Properties of Textile Fibers, The Textile Institute-Butterworths, Manchester and London, 1962; Y. Elmogahzy, Engineering textiles, in: Integrating the Design and Manufacture of Textile Products, first ed., Woodhead Publishing (Elsevier), UK, 2009; I. Block, Manufactured Fiber, AccessScience@McGraw-Hill, 2002, doi:10.1036/1097-8542.404050, http://www.accessscience.com, last modified: May 6; W. Klein, Man-Made Fibers and Their Processing, The Textile Institute, Manchester, 1994; T. Hongu, G.O. Phillips, New Fibers, second ed., Woodhead Publishing Limited, 1997.

8.2.6 Fiber surface characteristics

Different material categories are expected to have different surface structures by virtue of their atomic structure. For example, metals being largely crystalline structures are characterized by surfaces in which atoms are arranged in a largely regular manner [17]. Ceramics being essentially a combination of one or more metals and nonmetallic substance chemically bonded together are expected to exhibit different surface textures [18]. For composite products, surface characteristics of both the matrix and the reinforcing components represent a key structural aspect as it determines both the integrity and the protection of these products. In recent years, a great deal of development of surface physics has been witnessed as a result of the development

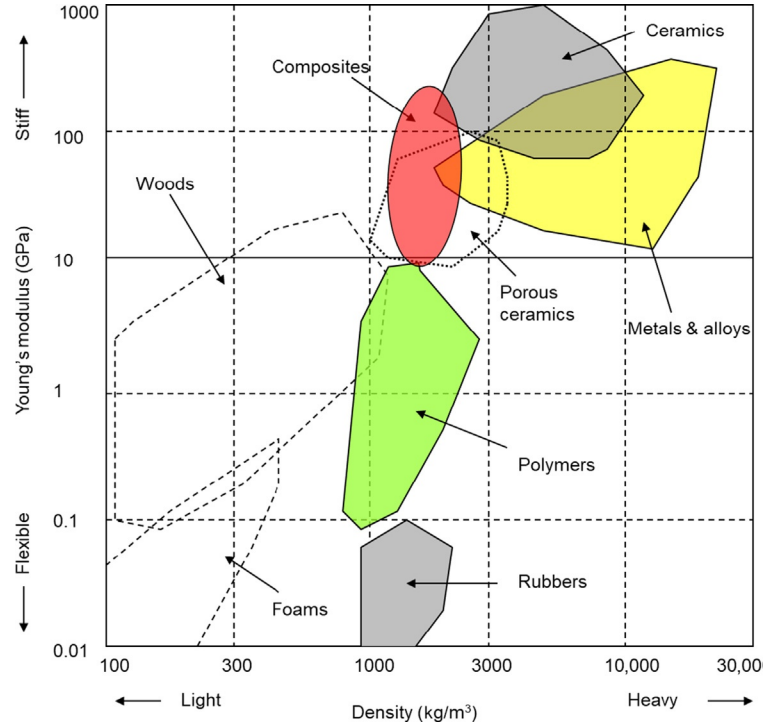

Fig. 8.6 Young's modulus density of different materials [7].

of vacuum technology, new surface sensitive probes, atomic microscopes, and powerful analytical methods [17, 18].

The surface morphology of fibers represents a key design aspect in many product development applications. Different natural fibers exhibit different inherent surface morphologies. For example, cotton fiber has a twisted-ribbon shape along the length of the fiber and a kidney-shaped cross section [19]. Wool fibers on the other hand exhibit a scaly surface, similar to that of human hair, leading to directional frictional effects [20]. Synthetic fibers stem their surface characteristics from various sources including [21] (a) the polymeric surface structure, (b) molecular orientation, (c) fiber cross-sectional shape, (d) fiber crimp, and (e) surface finish treatments. This provides a wide range of key characteristics such as surface cohesion, surface morphology, roughness, moisture management, and cleanability. In addition, the processing performance of most fibers is influenced by surface friction and fiber cohesion. During processing, fibers are subject to repeated rubbing between each other and against machine parts (wires, rollers, etc.). As a result, an optimum cohesion level should be determined for each fiber type [16]. In this regard, high enough cohesion may be required to maintain the bulk integrity of the fiber strand. Meanwhile, too low fiber cohesion may not be desirable as it can result in an

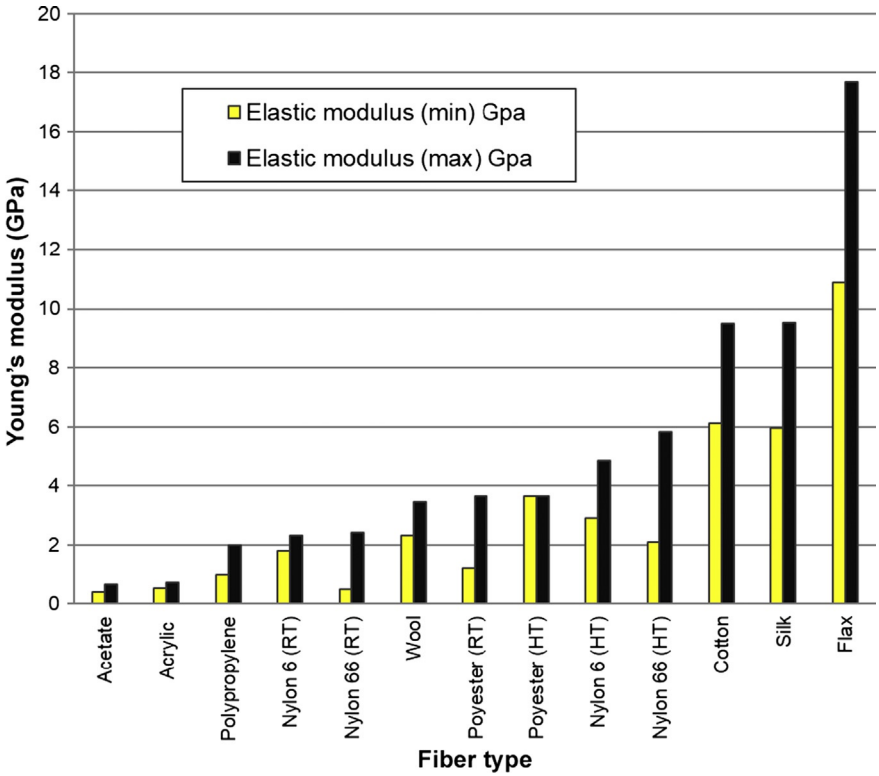

Fig. 8.7 Typical values of Young's modulus of conventional fiber types.
Graph developed from data of J. Gordon Cook, Handbook of Textile Fibers: Vol. II: Man-Made Fibers, Woodhead Publishing Limited, Cambridge, 2009 (Reprinted 1993, 2001, 2002); J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; J.W.S. Hearle, R.H. Peters, Fiber Structure, The Textile Institute, Butterworths, 1963; B. Lomas, J.W.S. Hearle, W.D. Cooke, Atlas of Fiber Fracture and Damage to Textiles, The Textile Institute, Woodhead Publishing Limited Cambridge, England, 1998; R.R. Franck, Bast and Other Plant Fibers, The Textile Institute, Woodhead Publishing Limited, England, 2005; W.S. Morton, J.W.S. Hearle, Physical Properties of Textile Fibers, The Textile Institute-Butterworths, Manchester and London, 1962; Y. Elmogahzy, Engineering textiles, in: Integrating the Design and Manufacture of Textile Products, first ed., Woodhead Publishing (Elsevier), UK, 2009; I. Block, Manufactured Fiber, AccessScience@McGraw-Hill, 2002, doi:10.1036/1097-8542.404050, http://www.accessscience.com, last modified: May 6; W. Klein, Man-Made Fibers and Their Processing, The Textile Institute, Manchester, 1994.

uncontrollable flow of material during manufacturing. Fibers may also be blended with other fibers, or they may be bonded with nonfibrous materials. This requires an optimum surface cohesion of fibers.

In closing this section, it is important to point out that the fiber-related aspects discussed earlier represent key design factors that should be taken into consideration in any product development project involving fibrous products. Understanding these

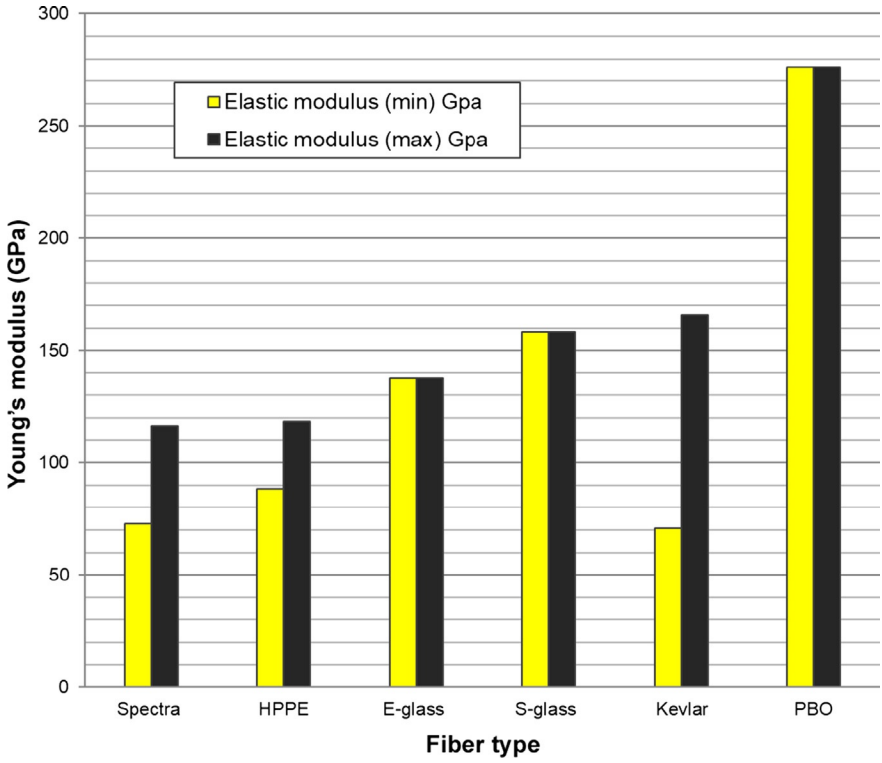

Fig. 8.8 Typical values of Young's modulus of specialty fiber types.
Graph developed from data of J.W.S. Hearle, High-Performance Fibers, The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2001; T. Hongu, G.O. Phillips, New Fibers, second ed., Woodhead Publishing Limited, 1997.

aspects can assist a great deal in exploring possible solutions to design problems. In addition to these aspects, design engineers should refer to the plausible ranges of various fiber characteristics available in the literatures or fiber producer documents. Fig. 8.13 provides a summary of the key fiber attributes that can influence the performance characteristics of fibrous products. In recent years, nanotechnology has introduced a new category of fibers called "nanofibers." In comparison with the microdenier fiber, which has a diameter of few microns, a nanofiber will have a diameter of less than 1 micron. This three-to-four-atom thick fiber will add new dimensions to the uniqueness of fiber attributes in comparison with those of other categories of material. In addition, it will allow a dominant use of fibers in critical applications such as precision medical products, electronics, precision filters, smart garments, composite, insulation, aerospace, capacitors, transistors, drug delivery systems, battery separators, energy storage, fuel cells, and information technology [22, 23].

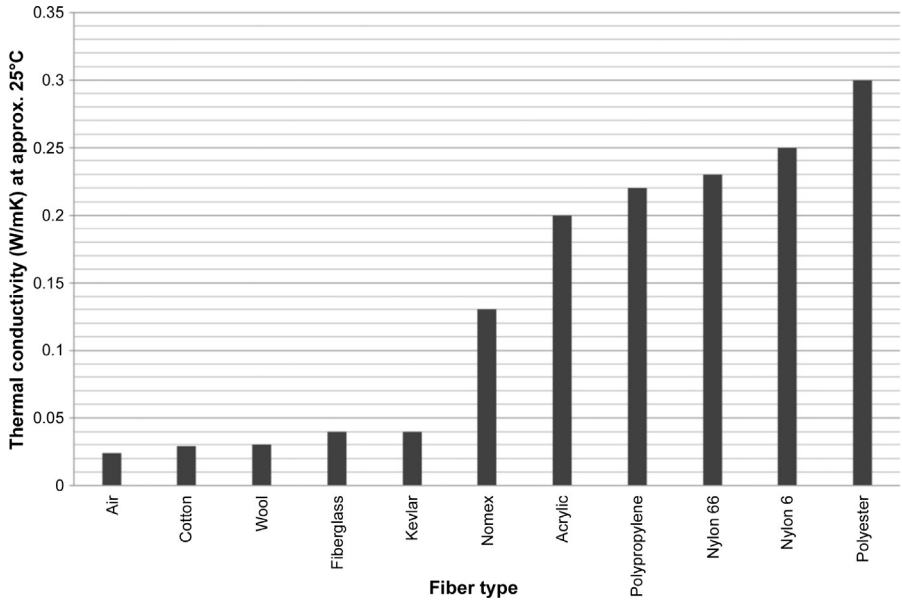

Fig. 8.9 Typical values of thermal conductivity of some fibers.1 Btu ft/(h·ft^{2}·°F = 1.730735 W/(m K).
Based on data from R.B. Seymour, Engineering Polymer Sourcebook, McGraw-Hill, NY, 1990; W.F. Smith, Materials Science and Engineering, AccessScience@McGraw-Hill, 2001, doi:10.1036/1097-8542.409550. http://www.accessscience.com, last modified: May 4; C.E. Carraher, Jr., Polymer, AccessScience@McGraw-Hill, 2004, doi:10.1036/1097-8542.535100. http://www.accessscience.com, last modified: March 12.

8.3 Review of different fiber types

Discussions on fiber types and their associated properties can be found in many literatures. For conventional fibers, an important classic book recommended is titled *Physical Properties of Textile Fibres* by Morton and Hearle [8]. This book covers many of the fundamental aspects associated with both the internal structures and the properties of conventional fibers. For synthetic fibers, technology, and properties, there are many sources of information including the ones listed in the references of this chapter [13, 14, 24–26]. For information regarding specialty fibers, fiber producer's technical reports obtained from their websites are recommended. In addition, some books were published that dealt specifically with specialty fibers [3, 15]. In this section, only a brief review of different fibers is presented as a quick reference for the reader.

8.3.1 Natural fibers

Natural fibers are those of natural sources, vegetable, or animal origins. Examples of the former include cotton, flax, and jute. Examples of the latter include wool and camel hair. Key points in dealing with these fibers in a product development project are as follows [16]:

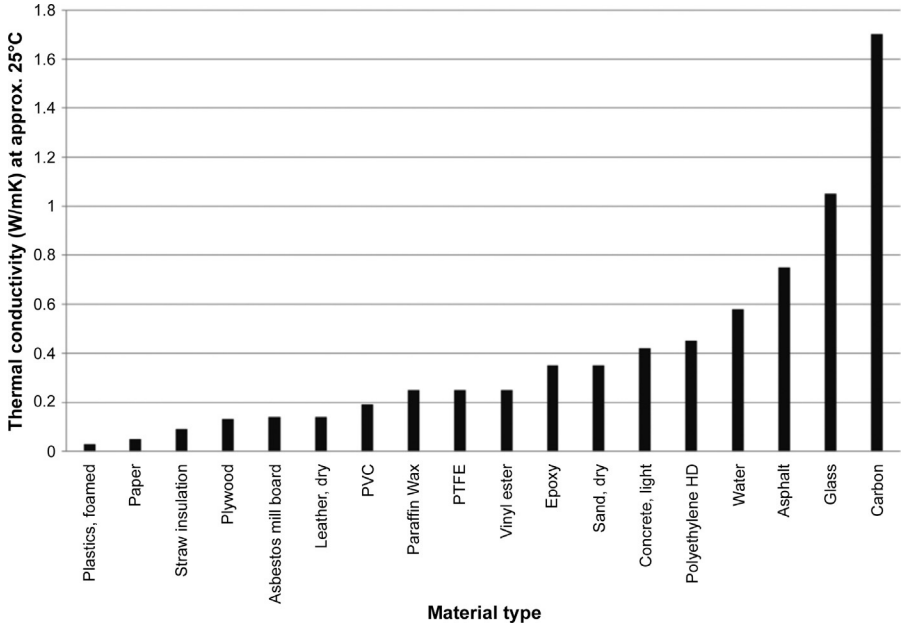

Fig. 8.10 Typical values of thermal conductivity of some materials.
Based on data from R.B. Seymour, Engineering Polymer Sourcebook, McGraw-Hill, NY, 1990; W.F. Smith, Materials Science and Engineering, AccessScience@McGraw-Hill, 2001, doi:10.1036/1097-8542.409550. http://www.accessscience.com, last modified: May 4; C.E. Carraher, Jr., Polymer, AccessScience@McGraw-Hill, 2004, doi:10.1036/1097-8542.535100. http://www.accessscience.com, last modified: March 12.

- Natural fibers are typically discrete (or staple fibers), and they are naturally produced of a wide range of fiber length, diameter, strength, and flexibility even within the same type of fibers.
- Natural fibers being unmanufactured and naturally produced will exhibit high degree of inherent variability in their properties. As a result, they should be described by both average values and associated variability measures such as range or variance.
- The inherent variability in the properties of natural fibers requires a great deal of effort in fiber selection and elimination of extreme undesired values.
- Blending of natural fibers, either within the same fiber type or of different fiber types, represents a key design aspect.
- Some properties of natural fibers (e.g., strength and color) may not exhibit linearly additive patterns upon blending. Therefore, experimental blending analysis is often critical in using natural fibers.
- When natural fibers are blended with synthetic fibers (e.g., cotton and polyester), the issue of linear additivity of fiber properties becomes more critical, and a great deal of experimenting may be required to reach optimum blends.
- Natural fibers will typically have low flame resistance, and they burn when ignited. Therefore, using these fibers in fire-retardant products will require special chemical treatments.

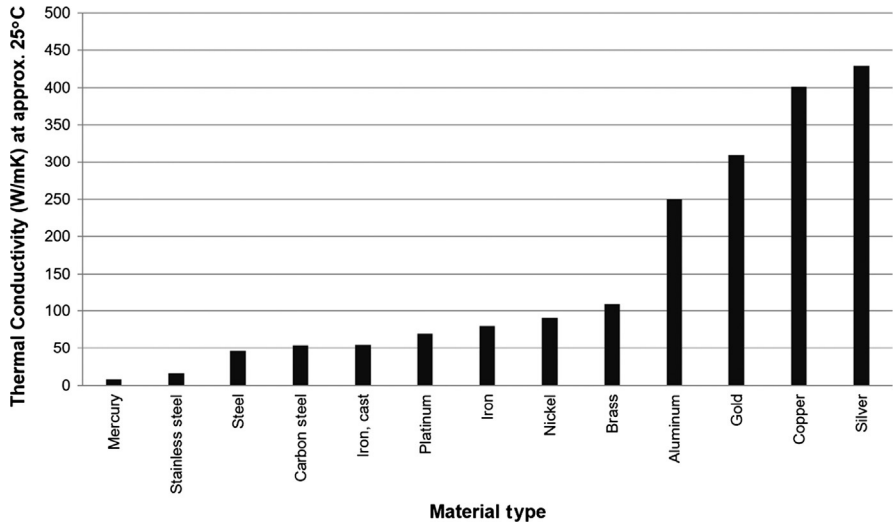

Fig. 8.11 Typical values of thermal conductivity of highly conductive materials. Based on data from R.B. Seymour, Engineering Polymer Sourcebook, McGraw-Hill, NY, 1990; W.F. Smith, Materials Science and Engineering, AccessScience@McGraw-Hill, 2001, doi:10.1036/1097-8542.409550. http://www.accessscience.com, last modified: May 4; C.E. Carraher, Jr., Polymer, AccessScience@McGraw-Hill, 2004, doi:10.1036/1097-8542.535100. http://www.accessscience.com, last modified: March 12.

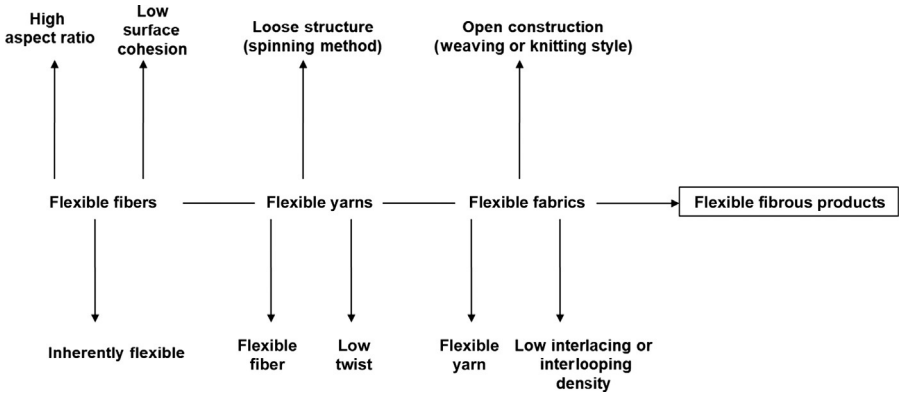

Fig. 8.12 Main factors determining flexibility of fibrous products.

8.3.1.1 Cotton fibers

Cotton is a natural cellulosic fiber made from long chains of natural cellulose (carbon, hydrogen, and oxygen). It exhibits a long linear molecular chain of over 10,000 cellulosic units held together with strong intermolecular forces [4, 8, 19]. As a result, it is reasonably strong within its use boundaries. The length-to-diameter ratio of the fiber is in the order of several thousand, which provides a great deal of flexibility, processing

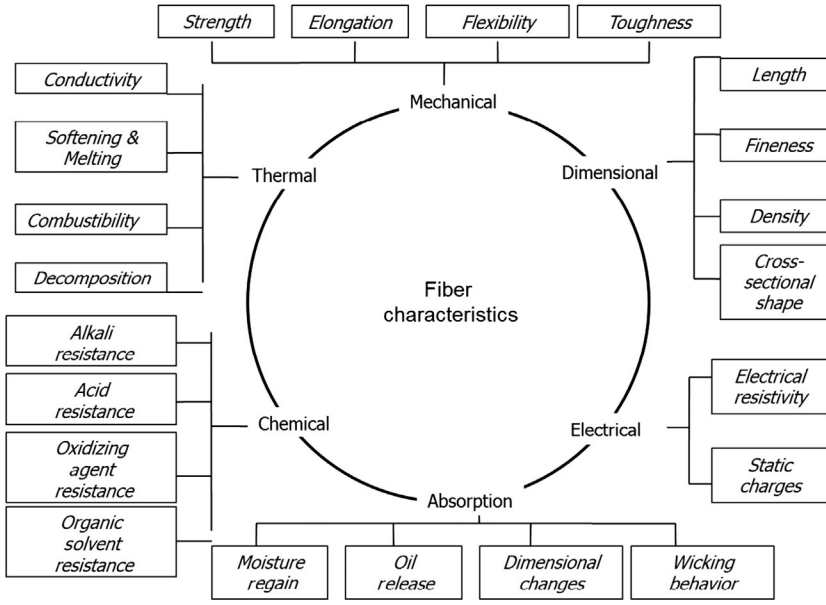

Fig. 8.13 Common performance-related fiber attributes.

ease, and product good-wearing performance. A typical cotton fiber length may range from 0.90 to 1.5 in., and fiber fineness may range from 100 to 200 millitex (0.9–1.8 denier). Most cotton fibers exhibit a range of fiber bundle tenacity from 25 to 35 g_f/tex (or 2.7–3.9 g_f/denier). Extralong staple (ELS) cotton can exhibit higher tenacity of up to 40 g_f/tex (4.4 g_f/denier). Cotton fiber breaking elongation typically ranges from 4% to 6%.

Most cotton fibers are used in traditional fibrous products, particularly apparels. This is due to their natural appeal and esthetic properties. Cotton fibers are also used widely for household and interior products such as towels, sheets, pillowcases, bedspreads, tablecloth, and upholstery. In recent years, efforts have been made to use cotton in technical fibrous products such as fire-resistant clothing and commercial carpets. In these applications, cotton fibers are treated with chemicals to enhance their performances. For example, chemical treatments such as Proban and Pyrovatex are used to make cotton fire-retardant products [27, 28]. In addition, cotton may be blended with wool and low-melt polyester fiber for utilization in carpets without the need of any topical finish.

8.3.1.2 Bast fibers

Another group of cellulosic fibers is Bast fibers or long-vegetable fibers. These include [29] flax, hemp, jute, and ramie. These fibers are relatively coarse, and they exhibit high levels of durability. Flax (also called linen) is the most commonly used fiber of this group. It is used to make a variety of apparel products including dresses, skirts, blouses, suits, coats, and hats. It is also used in interiors and home furnishing

products such as draperies and upholstery fabrics. Although flax exhibits approximately the same degree of polymerization as cotton, it is stronger than cotton as a result of its higher molecular orientation and higher crystallinity (see Table 8.1 and Fig. 8.3). It has a tenacity of about 6 g_f/denier and elongation at break from 1.5% to 3.5%. Like cotton, flax is stronger in wet conditions than in dry conditions (approximately 20% stronger).

Hemp is another long-vegetable fiber that was once the principal fiber used for marine cordage until replaced by abaca and sisal. It is still used extensively for twine and for many of the same products as linen. The fiber is usually about 4–7 ft (1–2 m) in length and 22 micron diameter. It is typically spun into coarser and strong yarns. The ends of the fibers are blunt and very thick walled, and they show some branching. This branching distinguishes hemp from linen under the microscope.

Jute fiber is commonly used for making strong and bulky fabric or twine that are used in wrapping or bag materials (e.g., Hessian, known as burlap in the United States, and a heavier weight fabric known as sacking). Jute fiber is usually 5–10 ft (1.5–3 m) or more in length and 20 micron diameter. Synthetic fibers, especially polypropylene, have made substantial inroads in the markets for jute. Polypropylene bags and prime back for tufted carpeting have displaced large quantities of jute. Also, bulk handling has eliminated much of the former market for grain bags, especially in the United States. Another competing fiber to jute particularly in products such as sacks, bags, and paper is kenaf. This is a long-vegetable fiber that has a similar appearance to jute, although the fiber is somewhat lighter in color. It also has similar or slightly lower strength than jute.

Ramie fiber is produced in length ranges from 28 to 60 in. (70–150 cm), and it can have up to 50 micron diameter. Ramie fabrics are typically very strong and stiff. They also gain strength when wet and are highly resistant to mildew and rot.

8.3.1.3 Wool fibers

Wool fiber is another common type of fibers used in traditional fibrous products. It is typically more expensive than cotton, and it is of limited supply as it primarily comes from the fleece of sheep. As an animal fiber, the main component of wool is protein (called keratin), which has a polypeptide chain with amino acid side chains. Keratin has a helical chain structure with strong hydrogen bonding [8]. The surface of the fiber has a unique surface morphology characterized by overlapping scales extending lengthwise from the cuticle. These scales provide a "differential frictional effect" with friction against the scales being significantly higher than that in the direction of the scales. Wool fibers may have fineness (diameter) ranging from 10 to 30 microns and fiber length ranging from 1 to 3 in. Coarse wool fibers can be stiff causing irritation and prickling effect when projecting from the fabric against the human skin. When wool fibers are used in carpets, this stiffness may provide a positive effect in terms of carpet integrity. The tenacity of wool fibers can vary significantly depending on the type of wool used; a typical range may be from 1.8 to 2.0 g_f/denier. Fiber elongation also varies from 25% to 45%. This high extensibility has a positive effect on its comfort characteristics. Like cotton, wool fibers are mostly used in

apparel products such as men's suits, women's suits and dresses, coats, casual shirts, and scarves or hats. More than 10% of the wool fibers are used for carpets and rugs. It also holds a place in household products such as blankets and upholstery.

8.3.1.4 Silk fibers

Silk is another protein natural fiber used in making traditional fibrous products, particularly luxury apparel products. It is produced by the silkworm and is the only naturally produced continuous filament, but it can be used in staple form. In the context of durability, silk is stronger than wool but is also stiffer. This strength is a direct result of high degree of polymer orientation and high crystallinity enhanced by strong hydrogen bonding. Although silk has long-chain molecules as its backbone, there are various sorts of side chains attached to these. One of the major problems of silk, which directly influences the performance characteristics of silk products, is its low crease resistance. This problem is typically handled by epoxide treatments [30].

8.3.2 Regenerated man-made fibers

Regenerated man-made fibers represent a unique category of fibers that is likely to attract more attention in product developments in the years to come because of their high sustainability. They are man-made fibers but made from natural resources, and they require lower energy (less use of fossil fuels). Regenerated fiber wastes can easily be used as a secondary raw material in producing new products. In the context of product development, the uniqueness of regenerated fibers stems from key characteristics such as high absorption, washability, softness, smoothness, tactile comfort, and good drape. New developments in the fiber industry have resulted in many derivatives of regenerated fibers with better physical properties (e.g., high tenacity and high wet modulus viscose). Viscose, rayon, acetate, triacetate, modal, Tencel, and Lyocell are all regenerated fibers. Regenerated fibers are mostly used in apparel products such as blouses, shirts, dresses, and slacks and lining fabrics for suits and coats.

Viscose rayon is a dominant regenerated fiber. In Chapter 2, the story of rayon development was introduced; it marked the beginning of unlimited development of man-made fibers. In comparison with cotton, conventional viscose rayon exhibits inferior physical properties as a result of its lower degree of polymerization and lower crystallinity. Regular viscose rayon fibers have medium strength, low modulus, and high elongation. Viscose fibers can be used as a filament yarn, woven or knitted into lustrous fabrics and crepe fabrics, and as a staple fiber, which can be blended with other fibers to add luster and absorbency.

Acetate fibers are made from cellulose acetate polymer solution. This fiber is relatively less durable than other fibers as it exhibits poor strength and poor abrasion resistance. Tencel and Lyocell are made, so they are fully recyclable and biodegradable; high strength when wet, minimal shrinkage, and good dye absorbency make them a popular blended fiber. Lyocell can also be used as a nonwoven fabric for wipes and swabs in medical situations and even for a disposable gown for medical staff.

8.3.3 Synthetic fibers

A wide range of synthetic fibers (oil and coal based) are used in making traditional fibrous products [13, 14]. The most commonly used fibers are polyester, nylon, acrylic, and polypropylene fibers. These fibers offer a wide range of values of different durability levels giving unlimited opportunities for designers of traditional fibrous products to select desirable levels of mechanical properties and other important characteristics. For example, melt-extruded fibers such as nylon 6,6 and nylon 6 are made in a wide variety of fiber fineness and cross-sectional shapes that are suitable for different types of traditional fibrous products. These fibers can be drawn at different draw ratios leading to different levels of strength and elongation. They are superior in elastic recovery and dimensional stability to many of the natural or regenerated fibers. A significant amount of nylon fibers is used for carpet and rug products; a relatively small amount is used for apparel products such as hosiery and socks, underwear, and nightwear. Nylon fibers can be made of regular tenacity suitable for apparel products or high tenacity suitable for the carpet market (see Tables 8.2 and 8.3).

Polyester fiber is also produced by melt spinning. This fiber is defined as any long-chain synthetic polymer composed of a least 85% by weight of an ester of a substituted aromatic carboxylic acid, including but not restricted to substituted terephthalate units and para-substituted hydroxybenzoate units. This fiber enjoys excellent strength and good elongation properties. The fact that this fiber can be effectively and efficiently blended with cotton provided a great market share in apparel and household products. Polyester has lower elastic recovery than nylon when elongated at 3%. As a result, nylon is more appealing for products such as women's sheer hosiery, and polyester is more appealing in durable clothing [29].

Acrylic fibers exhibit wool-like properties that make them attractive in the apparel market. They are known as manufactured fibers in which the basic substance is a long-chain synthetic polymer composed of at least 85% by weight of acrylonitrile units. These are spun into fibers by dry- or wet-spinning methods. Acrylic filaments are commonly converted into staple fibers for apparel products. They exhibit slightly higher tenacity and higher toughness than wool fibers. They also exhibit higher elastic recovery, which adds to their appeal in the apparel market. Indeed, over 75% of acrylic products are in the apparel market (e.g., sweaters, high-pile fleece for coats, and hosiery). Acrylic fibers also hold a solid place in the household and interior markets with products such as blankets, draperies, and upholstery.

Polyolefin fibers are commonly known as manufactured fibers in which the basic component is any long-chain synthetic polymer composed of at least 85% by weight of ethylene, propylene, or other olefin units [13]. They include polyethylene and polypropylene made by addition polymerization of ethylene and propylene and subsequent melt extrusion, respectively. Polyethylene fiber typically has low tenacity and low melting point (110°C). It is available in coarse deniers for some applications such as blinds, awnings, curtains, and car interiors. Polypropylene fibers, on the other hand, are widely accepted in the traditional market. They have high melting point of about 170°C, an average tenacity of 4 g_f/denier, and high breaking elongation. These properties enhance the polyolefin position in the carpet and rug industry and in many industrial applications [13].

Finally, a special category of fibers that has received increasing popularity in recent years is the elastomeric fiber. This is defined as the material that at room temperature can be stretched repeatedly to at least twice its original length and, upon immediate release of the stretch, will return to its approximate original length [13, 24, 25]. With at least 85% segmented polyurethane in their structure, elastomeric fibers are never used as the sole component of a product; instead, they typically play a supporting role by adding elastic features to fancy yarns and apparel products. The most common type of elastomeric fibers is spandex (commercially known as Lycra). This fiber is typically in a filament form of deniers ranging from 20 to 5400 denier. In the context of durability, spandex has lower tenacity than most fibers, but its high elongation and superior elastic recovery make it usable in many apparel products.

8.3.4 Fibers for high-performance applications

High-performance fibers represent a special category of fibers that is primarily made for technical products, but it can be used for some traditional fibrous products (e.g., some apparel support, upholstery, and floor coverings). From a design viewpoint, high-performance fibers provide additional design options in many products. They can be used in many fields from ground transportation to aerospace and from biotechnology to computer and communication applications. The key criteria of high-performance fibers are [31–36] very high strength, exceptionally high-temperature resistance, and unique geometrical characteristics (surface morphology and cross-sectional shapes). These criteria have been a result of major advances in polymer and fiber technology. Examples of high-performance fibers are discussed in the succeeding text. The reader should refer to Table 8.4 and Figs. 8.1, 8.4, 8.5, 8.8, and 8.10 for typical values of the characteristics of high-performance fibers.

8.3.4.1 Aramid fibers

Aramid fibers are polyamides, where each amide group is formed by the reaction of an amino group of one molecule with a carboxyl group of another. However, the presence of aromatic rings makes them more stable than with the linear arrangements of atoms. This provides great strength and heat stability. Two of the traditional aramid fibers are Kevlar, a high-strength fiber, and Nomex, a heat-resistant fiber. Kevlar was first produced by E.I. Du Pont de Nemours & Company, Inc. in the early 1970s as a candidate fiber for reinforcing tires and some plastics. Shortly after, this lightweight, strong, and tough fiber was incorporated in many products including composites, ballistics, tires, ropes, cables, asbestos replacement, and protective apparel [31]. Some radial automobile tires reinforced with Kevlar cords are like those reinforced with steel. Over the years, other Kevlar-like fibers were introduced such as Twaron by Accordis BV and Technora by Teijin Ltd.

Kevlar is commonly called para-aramid or poly(*p*-phenylene terephthalamide). It belongs to a class of materials known as liquid crystalline polymers [31]. In contrast with conventional flexible polymers, which in solution, they can easily bend and entangle (forming random coils), Kevlar polymers are very rigid and rodlike. As a result, in solution, they can aggregate to form ordered domains in parallel arrays.

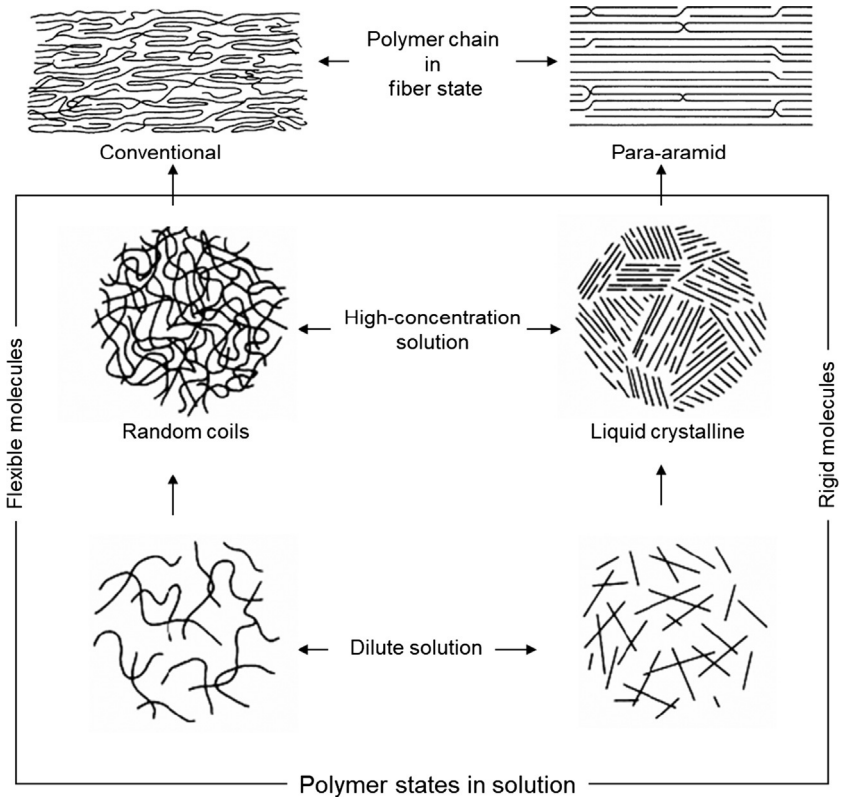

Fig. 8.14 Comparison of fibers from conventional flexible polymers and rigid polymers.

Fig. 8.14 shows comparison of fibers from conventional flexible polymers and rigid polymers. When the polymer solution (in concentrated sulfuric acid solvent) is extruded through a spinneret and drawn through an air gap during fiber production, the liquid crystalline domains are oriented and aligned in the direction of flow, yielding an exceptional degree of alignment of long, straight polymer chains parallel to the fiber axis. The final structure is an anisotropic, high strength, high modulus along the fiber axis. It is also fibrillar, which has a profound effect on fiber properties and failure mechanisms. Subsequent high-temperature processing under tension can further increase the orientation of the crystalline structure and result in higher fiber modulus. Kevlar fiber can be of continuous filament form or staple fiber form. This makes it formable into spun yarns, woven or knit fabric forms, textured yarn, needle-punched felts, spun-laced sheets, and wet-laid papers.

Nomex is the registered brand name of a flame-retardant meta-aramid material. This *m*-aramid or poly(*m*-phenylene isophthalamide) was first discovered by DuPont in the 1970s. The DuPont scientist responsible for discoveries leading to the creation of Nomex is Dr. Wilfred Sweeny. This unique material can be made in either sheet or fiber form. Nomex sheet is a calendered paper commonly used for electrical insulation

applications such as circuit boards and transformer cores and fireproof honeycomb structures where it is saturated with a phenolic resin [3]. These honeycomb structures and mylar-nomex laminates are used extensively in aircraft construction. In addition, both the firefighting and vehicle racing industries use Nomex fibers to design clothing and equipment that can withstand intense heat.

Although Nomex belongs to the class of aramid fibers like Kevlar and both are largely heat and flame resistant, Kevlar having a para-orientation can be molecularly oriented and aligned to provide exceptionally high strength. Meta-aramid, or Nomex, on the other hand, cannot be aligned during filament formation. As a result, it has lower strength and modulus than Kevlar. Under exposure to extreme heat, Nomex structures consolidate and thicken. When blended with a small percentage of Kevlar, a combination of high-temperature resistance and strength enables these swollen fabrics to remain intact. This is referred to as nonbreak-open protection [3, 15]. Another key attributes of Nomex is its light sheet weight (as low as 1.5 oz per square yard). This makes it possible to design fabrics and protective garments and gloves for various applications. It also extends its applications to areas such as reinforcement fabric in diaphragms and hose constructions. The fiber is also highly resistant to hydrolysis, alkali, and oxidative substances. This makes it an excellent candidate for a premium class of fabrics used for rubber reinforcement. Additional good attributes of Nomex is low shrinkage and good dye affinity.

Examples of Nomex products include Nomex hoods used as a common piece of firefighting equipment [31, 32]. This piece is typically placed on the head on top of a firefighter's face mask to protect the portions of the head not covered by the helmet and face mask from intense heat and fire. Race car drivers use similar hood to protect them in the event of fire engulfing their cars. Military pilots and aircrew wear one-piece coveralls (or flight suits) made of about 90% Nomex to protect them from the possibility of cockpit fires. The remaining 10% is usually Kevlar thread used to hold the fabric together at the seams. The US space program also used its share of Nomex and Kevlar, particularly for the extravehicular mobility unit and ACES pressure suit. These items require high fire resistance and high protection against extreme environmental conditions such as water immersion to near vacuum. Other Nomex products include thermal blankets on the payload bay doors, fuselage, and upper wing surfaces of the space shuttle orbiter.

8.3.4.2 Gel-spun polyethylene fibers

This category of fibers represents ultrastrong and high-modulus material derived from the simple and flexible polyethylene molecule. They are commonly called high-performance polyethylene (HPPE) fibers, high-modulus polyethylene (HMPE) fibers, or sometimes extended chain polyethylene (ECPE) fibers [33]. The molecular structure of this category of fibers is different from that of para-aramid fibers in that it is not a rodlike structure, which needs to be oriented in one direction to form a strong fiber. Instead, polyethylene has much longer and flexible molecules that, by physical treatments, can be forced to assume straight (extended) conformation and orientation along the fiber axis [34].

In the real world, polyethylene is probably the most commonly used polymer (or plastic) that human uses in daily life. This is the polymer that makes grocery bags, shampoo bottles, and children's toys. For such a diverse application, the normal polyethylene polymer has a very simple structure, the simplest of all commercial polymers. It is nothing more than a long chain of carbon atoms, with two hydrogen atoms attached to each carbon atom. In this simple form, the molecules are not oriented and can easily be torn apart. As a result, the formation of high-strength polymer requires stretching, orienting, and forming a highly ordered (crystalline) structure from a long molecular chain. Accordingly, the starting substance should be polyethylene with an ultrahigh molecular weight (UHMW-PE). This, in turn, creates a problem with spinning since extrusion of a very high-viscosity melt is extremely difficult. Drawing the filaments for high orientation is also difficult as a great deal of entanglement of the molecular chains is to be expected with this type of polymers. These two problems were solved using the so-called gel spinning [33]. In principle, gel spinning operates on the basis of dissolving the molecules in a solvent prior to extrusion through a spinneret [33, 34]. This only allows a smooth extrusion, but molecular entanglement has to be resolved through superdrawing of the gel material after spinning. Fig. 8.15 shows the basic difference between normal PE and HPPE.

The most common types of high-performance polyethylene fibers are Dyneema and Spectra. These are produced as multifilament yarns of a wide range of denier per filament (dpf) from 0.3 to 10 dpf. The tenacity of a single filament can be greater than 3 N/tex, and the modulus can be greater than 120 N/tex (see Table 8.4). Since fiber density is less than one, the fiber can float on water. The combination of high tenacity and low density makes the specific strength of this fiber higher than steel (10–15 times that of good quality steel). The modulus of high-performance polyethylene fiber is second only to that of special carbon grades. Elongation at break is relatively small, which is common in most high-performance fibers. However, the high tenacity makes these fibers extremely tough as indicated by their high values of energy to break [34]. The fibers are also highly resistant to abrasion, moisture, UV rays, and chemicals.

The Dyneema fiber, developed by the Dutch company DSM, has been used in many high-strength, low-weight applications. These include bulletproof armor and protective clothing for law enforcement and military personnel. Some body armors

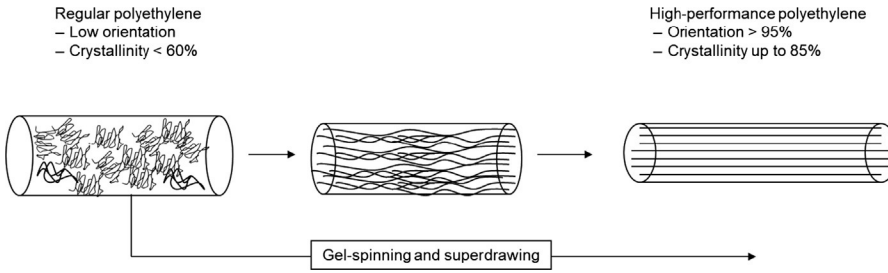

Fig. 8.15 Comparison of molecular structures of normal PE and HPPE.

have been designed from a combination of Dyneema high-performance polyethylene fiber and Steelskin steel cord material to provide stab protection against edged weapons, an application that traditionally required heavier and stiffer outfits, which were uncomfortable to use. The underlying design principle of this product is based on blunting and damaging a blade with each thrust using the steel wire while further absorbing the impact energy by the superstrong fiber to stop the damaged knife and minimize trauma (https://www.army-technology.com/contractors/personal/dsm-dyneema/).

The Spectra fiber produced by Honeywell has also been used in protective clothing (or shield technology), https://www.packagingcomposites-honeywell.com/spectra/product-info/spectra-fiber/. Shield technology lays parallel strands of synthetic fiber side by side and holds them in place with a resin system, creating a unidirectional tape. Two layers are then cross plied at right angles (0/90 degrees) and fused into a composite structure under heat and pressure. The preconsolidated cross-plied material is then packaged as rolls to make a ready for use product. This technology can use Spectra fiber or other fiber types such as aramid fiber. The distinct advantage of shield technology, especially in armor applications, is that it preserves the strength of the Spectra fiber or any other fiber encased within the resin matrix. Because the fibers are not crimped as they are in a traditional weaving process, the energy of the projectile is allowed to rapidly dissipate along the length of the fiber. Normally, the weaving process induces a great deal of bending and flexing, which reduce the characteristic molecular alignment of the high-performance polyethylene fiber.

8.3.4.3 Carbon fibers

Carbon fibers contain at least 90% carbon by weight. They are commonly derived from several organic polymers, such as rayon and polyacrylonitrile (PAN). The first commercial carbon fiber was rayon based introduced in 1959. This fiber found its applications primarily in military products. Since 1970, PAN-based fibers have largely replaced rayon-based fibers in most applications. This was attributed to their superior tensile strength. PAN-based carbon fibers are now used in a wide array of applications such as aircraft brakes, space structures, military and commercial planes, lithium batteries, sporting goods, and structural reinforcement in construction materials [35]. They can be woven into sheets, tubes, or other desired structures, and they are often used in making carbon fiber composites using epoxy resins or other binders.

Another more advanced carbon fiber is the so-called pitch-based carbon fiber. This is relatively very expensive, but it is unique in its ability to achieve ultrahigh Young's modulus and thermal conductivity. The high cost of this type of fibers has restricted their use to some specific military and space applications. A lower modulus, nongraphitized mesophase pitch-based fiber, of lower cost, was also introduced for extensive use in products such as aircraft brakes. In addition to strength and modulus characteristics, it also exhibits good thermal and electrical conductivity.

PAN-based carbon fibers are made using many different methods [35]. The polymer is made by free-radical polymerization, either in solution or in a solvent-water suspension. The polymer is then dried and redissolved in another solvent for spinning,

either by wet spinning or dry spinning. Melt-spinning PAN plasticized with water or polyethylene glycol is another spinning possibility that is under development. The preferred method for high-strength carbon fiber (i.e., 80% strength improvement over conventional carbon fibers) is wet spinning using clean room conditions followed by heat treatment. Examples of carbon fibers produced by these methods include Toray T800 and T1000. To make carbon fibers, the polymer is stretched into alignment parallel with what will eventually be the axis of the fiber. Then, an oxidation treatment in air between 200°C and 300°C transforms the polymer into a nonmeltable precursor fiber. This precursor fiber is then heated in a nitrogen environment. As the temperature is raised, volatile products are given off until the carbon fiber is composed of at least 90% carbon. The temperature used to treat the fibers varies between 1000°C and 2500°C depending on the desired properties of the carbon fiber. Under these high temperatures, carbon fibers of diameters ranging from 6 to 10 μm can be produced. With a fiber density ranging from 1.75 to 2.0 g/cm^3, fiber strength can range from 3 to 7 GPa, modulus from 200 to 500 GPa, compressive strength from 1 to 3 GPa, and shear modulus from 10 to 15 GPa. Carbon fibers made from pitch can have modulus, thermal, and electrical conductivities as high as 900 GPa, 1000 W/mK, and 106 S/m, respectively.

Graphite fibers can be considered as derivatives of carbon fibers. If during the treatment process of carbon fibers, the temperature is raised above 2500°C, graphite will be formed instead of carbon fibers [36, 37]. However, most of the graphite used in industry is manufactured by heating petroleum by-products to about 2800°C. The petroleum by-products are similar to the polymers used in the carbon fiber process in that both contain chains of carbon atoms. One may consider graphite as a soft form of carbon, which exhibits a unique combination of very low density and high elastic modulus with mechanical strength increasing with increasing temperature. Indeed, this unique material is capable of mechanical service at temperatures of 2200°C (4000°F) or higher. The main problem with graphite is its vulnerability to oxidation since it is essentially a form of carbon.

8.3.4.4 Glass fibers

The art of heating sand and limestone to form a molten liquid has been known from the time of the ancient Egyptians. Since the 1930s, glass has been spun into fiber that is sufficiently pliable to be woven into fabrics. Some believe that Napoleon's funeral coffin was decorated with glass fiber textiles. Glass fibers are prepared by the melt spinning of previously formed glass marbles, and the molten filaments are drawn down to very fine dimensions [38]. Glass fibers are inherently stiff, but they stem their flexibility from fiber fineness. Indeed, the fibers are so stiff that when broken, they can penetrate the human skin, making them unsuitable for use in apparel or upholstery. Because of their good resistance to the degrading effects of sunlight and their flame resistance, they can be used for curtains and drapery. They also provide a nonrotting, nonsettling insulating material for homes and industrial uses.

In Chapter 7, it was indicated that glass fibers have been used as a substitute to asbestos fibers in high-temperature applications because of their high heat resistance

(up to 450°C). From a design viewpoint, the thermal performance of glass fibers is attributed to two key factors: the thermal conductivity of the glass itself (see Fig. 8.10) and the structural features of a fiber glass product (structure density, fiber dimensions, and air/fiber volume ratio). Fiber glass is also commonly used for filtration purposes. For these applications, the surface area of fibers and the structural pore size represent the key design parameters. In this regard, fiber glass can be made of superfine to medium or coarse diameters (0.05–25 μm). For apparel applications, fiber glass has poor esthetic characteristics and high densities and is difficult to process. Another critical field of fiber glass is electronic and communication. For these applications, optical fibers made from fiber glass are extremely effective.

Since silica is an excellent glass base, inorganic glasses are all made from silica. The problem is that silica $(SiO_{4/2})_n$, being a three-dimensional network cannot be converted into a liquid form easily. It fails to exhibit a sharp melting point and starts to soften at 1200°C, but even at this point, it is not fluid enough for extrusion into filaments; this requires a higher temperature of up to 2000°C. Some additives may be used to reduce the melting point of silica [38, 39]. The majority of continuous glass fibers are spun from the so-called E-glass formulation. E-glass fibers can be used as reinforcing materials for resins, rubber, or polymer composites. Some E-glass fibers are used for fire-resistant applications. Another type of glass fiber is the so-called A-glass. This is more economically attractive as it utilizes plate glass scrap, made in a remelt process rather than difficult direct melting. A-glass normally exhibits half the strength of E-glass, and it is commonly used as insulation materials in many thermal or acoustic applications [39]. Another glass formulation is the so-called C-glass, which commonly used to substitute for the deficiency of E-glass in applications requiring better acid and alkali resistance. C-glass may also be used in place of E-glass for the reinforcement of bitumen for roofing mats. For high-strength composite structures, S-glass developed by Owens Corning Fiberglass is commonly used. Other common applications for glass fibers include electrical circuit boards, automobile water-pump housings, and durable pipes.

8.3.4.5 *Metallic and ceramic fibers*

Metallic and ceramic fibers represent a special category of fibers that aims at using the outstanding features of metal alloys and ceramic material in a semiflexible form to allow easier manipulation of these materials in applications requiring their precise and directed incorporation in various structures [40, 41]. Metallic fibers of silver and gold have been used for millennia to decorate fabrics. Today, metallic fibers serve functional and decorative purposes. These fibers are formed by drawing metal wires through successively finer dies to achieve the desired diameter. Although gold and silver are the easiest to draw, modern methods have allowed the manufacture of steel, tantalum, and zirconium fibers [13]. Because they are electrical conductors, metal fibers have been blended into fabrics to reduce the tendency to develop static electrical charges.

The idea of developing ceramic fibers was largely driven by the need for reinforcing ceramic matrix composites in applications where temperatures can be elevated

to above 1000°C. This type of applications required ceramic structures that are fine and flexible for easy manipulation and directed functions. Now, many ceramic fibers (oxide and nonoxide) are available in the market with diameters ranging from 10 to 20 μm. In addition, larger diameters ceramic fibers (over 100 μm) are also available for applications such as gas turbines, heat exchangers, and contaminant walls for fusion reactors [5].

In comparison with organic fibers or even glass fibers, ceramic fibers are uncontested in withstanding high-temperature applications. In comparison with carbon fibers, ceramic fibers will prevail based on the oxidizing and corrosive issues associated with carbon fibers. Carbon fibers will also degrade at temperatures above 300°C. The inherent stiffness of ceramic fibers can limit their formation into fabrics as they must be woven to meet this requirement. However, this manufacturing limitation can be largely overcome using finer ceramic fibers (about 10 μm) to allow enough flexibility for fabric formation.

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