

**Fibers**  
**Volume 1**





# Fibers, 1. Survey

FRITZ SCHULTZE-GEBHARDT, Düsseldorf, Federal Republic of Germany (Chaps. 2–7)

KARL-HEINZ HERLINGER, Institut für Chemiefasern der Deutschen Institute für Textil- und Faserforschung Stuttgart, Denkendorf, Federal Republic of Germany (Chaps. 2–8)

1. Introduction . . . . .	3	5.4. Crystallization . . . . .	9
2. History . . . . .	4	5.5. Organization of Structural Elements . . . . .	9
3. Characteristics of Fibers . . . . .	4	5.6. Structural Models . . . . .	10
3.1. Fineness . . . . .	4	5.7. Molecular Symmetry and Physical Properties . . . . .	10
3.2. Tenacity and Modulus of Elasticity . . . . .	5	5.8. Changes in Properties Caused by Symmetry Defects . . . . .	11
3.3. Elongation . . . . .	5	6. Fiber Properties Required by Textiles . . . . .	12
4. Spinning . . . . .	5	6.1. Requirements to Be Met by Textiles . . . . .	12
4.1. Wet Spinning . . . . .	5	6.2. Modification of Fiber Properties . . . . .	12
4.2. Dry Spinning . . . . .	6	6.3. Comfort Properties of Textiles . . . . .	14
4.3. Melt Spinning . . . . .	6	7. Economic Aspects . . . . .	14
5. Prerequisites for Fiber Formation . . . . .	6	8. Tabular Survey of Fibers . . . . .	15
5.1. Molecular Mass and Fiber Formation . . . . .	6	9. References . . . . .	36
5.2. Molecular Structure and Fiber Properties . . . . .	7		
5.3. Property Requirements for the Formation of Fiber Structures . . . . .	8		

## 1. Introduction

The term fibers refers collectively to a wide variety of forms of fibrous materials. Standards have been established to introduce order into the field. The most frequently employed terms are defined here. Natural fibers that can be spun into yarn are called *staple fibers*. The primary spinning of man-made fibers results in the production of *continuous filaments* (endless fibers). Indeed, both *monofilaments* (threads; spinneret has one hole) and *multifilaments* (spinneret has many holes) can be produced. A *filament yarn* consists of a large number of filaments that can be given texture by twisting, crimping and/or heat setting.

The word *tow* refers to a *fiber tape* made from thousands of filaments. If a tow is cut or torn, it gives rise to staple fibers. Fiber tapes obtained by cutting or tearing parallel to the fibers are known as *fiber bands*.

Conventional standards divide fibers into (1) *natural fibers* and (2) *man-made fibers* (also called chemical fibers).

Natural fibers are subdivided into plant and animal fibers. Man-made fibers are subdivided

into natural materials brought into fiber form by a chemical reaction (regenerate fibers) and fibers made from synthetic polymers (synthetic fibers). The following classification includes standardized abbreviations that are used occasionally throughout this article:

1. Natural fibers
  - 1.1. Plant fibers, e.g.,
    - cotton
    - flax
    - hemp
    - jute
  - 1.2. Animal fibers, e.g.,
    - wool
    - camel hair
    - angora
    - silk
2. Man-made fibers
  - 2.1. Fibers based on natural polymers, e.g.,
    - viscose rayon (CV)
    - Lyocell (CLY)
    - cellulose acetate (CA)
    - elastodiene (LA)
  - 2.2. Fibers based on synthetic polymers (synthetic fibers), e.g.,
    - polypropylene (PP)

polyacrylonitrile (PAN)  
 poly(vinyl chloride) (PVC),  
 polyamide 6 (PA 6, nylon 6)  
 polyamide 66 (PA 6,6; nylon 66)  
 poly(ethylene terephthalate) (PET)  
 poly(ether ether ketone) (PEEK)  
 polyurethane (PUR; spandex)

## 2. History

**Natural Fibers.** Natural fibers have been used by humans for thousands of years. Animal hair and plant fibers were spun into yarn and woven into textiles. Indeed, the textile industry today is still based on this ancient technology.

**Man-Made Fibers.** The idea of making “artificial” fibers and threads is over 300 years old. In fact, the start of the chemical fiber industry dates from about 1884. The process of regenerating fiber-forming cellulose was based on the discovery of solvents such as copper oxide–ammonia by E. SCHWEIZER in 1857. Later, Count CHARDONNET succeeded in forming derivatives of cellulose which could be solubilized and spun into threads; “Chardonnet silk” was first made in 1884. A detailed account of the history of man-made fibers is not given in this article. The subject was dealt with competently by H. KLARE in 1985 [19].

The most important developments in the production of man-made fibers based on cellulose were:

- 1) the cuprammonium process for solubilization and spinning of cellulose;
- 2) the formation of spinning solutions of cellulose derivatives, such as cellulose nitrate and cellulose acetate;
- 3) the intermediate derivatization of cellulose to cellulose xanthate which in turn is spun into cellulose fibers;
- 4) the development of new solvent systems for cellulose, such as *N*-methylmorpholine oxide (NMMO) or dimethylacetamide–lithium chloride.

In 1927, H. STAUDINGER used polyoxymethylene as a model of cellulose to demonstrate that fiber-forming polymers were linear polymeric molecules.

The production of synthetic fibers was the result of pioneering work on the formation of synthetic polymers and the development of extrusion techniques known as wet, dry, and melt spinning.

Nylon 66 was first synthesized by W. H. CAROTHERS in 1935. This was closely followed by the discovery of nylon 6 by P. SCHLACK in 1938. The work of J. R. WHINFIELD and I. T. DICKSON led to the development of polyester fibers in 1941. Today, polyamides and polyesters are the largest-volume polymers capable of being melt-spun. The production of synthetic fibers based on familiar polymers such as polyacrylonitrile, which cannot be melt-spun, was made possible by the introduction of new solvents, e.g., dimethylformamide (H. REIN, 1942). Discovery of the stereospecific polymerization of propylene (G. NATTA, 1954) led to the introduction of polyolefins into the fiber industry. The development of technology and the simultaneous elucidation of structure and properties resulted in “tailor-made” polymers and fibers. Specific properties such as rubber elasticity (O. BAYER, 1947) or extreme tenacity and stiffness were realized (high-modulus fibers, P. W. MORGAN and S. L. KWOLEK, 1968). In addition, high-temperature fibers were made from polyheterocyclic compounds.

Apart from organic polymers, inorganic substances such as glass, carbon, BN, and SiC were also spun into fibers.

Future developments are likely to be directed toward classical mass production, particularly towards the attaining of optimal processing characteristics and clothing comfort. New types of application – above all in the field of industrial fibers and in medical technology – will stimulate the development of special fibers with very specific properties.

## 3. Characteristics of Fibers

### 3.1. Fineness

The thickness of fibers and filaments ranges from 1 to 100  $\mu\text{m}$ . Measuring thickness by means of conventional instruments is very difficult. Indeed, even small variations in fiber uniformity, thickness, and cross-sectional area hinder microscopic measurement. To make a sta-

tistically valid statement about the fineness of a fiber (fiber density), length and mass are computed instead of thickness. The unit *tex* is used to express fiber fineness. According to the ISO,

$$1 \text{ tex} = 1 \text{ g per } 1000 \text{ m}$$

If 1000 m of fiber weigh 1 g, the fineness is 1 tex. Another unit commonly used to express fineness is dtex. If the mass per length is given in dtex, the numerical values will be comparable to those in the formerly used unit *denier* [46]:

$$1 \text{ denier} = 1 \text{ g per } 9000 \text{ m}$$

### 3.2. Tenacity and Modulus of Elasticity

The cross-sectional area of fibers is generally nonuniform and cannot be determined easily. Hence, measurements based on area have limited applicability. For this reason, tenacity is not measured in gigapascal (GPa) units (ISO) but is expressed relative to the fineness. Usually, the maximal tensile force (at break) is employed, expressed in centinewtons per tex (cN/tex); other units used are cN/dtex (1 cN/dtex = 10 cN/tex) or N/tex (1 N/tex = 100 cN/tex). Textile and industrial fibers have tenacities ranging from 10 to more than 300 cN/tex (see Table 4). The modulus of elasticity corresponds to the tangent to the stress–strain curve at the origin (→ Fibers, 6. Testing and Analysis, Chap. 3.). It is also expressed relative to the fineness, in cN/tex. Typical moduli range from 50 to 1000 cN/tex for textile fibers and from 1000 to 40 000 cN/tex for industrial fibers. (See Table 5.)

### 3.3. Elongation

The highest possible degree of elongation at break (→ Fibers, 6. Testing and Analysis, Chap. 3.) varies greatly with the type of fiber. Industrial fibers, e.g., carbon fibers and high-modulus aramids, have values of 0.1–2%; textile fibers and yarns have values of 5–70%; and values of 300–700% are obtained for spandex fibers (see Table 4).

In practical applications, fibers are elongated only to a small extent. Maximal elongation is

never attained because otherwise fibers undergo partially irreversible stretching.

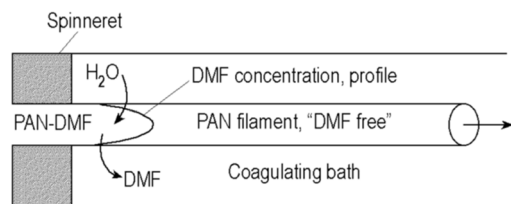
Temperature and moisture (weather) affect both the tenacity and the elongation of fibers to varying extents, depending on the type of polymer. The same applies to dimensional stability and wrinkling tendency, properties that are also influenced by the type of fiber and by the textile structure.

## 4. Spinning

Both natural and synthetic fibers are consisting of linear polymers. These polymers are converted into fibrous form by growth (animal hair, plant fibers) or extrusion (spider, silkworm, spinning technology) and are specifically oriented to the fiber axis. The many mechanisms found in nature for the formation of filamentous structures are, by no means completely understood (see e.g. [87]). Only a few processes are available for large-scale production of man-made fibers. Specific production techniques are based on the deformability of fiber polymers. In principle, a distinction is made between spinning methods involving solutions and those involving molten polymer. For a detailed description of spinning, see → Fibers, 3. General Production Technology.

### 4.1. Wet Spinning

Polymer solutions are converted into fibers by diluting a highly concentrated polymer solution in a coagulating bath. The extremely viscous polymer solution, e.g., 3.5–10 Pa·s (still higher values are obtained with viscose rayon) can be extruded, i.e., spun, by forcing it through a spinneret to form threadlike structures. In general, polymers are soluble only in specific solvents. The viscous polymer solution is extruded into a coagulating bath where the solvent is diluted, which results in precipitation of polymer threads. For instance, polyacrylonitrile is soluble in dimethylformamide (DMF). In the coagulating bath, DMF is washed out of the viscous polymer threads with water, and polyacrylonitrile fibers precipitate (Fig. 1).



**Figure 1.** Fiber formation by solvent extraction in the spinning bath  
 PAN = polyacrylonitrile; DMF = dimethylformamide

The solvent concentration in the fiber decreases along the length of the coagulating bath. In wet spinning, several physicochemical processes occur simultaneously, e.g., solvent diffusion, polymer precipitation, and formation of membrane-like interfaces and system-specific morphological structures. One of the main purposes of developing wet-spun polymers is to produce specific fiber structures in the coagulating bath. This is achieved, in principle, by modification in the coagulating bath, which is described in more detail under → Fibers, 4. Synthetic Organic, Chap. 5.3.3., wet spinning of polyacrylonitrile. In a spinning process of this type, the polymer can also undergo a chemical reaction; e.g., the viscose process involves acid hydrolysis of cellulose xanthate in the coagulating bath (→ Cellulose, Chap. 3.1.3.).

To make the process economical, the polymer concentration should be kept as high as possible during spinning. In the case of soluble polymers, the viscosity of the spinning solution, and thus its basic spinnability, are directly related to the concentration and solvation of the polymers. However, complicated processes, such as exchange, diffusion, and drying, that occur during wet and dry spinning result in polymer- and solvent-dependent limitations on the polymer concentration.

## 4.2. Dry Spinning

In dry spinning, the polymer solution is also forced through a spinneret. Solvent is then evaporated in a warm current of air to produce almost solvent-free filaments. Cellulose acetate, polyacrylonitrile, and polyurethane are spun by this technique (→ Fibers, 4. Synthetic Organic).

## 4.3. Melt Spinning

In melt spinning, the polymer is melted by heating and then passed through a spinneret via a spinning pump. Only polymers that are thermally stable under melt conditions can be subjected to this extrusion (i.e., spinning) process. The fluid threads emerging from the spinneret solidify on cooling (usually air cooling) to form filaments. This technique is applied in spinning, e.g., nylon 6, nylon 66, or poly(ethylene terephthalate) (→ Fibers, 4. Synthetic Organic).

The difference between melting and spinning temperatures depends on the viscosity of the melt. Usually, the spinning temperature is about 30 K higher than the melting temperature  $T_m$ . However, if the viscosity is still too high, the spinning temperature must be increased even further. For example,  $T_m$  of polypropylene is 170 °C but the polymer is spun at 260 °C. The melt index, not the viscosity, is generally used to characterize the melting properties of polymers. In fact, the tedious measurement of melt viscosity has now been replaced by simple mass determination (→ Fibers, 6. Testing and Analysis).

Hence, melt spinning requires polymers that are thermally stable and, as far as possible, resistant to thermal oxidation at temperatures approximately 30 K higher than their melting temperatures (PA-6, PA-66, and PET).

Production conditions must be optimally coordinated with the properties of the product to achieve the desired melt viscosity, on the one hand, and the required fiber tenacity, on the other. Rapid advances in process technology, however, have made possible not only the processing of very highly viscous melts, but also the extrusion of solids.

## 5. Prerequisites for Fiber Formation

### 5.1. Molecular Mass and Fiber Formation

The spinnability of polymer melts or solutions depends on their viscosity at technically feasible spinning conditions. The viscosity  $\eta$  of linear polymers depends, in turn, on the molecular mass  $M_T$ :

**Table 1.** Polymer type and molecular mass suitable for fiber formation

Polymer	Repeating unit	Fiber formation at $M_r$	Degree of polymerization
Polyethylene	$-\text{CH}_2-\text{CH}_2-$	> 1 000 000	> 62 500
Polypropylene	$-\underset{\text{CH}_3}{\text{CH}}-\text{CH}_2-$	> 1 000 000	> 45 455
Polyacrylonitrile	$-\underset{\text{C}}{\underset{\text{N}}{\text{CH}}}-\text{CH}_2-$	> 30 000–70 000	> 1070–2500
Aliphatic polyamides	$-\text{CH}_2-\text{NH}-\text{CO}-\text{CH}_2-$	15 000–30 000	380–770
Aliphatic polyesters	$-\text{CH}_2-\text{O}-\text{CO}-\text{CH}_2-$	50 000	1300
Aliphatic–aromatic polyesters	$-\text{O}-\text{CH}_2-\text{CH}_2-\text{O}-\text{CO}-\text{C}_6\text{H}_4-\text{CO}-$	22 000–26 000	220–260
Aromatic polyamides	$-\text{NH}-\text{C}_6\text{H}_4-\text{NH}-\text{CO}-\text{C}_6\text{H}_4-\text{CO}-$	60 000	550

$$\eta = K \cdot M_r^\alpha$$

where  $K$  is a constant that is known for most common polymers.

The fiber-forming tendency of a polymer increases with increasing molecular mass. The varying forces of interaction between individual structural groups of polymers are directly related to the chemical nature of these linear molecules. For this reason, optimal conditions for fiber formation are very polymer-specific. In principle, the weaker the interaction between structural segments, the higher is the molecular mass required (Table 1) [47].

## 5.2. Molecular Structure and Fiber Properties

The thermochemical and photochemical stability of a fiber polymer is controlled by its chemical structure. The possibility of chemically modifying textile properties is determined by the chemical reactivity and polarity of the individual structural units (Table 2). The type of chemical bonds and the stereochemistry are important for molecular geometry, interaction of structural units, and thermal conformational stability. Low conformational mobility is generally related to high mechanical tenacity, modulus, and torsion modulus. Finally, the molecular organization is influenced by the symmetry of the structural units and of the entire molecular chain.

The interaction energy (cohesion energy) controls the solubility and compatibility of structural units with each other. These factors finally lead to specific morphological domains, which frequently occur in block structures of varying chemical composition along the polymer chain, e.g., in polyurethane (spandex) fibers. The general relationship between the structure and properties of polymers suitable for fiber production is discussed in the literature [47]. In this section the structural elements of technically important fibers are compared.

**Table 2.** Structural characteristics of polymers and their importance for fiber properties

Structural characteristics	Importance for fiber properties
Chemical structure (primary structure)	thermochemical and photochemical stability, textile chemical processes (dyeing, textile finishing)
Molecular organization and symmetry	general properties, melting point, shrinkage behavior
Type of binding and stereochemistry (secondary structure)	thermophysical and thermomechanical properties (moduli, elasticity)
Conformation and conformational mobility	
Morphological structures, superstructures	diffusion (dyeing), breaking mechanism

*Crystallization.* The interaction between structural units is of considerable importance for crystallization. The chemical structure, stereochemistry, and symmetry of polymers determine, to a large extent, the structural conforma-

tion of the polymer under prevailing conditions such as temperature (melt or solid), condition of solution (solvation of molecules), coil structure, and aggregation. Higher orientation or parallelism of the chain molecules increases orientation of the structure elements. Their interaction also depends on the possible molecular conformations.

During spinning, a preliminary orientation of the molecules occurs, which is enhanced during drawing, and stabilized by partial crystallization. The individual segments usually crystallize independently of each other; hence amorphous intercrystalline areas exist unavoidably. The course of polymer crystallization, especially of fibers, is quite different from the crystallization characteristics of low molecular mass compounds.

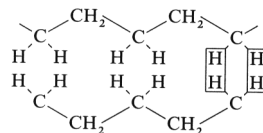
### 5.3. Property Requirements for the Formation of Fiber Structures

Fiber-forming polymers require certain properties that make possible the formation of typical fiber structures; these are linearity, intermolecular forces, and the possibility of crystallization whereby, in general, supermolecular structures result.

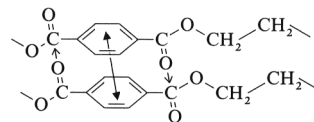
- 1) *Linearity.* Only linear polymers can be expected to have optimal fiber-forming properties. Linearity is specifically a prerequisite for the spinnability of polymer solutions and melts.
- 2) *Intermolecular Forces.* After orientation of linear polymers during spinning and drawing, dispersion forces, e.g., dipole-dipole interactions or hydrogen bonds between the polymer segments contribute to the fixation of the polymer chains.
- 3) *Crystallization.* The well-developed organization of the polymer chains usually results in crystallization. Polymer-specific crystallization results in crystalline domains and amorphous intercrystalline areas.
- 4) *Supermolecular Structure.* The crystallites are oriented so that they lie parallel to the fiber axis, which results in supermolecular structures, e.g., fibrils and fibril bundles ( $\rightarrow$  Fibers, 2. Structure).

These requirements were fulfilled by STAUDINGER's model of cellulose as polymeric formaldehyde [48]. Even this simple compound met all the conditions for fiber formation. It is a melttable linear polymer, capable of crystallization with formation of fiber fibrils.

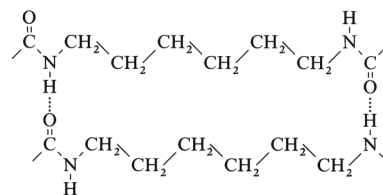
The simplest model for intermolecular dispersion forces (van der Waals forces) is shown in a polyolefin molecule such as polyethylene or polypropylene:



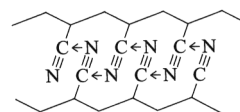
In poly(ethylene terephthalate), interaction between the aromatic  $\pi$ -electron systems of the benzene rings and of the carbonyl groups makes dipole – dipole interaction possible:



Hydrogen bonds act on amide or urea groups in polyamides, such as nylon 66 or nylon 6, or in polyurethane, respectively:

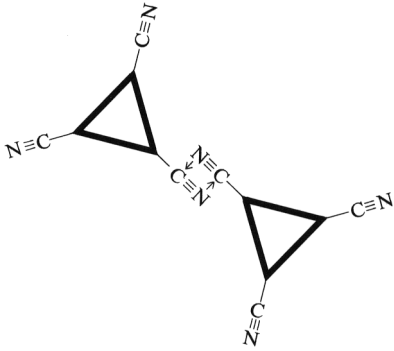


The OH groups of poly(vinyl alcohol) and of cellulose (viscose rayon) are also able to form hydrogen bonds. Very strong dipole – dipole interaction occurs between the nitrile groups of polyacrylonitrile:



However, this all-trans conformation of polyacrylonitrile can change into lower energy helical structures [49]:





The strong dipole–dipole interaction of polyacrylonitrile is one of the reasons for the specific solubility behavior of that polymer.

Weak dispersion forces are effective only in a highly symmetrical conformation. This high degree of symmetry, in turn, is possible only with a highly symmetrical arrangement of substituents, e.g., along an aliphatic carbon chain. Such a high degree of symmetry in linear polymers can be achieved only by coordination polymerization, in the presence of organometallic catalysts (Ziegler–Natta), to yield isotactic polymers. If this symmetry (e.g., in polypropylene) is disturbed by the presence of other structural units (e.g., carboxylic acid ester groups; acrylic acid comonomers), both polymer and fiber properties change drastically.

#### 5.4. Crystallization

The flexible linear polymer takes on a variety of conformations during fiber formation, seeking the conformation with the lowest free energy (i.e., highest molecular organization). However, spinning conditions do not allow polymers to attain this state completely, and fiber polymers usually undergo only partial crystallization. The ratio of crystalline to amorphous regions varies from almost totally amorphous to highly crystalline, single-phase systems (Fibers, 2. Structure).

Linear polymers exist in solution or as molten polymer in a more or less coiled form (Fig. 2 A). In the shearing field during spinning, the molecules are partially uncoiled and oriented in the direction of flow (Fig. 2 B). A higher degree of orientation is achieved during the subsequent drawing operation (Fig. 2 C).

In this step, spun fibers are stretched by more than 200 %, resulting in partial crystallization of polymer molecules (Fig. 2 D). In high-speed spinning, the extremely high windup speeds (3000–6000 m/min; 50–100 m/s) induce crystallization during fiber formation. The resulting preoriented yarns (POY) have to be stretched by only 40–100 % in subsequent steps (texturing). Additional polymer-specific increases in windup speeds lead to fully oriented yarns, which require almost no further stretching.

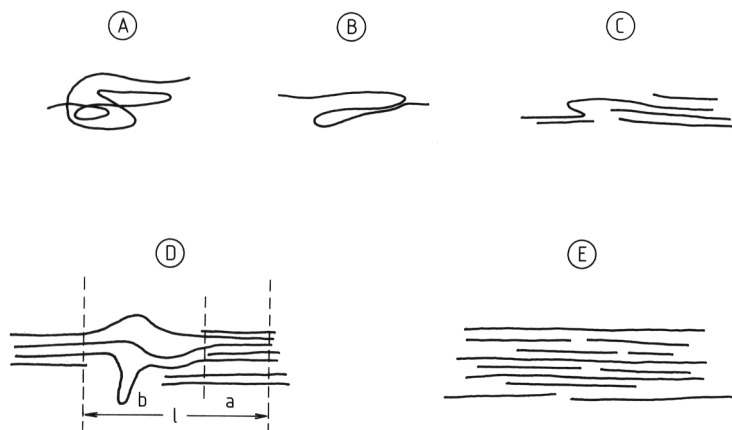
WU et al. [77] succeeded to orientate spinning PET in a threadline modification process. The one-step orientation (without separate drawing) could be realized by the installation of a liquid bath in the spinline. High-performance filaments, however, have to be drawn after spinning to reach maximum fiber strength.

*Liquid Crystals.* Some linear polymers, in solution or molten form, tend to undergo self-organization by forming liquid–crystalline structures. Soluble linear polymers (lyotropic systems) form liquid crystals as a result of their rigid conformation and the formation of polyelectrolytes, e.g., the system poly(*p*-phenylene-terephthalamide)–H<sub>2</sub>SO<sub>4</sub>. Liquid crystals can also be formed in polymer melts (thermotropic systems). Examples of suitable systems are the aromatic polyesters of the poly(4-hydroxybenzoic acid) type or aromatic blocks built up in segments and separated by flexible spacers. Figure 2 E shows the resulting structures of some high-modulus aramids; pronounced amorphous intercrystalline areas are not visible.

#### 5.5. Organization of Structural Elements

The arrangement of fibrils and fibril bundles in man-made fibers is controlled by the production procedure, i.e., by physical and physicochemical processes. Therefore, resulting structures depend on production parameters, and despite the different types of polymers employed, the tertiary structures of all man-made fibers are very similar.

In contrast, natural fibers have organized, evolved structures which differ considerably from each other, depending on the organism. Structural variations are reflected in different geometric positions of the fibrils with respect to the



**Figure 2.** Various conformations of fiber polymers

A: Unstirred solution (coil of polymer molecules)

B: Molecular orientation in the shearing field during spinning

C: Molecular orientation during drawing or liquid crystal formation from the melt or solution (polyelectrolyte molecules)

D: Formation of structure on crystallization of flexible polymer chains. Examples are polyethylene, polypropylene, polyamide, and polyester.

a) Crystallite; b) Intercrystalline (amorphous) region; l) Long period (10–20 nm)

E: Formation of structure of lyotropic and thermotropic systems, such as crystallization of rigid polymer chains. Examples are high-modulus fibers of the aramid type, polyesters, and carbon fibers.

fiber axis (e.g., in cotton fibers) or in different chemical structures along the fiber cross section (e.g., in animal hair, such as wool). Fibers could thus be classified into two principal structural categories, namely, organized and unorganized, if the structure of each fiber were known.

## 5.6. Structural Models

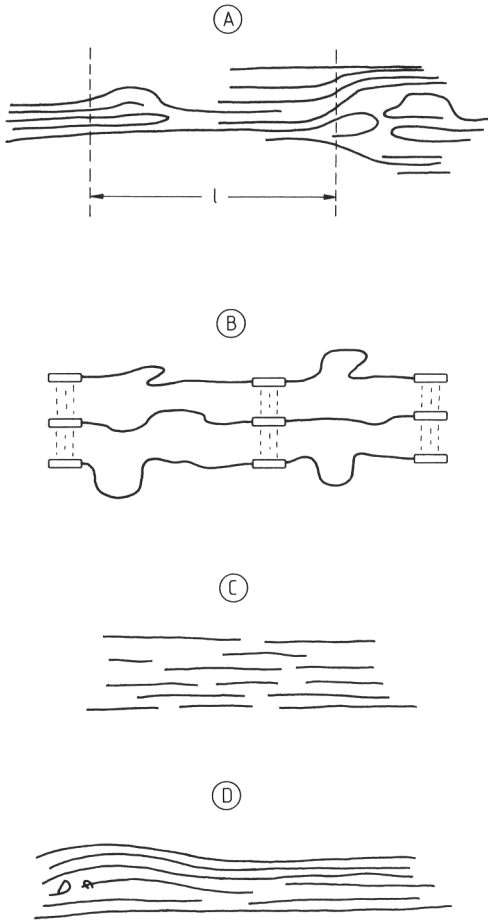
The chemical structure of linear polymers determines the degree of conformational mobility of the chain segments of these molecules. Both chain mobility and molecular structure, in turn, greatly influence fiber structure. Flexible chain molecules may crystallize partially to form structures that conform with the classical crystalline–amorphous model (Fig. 3 A). Spandex fibers, on the other hand, have a special domain structure, because the chemical structure of these polymers changes considerably in the various segments along the polymer chain (Fig. 3 B).

The relatively planar structure of aramids and polyheterocyclic compounds, their conformational rigidity, and their tendency to form lyotropic structures in the spinning solution are consistent with a structural model in which the intercrystalline segments are bridged (Fig. 3 C).

Even more planar molecules form graphite-like structures (Fig. 3 D). Structural defects lead to cavities and weakly bent planes of the aromatic systems; for more details on carbon fibers, see → Fibers, 5. Synthetic Inorganic.

## 5.7. Molecular Symmetry and Physical Properties

The importance of molecular symmetry for thermophysical properties (melting point, glass transition temperature) can be demonstrated for polyamides. Figure 4 shows the fluctuation of melting points in the series of polyamides PA-3 to PA-13 (nylon 3 to nylon 13). Apparently, polyamides with an even number of carbon atoms and those with an odd number of carbon atoms belong to different structural series [47]. This can be explained by the different overall symmetry and, consequently, the different possibilities for hydrogen-bond formation (Fig. 5). In PA-7, more hydrogen bonds can be formed—at least in the all-trans conformation—than in PA-6. Analogously, all nylon types with an even number of carbon atoms have lower melting points than those with an odd number of carbon atoms (Fig. 5).



**Figure 3.** Various structural models of different polymer types

A: Classical structural model of amorphous-crystalline fiber polymers. Examples are polyamide, polyester, and viscose rayon. Long period ( $l$ ) 10–30 nm.

B: Structural model of spandex fibers (polyurethane). Length of hard segment 2.5 nm; length of soft segment 15.0 nm

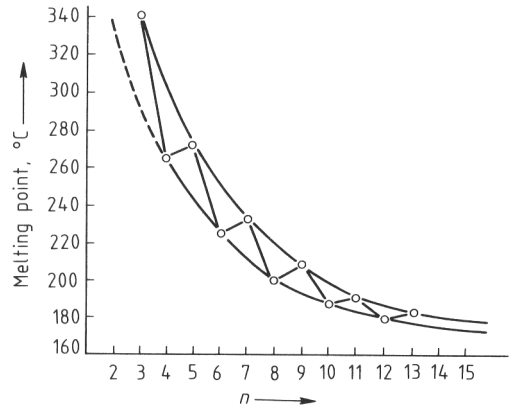
C: Structural model of aramid fibers (p-structures). No amorphous phases present; stretched molecules due to lyotropic structures during fiber formation

D: Structural model of carbon fibers; graphite structure with defects (cavities, bent layers; D = position of defect).

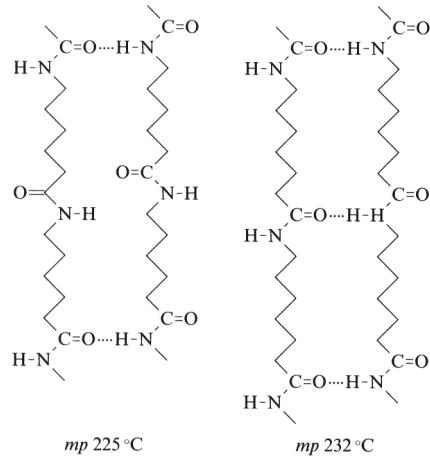
### 5.8. Changes in Properties Caused by Symmetry Defects

The incorporation of comonomers affects not only chemical structure, but also symmetry and, therefore, other fiber properties. For instance, the tacticity of polypropylene is changed by the

insertion of comonomers, such as vinyl compounds. The resulting copolymer has altered properties and is no longer suitable for textile production. In addition, polar comonomers interfere with the isotactic course of the polymerization process itself.



**Figure 4.** Melting points of nylons as a function of chain length  $n$ .



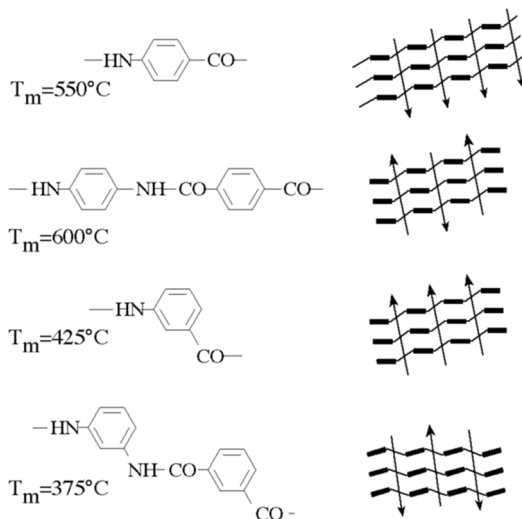
**Figure 5.** Hydrogen bonding in nylon 6 (A;  $mp$  225 °C) and nylon 7 (B;  $mp$  232 °C)

Polyacrylonitrile is rarely used for textile fibers without comonomers being incorporated into the polymer, because the desired fiber properties (e.g., deformability, dyeability) cannot be achieved with polyacrylonitrile alone. This, of course, changes the solubility of the polymer.

Polyesters of similar chemical structure, but quite different molecular symmetry, also have very different melting points. For example, the

highly symmetrical poly(ethylene terephthalate) has a melting point of 265 °C, whereas the melting point of poly(*m*-phenyleneisophthalamide) is only 102 °C [47].

The same situation arises with aramids. Here, too, the highly symmetrical para-linked polyamides have higher melting points (in this case, decomposition temperatures) than the less symmetrical meta-linked polymers (Fig. 6). The different dipole orientation, oppositely directed or in the same direction (arrows in Fig. 6), and the total symmetry cause higher fiber tenacity and modulus.



**Figure 6.** Effect of dipole orientation on the melting point (decomposition temperature) of aramids

## 6. Fiber Properties Required by Textiles

Despite the fact that a large number of polymers possess the basic properties required for fiber formation, they are not all suitable for large-scale production of fibers. In textile production and in commercial applications, polymers must fulfill a variety of requirements:

- 1) *Chemical Stability.* Polymers must be stable under the influence of heat, light, air, water, and the chemicals commonly used in textile finishing and care.
- 2) *Thermomechanical Stability.* Polymers must possess the ability to be solution- or melt-

spun and, at the same time, retain their dimensional stability during processing, use and care.

The requirements to be met by fibers and their parent polymers are, therefore, determined by the demands on the final products.

### 6.1. Requirements to Be Met by Textiles

The need for a variety of textile fabrics having specific properties should be clear from the diversity of textile uses. The priorities and order of importance of properties depend on the application in question.

For *clothing*, textile properties like appearance, aesthetics, optics, drape, formability (ironing, pleating), comfort, heat and moisture transport, handle, ease of care, and fastness of all types are of considerable importance. In addition, certain chemical requirements, such as dyeability, crease-resistant finishing, and dimensional stability, must be met in the production of textile materials. Finally, processibility to the finished textile product in partially automated production lines has become increasingly important.

*Industrial textiles* must also possess specific properties, depending on their application. For example, high tenacity is required for ropes; high modulus, for fiber reinforcement; heat stability, for protective clothing and insulation; high water absorption, for articles of hygiene; resistance to chemicals and flue gas, for filter materials; and long-term stability, for geotextiles [45].

In the past, fiber production and the utilization of specific properties were optimized primarily. Today, fibers with desired properties are made specifically to fulfill the requirements of the final product. The correlation between requirements and properties of the finished product and corresponding fiber (polymer) properties is given in Table 3.

### 6.2. Modification of Fiber Properties

The specific properties of the finished product depend directly on its end use. Since the fiber itself is not the final product, changes in fiber structure result in changes in the property profile

**Table 3.** Correlation of textile properties with fiber properties

Properties of the final product	Corresponding fiber properties
<b>Optical properties</b>	luster, fiber surface
<b>Aesthetics</b>	profile, fiber cross section
<b>Mechanical properties</b>	modulus of elasticity, tenacity, elongation
<b>Comfort</b>	
Physiological properties of clothing	moisture absorption, moisture transport
Antistatics	electrical resistance
Thermal insulation	heat capacity, porosity, heat conduction *
Hand	textile structure, bending modulus
Feel	roughness, modulus of elasticity, fineness
Ease of care and washability	wetting, moisture absorption, glass transition temperature (wet and dry) [78]
Dry cleaning	polymer (in)solubility, swelling
Soiling characteristics	zeta potential, adsorption and dissolution of soil components
<b>Fastness</b>	
Mechanical stability	tenacity, elongation, moduli, abrasion resistance
Dimensional stability	melting point, glass transition point (wet and dry)
Forming (e.g., pleating)	thermoplasticity, glass transition temperature ( $T_g$ )
Lightfastness	chemical structure, sensitizers, stabilizers
Lightfastness of dyeing	polymer–dye interaction, radical lifetime
<b>Specific properties</b>	
Flame resistance	chemical structure, combustion mechanism
Impermeability to water	moisture absorption, wetting properties
Water vapor permeability	surface properties, morphology, yarn structure
Dyeability	glass transition point during dyeing
Mechanical properties (ropes, material, tire cord)	modulus of elasticity, tenacity, elongation, dynamic modulus
Rubber elasticity	chemical structure, glass transition temperature, morphological structure, domain structure

\* The thermal insulation of a textile is largely due to the air inside the pores, which is of low thermal conductivity.

of the finished product. Matching the requirement profile with the property profile is not always possible. The purpose of numerous modification procedures (e.g., of the fiber polymer, production method, processing, and finishing) is to confer special functional properties on the end product. Some of these procedures are described in more detail in the following sections.

**Copolymers.** Fibers are used predominantly as raw materials in textile manufacture. Specific fabric properties, such as dimensional stability, brightness, color, pattern, or luster, are imparted to textiles during the physical and physicochemical processes of textile finishing. These characteristics should remain unchanged, particularly during use and cleaning. Chemical modification of the fiber polymer is generally employed to achieve this goal. Chemical treatment involves, above all, the introduction of special structural groups into the basic polymer, groups that are capable of taking part in polar and homopolar interactions with the chemicals used in textile finishing. Some examples are

- 1) introduction of a sulfonic acid group into poly(ethylene terephthalate) to bind cationic dyes (sulfoisophthalic acid as comonomer);
- 2) introduction of a sulfonic acid group into polyacrylonitrile with the help of vinylsulfonic or styrenesulfonic acid or a similar comonomer to make possible the use of cationic dyes;
- 3) introduction of flexible chain segments into poly(ethylene terephthalate) to change its dyeing characteristics. Polymer modification [copolycondensation with poly(ethylene glycol)] in the production of carrier-free dyeable polyester makes use of this principle.

**Polymer Mixtures.** Polymers are generally incompatible. If two different polymers are spun together, fibril structures are formed (matrix fibril fibers) that are known as *biconstituent fibers*. If two polymer streams are combined in the spinneret without blending, *bicomponent fibers* are obtained ( $\rightarrow$  Fibers, 3. General Production Technology).

**Additives.** Many specific fiber characteristics can be achieved by use of additives in the spinning solution or the melt. For example, the following effects can be obtained:

- 1) Delustering: use of titanium dioxide as additive in spinning
- 2) Spin dyeing: use of pigments as additives in spinning
- 3) Antistatic properties: use of electrically conducting additives in spinning
- 4) Flame resistance: use of flame retardants as additives in spinning

The use of additives in spinning produces a very broad spectrum of properties. For economic reasons, this type of fiber modification is the method of choice, if it produces the required effect. By comparison, the development of special polymers is a much more expensive procedure.

### 6.3. Comfort Properties of Textiles

Fibers used to produce clothing must possess a variety of properties. The term comfort refers to those properties responsible for the wash and wear performance of garments. Physiological studies have shown that apart from fiber substance, i.e., the chemical structure of the fiber polymer, the most important factors that influence textile wearability are fiber, yarn, and textile construction [50]. Along with moisture absorption, moisture transport across the fiber surface or through textile spaces is of particular significance for the moisture balance of textiles. Textiles must retain their appearance and form during washing and dry cleaning. In this connection, certain inherent fiber properties are of vital importance. The thermomechanical stability of textiles is controlled by the glass transition temperature ( $T_g$ ) of the fiber polymers. However, this temperature is not a structural property but, rather, is directly related to the fiber system, e.g., the type of polymer and polymer – water interaction. Deformability generally increases with increasing moisture absorption because the chain-segment mobility of polymers is increased. The glass transition temperature of fiber polymers with a high moisture-absorbing capacity decreases dramatically with increasing moisture content. The resulting structural changes in the

fiber lead to fiber shrinkage or stretching, depending on the degree of thermosetting. In other words, the textiles lose their shape.

Even in the dry state, dimensional stability decreases with increasing temperature, fibers can undergo permanent deformation at dry heat. Suitable fixation and textile finishing, e.g., thermofixation (heat setting) of polyester, felting or shrink-resistant finishing of wool, and crease-resistant finishing of cotton, can enhance dimensional stability and ease of care. Textiles that are still not dimensionally stable enough to be washed with water must be dry-cleaned. Here, soil release is achieved by using organic solvents such as perchloroethylene or fluorochlorohydrocarbons; the temperature must be maintained below the glass transition points of the fiber – solvent system throughout the process.

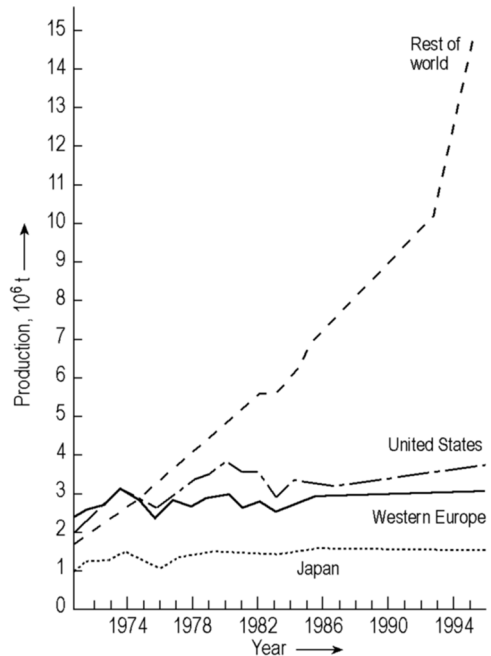


Figure 7. Total production of man-made fibers [2]

## 7. Economic Aspects

The production of natural and man-made fibers is influenced by a number of factors, such as demand (state of the economy), availability (production and trade), prices, and availability of raw materials. The per capita consumption varies considerably from country to country and de-

depends on climate, supply, domestic production versus imports, standard of living, fashion, state of the economy, and degree of industrialization.

The balance between the consumption of natural and of man-made fibers is also controlled by these factors, although a certain "awareness of nature" currently tips the scales in favor of natural fibers. The production of natural fibers, e.g., cotton or wool, is determined in terms of the profit made per area cultivated. A dramatic increase in production cannot be expected at present. However, new developments in genetic engineering could rapidly improve the yields obtained per given area.

The economic importance of individual fiber types can be deduced from their annual worldwide consumption [51], and Figure 7 shows the worldwide production of man-made fibers.

Both the consumption and the production of fibers also depend directly on the level of development and on per capita income [52]. The consumption per person in individual countries differs considerably for a variety of reasons. Some countries have already reached a high level of consumption, and despite their high standard of living, the population spends only a fixed percentage of their available income on textiles. The growth of fiber production for industrial use, on the other hand, is likely to continue. In 1984, 7 kg of fiber was consumed per capita; for the year 2000, a total fiber production of  $43 \times 10^6$  t is expected if per capita consumption remains at 7 kg, or  $48.6 \times 10^6$  t if it increases to 8 kg. The growth rate of 2.8 % achieved in the period 1968–1984 is not expected to continue. Up to 1995 the average growth rate was only 2.3 %/a. Nevertheless, a world fiber volume of about  $50 \times 10^6$  t is expected in the year 2000 [52], [79].

The limited means of production in Eastern Europe also contributed to reduced consumption. In the developing countries, lack of spending power, capital, and means of production all combine to reduce growth of consumption. Regional differences in population growth will lead to an increase in fiber consumption in the developing countries.

## 8. Tabular Survey of Fibers [6], [53], [54]

A quantitative survey of the most important properties of fibers based on polycondensation and polymerization, as well as some inorganic fibers, is shown in Tables 4, 5, 6, 7, 8, 9, 10. Properties of these fibers, are compared with those of natural and semisynthetic fibers. The properties of all textile and industrial fibers are determined by variables related to production and aftertreatment. Hence, in general, only a range of values characteristic of individual fiber classes is given in this survey. In fact, only the order of magnitude is indicated for electric resistance of fibers because of considerable variations in measured values. No entries have been made when reliable information was unavailable.

The numbers in brackets are plausible estimated values. Figures for tenacity and modulus are based on both fiber fineness ( $1 \text{ tex} = 1 \text{ g/km}$ ) and cross-sectional area of the sample. The following relationship is applicable:

$$\text{Fineness (tex)} = 10^5 \times \text{Density (gcm}^{-3}) \times \text{Crosssection (cm}^2)$$

In general, the characteristic stress–strain curve  $\sigma(\varepsilon)$  of fibers does not show a constant gradient, even at low elongation. Hence, the modulus of elasticity is usually defined as the differential quotient  $d\sigma(\varepsilon)/d\varepsilon$ . Experimental determination at low fiber elongation  $\varepsilon$  is difficult but can be conducted successfully by extrapolation of the function  $d\sigma(\varepsilon)/d\varepsilon$  for  $\varepsilon = 0$  [55].

The elastic recovery of a fiber (in percent) can be measured by standard methods [56] and is shown in Table 5 as

$$\left(1 - \frac{\varepsilon_r}{\varepsilon}\right) 100$$

where  $\varepsilon_r$  = residual elongation,  $\varepsilon$  = total elongation.

Table 4. Mechanical properties of fibers (data at break)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Density ( $\rho$ ), g/cm <sup>3</sup>	Elongation $\epsilon_H$ (21 °C)		Tenacity ( $\sigma_H$ ) at 21 °C		Relative		
				at 65 % R.H. <sup>b</sup> , %	“wet/dry,” %	$\sigma_H/\rho$ , cN/tex	$\sigma_H$ GPa	loop tenacity [62], %	knot tenacity [63], %	
<b>Natural fibers</b>										
Cotton		st	1.50–1.54	6–15	100–110	25–50	0.35–0.7	100–110	65–75	60–100
Wool		st	1.32	25–50	110–130	10–20	0.15–0.25	70–90	75–85	80–85
Silk		fi	1.25	10–30	120–200	25–50	0.3–0.6	75–95	60–80	80–85
Hemp		st	1.48	2–5	≈100	36–75	0.5–1.1	100–106		
Flax		st	1.438–1.456	1–4	110–125	30–55	0.43–0.8	105–120	20–40	
Jute		st	1.436	1.3	100	20–40	0.3–0.57	99–104		
<b>Regenerate cellulose</b>										
Viscose rayon, Viscose Modal	Evlan, Fibro, Sarille,...	st/fi	1.52–1.54	10–30	100–130	16–45	0.25–0.7	40–80	25–65	25–60
Cuprammonium rayon	Asahi Bemberg, Bemberg	st/fi	1.52	10–40	170–200	14–21	0.2–0.32	60–70	60–75	60–85
Cellulose acetate	Arnel, Celco,	st/fi	1.29–1.32	20–45	120–150	10–15	0.13–0.2	50–80	70–95	80–90
Cellulose triacetate	Dicel	st/fi	1.29–1.32	20–45	120–150	10–15	0.13–0.2	50–80	70–95	80–90
NMMO fibers [88]	Estron, Silene, Tricel, Lyocell, Tencel,...	st	1.5	10–16	110–115	32–48	0.5–0.7	55–70	45–50	≈75
Protein fibers		st	1.315	25–60	60–110	11–12	0.14–0.16	40–65		
Alginat fiber (Ca-Alginat)		fi	1.78	5		11–18	0.2–0.3	27–30		
<b>Polycondensate fibers</b>										
Nylon 6 (PA 6)	Perlon, Acelon, Amilan, Anso, Caprolan, Crilon,...	st	1.14	30–70	105–125	30–40	0.35–0.45	80–90	65–85;	
Nylon 66 (PA 66)		fi	1.14	20–45	105–125	40–60	0.45–0.7	85–90	70–95	80–90;
		hd	1.14	15–20	105–125	60–90	0.7–1	85–90	70–90	60–70
		st	1.14	30–60	105–125	35–40	0.4–0.45	see PA 6	see PA 6	see PA 6
	Nylon, Antron, Cantrece, Meryl, Timbrelle, Ultron,...	fi	1.14	20–40	105–125	40–60	0.45–0.7			
		hd	1.14	15–20	105–125	60–90	0.7–1			



Table 4. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Density ( $\rho$ ), g/cm <sup>3</sup>	Elongation $\varepsilon_H$ (21 °C)		Tenacity ( $\sigma_H$ ) at 21 °C		Relative		
				at 65% R.H. <sup>b</sup> , %	"wet/dry," %	at 65% R.H. $\sigma_H/\rho$ , cN/tex	$\sigma_H$ GPa	Wet/dry (relative), %	loop tenacity [62], %	knot tenacity [63], %
<i>Aramids</i>										
Poly( <i>m</i> -phenyleneisophthalamide)	Nomex, Conex	fi	1.38	15–30	60–80	185–195	2.7–2.8	0.35	≈95	80–85
	Kevlar 29, Twaron	fi	1.44	3–4					≈45	≈50
Poly( <i>p</i> -phenyleneterephthalamide) (PPTA)	Kevlar 49	fi/an	1.45	2–2.5		185–195	2.7–2.8	0.365	50–78	35–50
	Kevlar 149	fi/an	1.47	1.2–1.9		150–160	2.2–2.4			
	Kevlar 981, Twaron	fi/hd		2.8–3.5		230–260	3.5–3.8			
	Kevlar Hp	fi	1.44	3.6		140–150	2.05			
Poly(ethylene terephthalate) (PET)	Dacron, Drolen, st	st	1.36–1.41	25–50	100–105	30–55	0.4–0.75	95–100	75–95	
	Fortrel, Grilene, st/ap	st/ap	1.36–1.41	30–55	100–105	25–40	0.35–0.55	95–100	75–85	
	Serene, Terylene,	fi	1.36–1.41	20–30	100–105	40–60	0.55–0.85	95–100	70–98	70–80
	Trevira.....	fi/hd	1.36–1.41	8–20	100–105	60–100	0.85–1.5	95–100	60–90	40–70
	Trevira 810, Trevira 813	st/fi	1.25	35–40		40–45	0.5–0.56			
Poly(butylene terephthalate) (PBT)	Kodel	st	1.22–1.23	15–35		22–36	0.37–0.45	≈100	30–95	
Poly(1,4-dimethylenecyclohexane terephthalate) (PDC) [59]	Ekonor [60], Vectran	fi	1.40–1.41	2–5		200–280	2.8–3.9	Compressive strength, axial [80], [81], [82] GPa	23–34	
Polyarylate								0.04–0.075	55–80	65–68
Poly(etherether ketone) (PEEK)	Zyex	fi	1.27–1.298	15–60		20–100	0.25–1.3		60–65	70–75
Polyimide (PI)	P 84	st/fi	1.41	for st 30–38 and for fi 19–21		27–37	0.38–0.53			
Novolak	Kynol, Phylene, Novoloid	st	1.2–1.3	20–60		13–22	0.17–0.27		70	80
	Poly(amide imide) (PAI)	st		10–25		25–60				
Poly(ether imide) (PEI)	Kermel	st/fi		16–38		15–27	0.2–0.35			
Polyurethane elastomers (spandex)	Dorlastan, Lycra, ...	fi	1.1–1.3	400–700	≈100	5–12; 30–70= $\sigma_H(1+\varepsilon_H)/\varepsilon^c$	0.06–0.15	75–100		

Table 4. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Density ( $\rho$ ), g/cm <sup>3</sup>	Elongation $\epsilon_H$ (21 °C)		Tenacity ( $\sigma_H$ ) at 21 °C		Relative	
				at 65 % R.H. <sup>b</sup> , %		at 65 % R.H.		loop	knot
				R.H. <sup>b</sup> , %	%	$\sigma_H/\rho$ , cN/tex	$\sigma_H$ GPa	tenacity [62], %	tenacity [63], %
<b>Polymerizate fibers</b>									
Polyethylene (HD - PE) (HM - HD - PE: $M_r > 10^6$ )	Hiralon, Vegon,...	fi	0.95 - 0.96	10 - 45	100	30 - 70	0.3 - 0.65	60 - 90	70 - 90
Polypropylene (PP)	Spectra 1000...	hd	0.97	3 - 6	100	270 - 370	2.6 - 3.6		≈ 50
	Herculon, Meraklon...	st/ft	0.90 - 0.92	15 - 50	100	25 - 60	0.22 - 0.55	85 - 95	70 - 90
Polyacrylonitrile (PAN)	Dralon T,...	st/ft	1.17 - 1.19	25 - 40	≈ 100	35 - 58	0.42 - 0.69	≈ 60	≈ 70
	Dolan, Dralton,	st	1.17 - 1.19	20 - 60	100 - 120	18 - 32	0.2 - 0.37	30 - 80	75 - 80
Copolymerizates with PAN $\geq 85$ %	Euroacril, Leacril,...	fi	1.17 - 1.19	15 - 40	100 - 120	35 - 45	0.42 - 0.53	30 - 80	≈ 70
Modacrylies (50 - 84 % PAN)	Kanekalon, SEF,...	st	1.3 - 1.4	25 - 50	100 - 110	15 - 25	0.2 - 0.35	50 - 70	≈ 80
Poly(vinyl chloride) (PVC) atactic	Clevil, Rhovil,...	st/ft	1.38 - 1.40	10 - 40	100	20 - 24	0.28 - 0.34	35 - 70	
	syndiotactic [61]	st	1.40	35 - 60	100	25 - 30	0.35 - 0.42	60 - 90	65 - 85
Poly(vinyl alcohol) (PVA)		Mewlon, Solvron,	1.26 - 1.31	13 - 26	120 - 140	20 - 55	0.25 - 0.7	35 - 40	55 - 65
	Vilton,...	fi	1.26 - 1.31	9 - 22	120 - 140	55 - 77	0.7 - 1	35 - 40	55 - 65
(HM: $M_r > 10^6$ )	Gore-Tex Fibers,...	hd	1.31	3 - 4	100	150 - 230	2 - 3	60 - 90	75 - 90
Polytetrafluoro-ethylene (PTFE)		st/ft	2.1 - 2.3	20 - 40		8 - 18	0.16 - 0.38		
Poly(phenylene sulfide) (PPS)	Procon, Rylon	st/ft	1.37 - 1.38	25 - 40		28 - 47	0.4 - 0.65	78	60 - 80
		Basofil	1.4 - 1.5	15 - 25		15 - 40	0.2 - 0.6		

Table 4. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Density ( $\rho$ ), g/cm <sup>3</sup>	Elongation $\epsilon_H$ (21 °C)		Tenacity ( $\sigma_H$ ) at 21 °C		Wet/dry (relative), %	Relative	
				at 65 % R.H. <sup>b</sup> , %	"wet/dry," %	at 65 % R.H. $\sigma_H/\rho$ , cN/tex	$\sigma_H$ GPa		loop tenacity [62], %	knot tenacity [63], %
<b>Inorganic fibers</b>										
Textile glass	Gevetex, Fibreglas		2.45–2.6	2–5	100	70–120	1.7–2.7		15–30	
E glass	E-Fiber, Enkafort	5–15	2.52–2.54	2–3.5	100	80–140	2–3.5	0.5		
Aluminum silicate (e.g., 3 Al <sub>2</sub> O <sub>3</sub> · 2 SiO <sub>2</sub> · B <sub>2</sub> O <sub>3</sub> )	Nextel 312	17	2.63–2.7			65	1.7			
	Nextel 440		3.1							
$\beta$ -Silicon carbide	Nextel 480		3.05	1.1		75	2.3			
	Nicalon	5–20	2.6–3.1	1		≈ 100	3			
	(Nippon Carbon)									
Silica (SiO <sub>2</sub> ) Steel (20 % Cr, 7 % Ni) Carbon (pitch based)	FP (DuPont)	20		0.4			1.4–1.5			
	Saffil, Saffimax (ICI)	3–3.2	2.8–3.3	0.7		30–60	1–2			
	Silica (Akzo)	9–10	1.8–2.0	1.4–2.0		15–40	0.25–0.8		65–75	60–70
High-modulus types (HM)	Bekinox	fi	7.9	1–2	100	22–29	1.75–2.25			
	Tornel, Grafil,	6–9	2.0–2.06	0.4 (c-2)		≈ 100	2 (+)	0.4–0.8	0	
High-strength types (HS) Carbon (PAN based)	Fiber G	9–12	2.02	0.5–2		≈ 250	≈ 5	0.5–1.1	0	
	Magnamite, Pyrofil,	6–7	1.8–1.96	0.4–1.2		100–180	1.9–3.5	1.4–1.5	0	
High-modulus types (HM) High-strength types (HS)	Torayca...	7–9	1.74–1.82	1.5–2.4		170–380	3–7	1.44–4	0	

<sup>a</sup> st = staple fiber, fi = filament, hd = highly drawn, an = annealed, ap = antipilling; <sup>b</sup> R.H. = relative humidity; <sup>c</sup> effective breaking strength

Table 5. Elastomechanical properties of fibers

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Elastic recovery, %: ( $1 - \epsilon_r/\epsilon$ ) 100 for $\epsilon = 2\%$ (5%)	Initial Modulus			Torsion modulus [64]		Torsion brittleness [66], degrees
				$E/\rho$ , N/tex	(elongation $\epsilon \rightarrow 0$ ) $E$ , GPa	$E$ , GPa	$G/\rho$ , N/tex	G, GPa	
<b>Natural fibers</b>									
Cotton		st	75	3-6	4.5-9	1.6	2.4	53-56	
Wool		st	95-99	1.5-3	2-4	0.8-1	$\approx 1$	48-52	
Silk		fi	95	7-10	9-12.5	1.5-2.3	1.9-2.9	51	
Hemp		st	$\approx 60$	60	90				
Flax		st		8-25	12-36	0.95	1.3-1.4	68	
Jute		st		21-22	30-31				
<b>Regenerate cellulose</b>									
Viscose rayon, Viscose Modal	Eylan, Fibro, Sarille...	st/fi	70-100	2-3 (6.5-7.5)	3-4.5 (4.2-4.9)	0.5-1	$\approx 1$	51-55	
Cuprammonium rayon	Asahi Bemberg, Bemberg	st/fi	70-95	2-3	3-4.5			48-57	
Cellulose acetate	Arnel, Celco, Dacel,	st/fi	90-95	2-3.5	2.5-4.5	0.6-0.8	$\approx 1$	44-50	
Cellulose triacetate	Estron, Silene, Tricel...	st/fi	90-95	2-3.5	2.5-4.5	0.6-0.8	$\approx 1$	44-50	
NMMO Fiber	Lyoceel, Tencel...	st/fi		4	6				
Protein fiber		st		2	2-3	0.9	$\approx 1$	30-40	
Alginat fiber (Ca-Alginat)		fi	26	7	12-13	1.2	$\approx 2$		
<b>Polycondensate fibers</b>									
Nylon 6 (PA 6)	Perlon, Acelon, Amilan, Anso,	st fi	95-100	0.5-3	0.6-3.5	$\approx 0.3$	$\approx 0.3$	27-41	
	Caprolan, Grilon...	hd	95-100	4-5	4.5-5.5	0.7	0.8	33-42	
Nylon 66 (PA 66)	Nylon, Antron, Canirece, Meryl, Timbrelle, Ultron...	st fi hd	95-100	0.5-3	0.6-3.5	0.45	0.5	27-41	
			95-100	4-5	4.5-6			40-41	

Table 5. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Elastic recovery, %: (1 - $\epsilon_r/\epsilon$ ) 100 for $\epsilon = 2\%$ (5%)	Initial Modulus		Torsion modulus [64]		Torsion brittleness [66], degrees	
				(elongation $\epsilon \rightarrow 0$ ) $E/\rho$ , N/tex	$E$ , GPa	$G/\rho$ , N/tex	$G$ , GPa		
<i>Aramids</i>									
Poly( <i>m</i> -phenyleneisophthalamide)	Nomex, Conex,	fi	95–100	8–14	11–20			$\approx 50$	
	Kevlar 29,	fi		41–53	59–77				
Poly( <i>p</i> -phenyleneterephthalamide) (PPTA)	Twaron,	fi/an	95–100	85	124				
	Kevlar 49,	fi/an		103	150				
	Kevlar 149,	fi/hd		70–83	102–120				
	Kevlar 981,	fi		50	72				
	Twaron,	st		2.5–4	3.4–5.5				
Poly(ethylene terephthalate) (PET)	Kevlar Hp	ap	90–98	2.5–4	3.4–5.5			30–49 $\approx 48$	
	Dacron, Dtolen,	fi		7–18	10–25				
	Terylene,	hd		7–18	10–25				
	Trevira,	st		4–5	5–6				
Poly(butylene terephthalate) (PBT)	Fortrel, Grilene,	fi	100	2.5–4	3–5			41–48 47–48	
	Serene,...	hd		70–90	0.65				0.9
	Trevira 810...813	fi		99–100	1.1				1.5
	Poly(1,4-dimethylene cyclohexane terephthalate) (PDCT) [59]	st		50–60					
	Polyarylate	fi			60–128				80–180
Poly(ether ether ketone) (PEEK) Polyimide (PI) Novolak	Vectran, Ekonol [61]	fi	93–98 for $\epsilon = 300\%$					0.004	
	Zyex	fi		4–12	5–15				
	P84	st/fi		3.5–5	5–7				
	Kynol, Philene, Novoloid	st		2.6–3.6	3.3–4.6				
Poly(amide imide) (PAI) Poly(ether imide) (PEI)	Kermel	st		3.5–7.5					
	Dorlastan, Lyera,...	st		2.7–4.2	3.5–5.1				
Polyurethane elastomers (spandex)		fi		$\approx 0.005$ –0.01	0.006–0.012			0.005	

Table 5. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Elastic recovery, %: ( $1 - \epsilon_r/\epsilon$ ) 100 for $\epsilon = 2\%$ (5%)	Initial Modulus		Torsion modulus [64]		Torsion brittleness [66], degrees
				(elongation $\epsilon \rightarrow 0$ ) $E/\rho$ , N/tex	$E$ , GPa	$G/\rho$ , N/tex	$G$ , GPa	
<b>Polymerizate fibers</b>								
Polyethylene (HD-PE)	Hiralon, Vegon,	fi	95-100	0.2-5	0.05	0.05	0.05	
(HM-HD-PE: $\bar{M}_r > 10^6$ )	Spectra 1000...	hd	100	51-165	1.5 [65]	1.5 [65]	1.5 [65]	
Polypropylene (PP)	Herculon,	st/fi	95-100	0.5-5				
	Meraklon,...							
Polyacrylonitrile (PAN)	Dralon T,...	st/fi	90-95	9.5-14	1.5-1.7	1.5-1.7	1.8-2	
Copolymerizates with PAN $\geq 85\%$	Dolan, Dralon	st	90-95	3-5				45-52
	Euroacril,	fi	90-95	9-10	1	1	1.2	55-60
	Leacril,...							
Modacrylics (50-84% PAN)	Kanekalon, SEF,...	st	95-99	1-2.5	1.3-3.5			
Poly(vinyl chloride) (PVC)								
atactic	Clevyl, Rhovyl,...	st/fi	70-90	2-4	0.6-0.7	0.6-0.7	0.8-1	27-50
syndiotactic [61]								
Poly(vinyl alcohol) (PVA)	Kuralon, Mewlon	st	90-95	2.5-3			1.2	
			60-80	3-4	0.9			
	Solvron, Vilon,...	fi	60-80	3-4.5	1.2-1.5	1.2-1.5	1.6-2	
(HM: $\bar{M}_r > 10^6$ )		hd		30-60				
Polytetrafluoroethylene (PTFE)	Gore-Tex Fibers	st/fi		0.35-2	0.2-0.3	0.2-0.3	0.4-0.7	
Poly(phenylene sulfide) (PPS)	Procon, Ryton,...	st/fi		2.7-5	3.7-6.8			

Table 5. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Elastic recovery, %: (1 - $\epsilon_{1/2}$ )/ $\epsilon$ 100 for $\epsilon = 2\%$ (5%)	Initial Modulus		Torsion modulus [64]		Torsion brittleness [66], degrees
				$E/\rho$ , N/tex	$E$ , GPa	$G/\rho$ , N/tex	$G$ , GPa	
<b>Inorganic fibers</b>								
Textile glass	Gevetex, Fiberglas,...		100	28–34	70–90	$\lesssim 16$	$\lesssim 40$	85–88
E glass	E-Fiber, Enkafort,...	5–15	100	28–34	70–90	$\lesssim 16$	$\lesssim 40$	85–88
Aluminum silicate (e.g. $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot \text{B}_2\text{O}_3$ )	Nextel 312,	17		5.5–52	15–140			
	Nextel 440, Nextel 480 [89]			65 73	200 224			
$\beta$ -Silicon carbide	Nicalon (Nippon Carbon)	5–20		67–100	200–300			
	FP (DuPont) Saffil, Saffimax (ICI)	20 3–3.2		120–125 33–83	350–385 100–250			
Silica (SiO <sub>2</sub> )	Silica (Akzo)	9–10		6–30	12–56			
Steel (20% Cr, 7% Ni)	Bekinox	fi	100 for $\epsilon = 1\%$	19–25	150–200	7.9–9.5	60–70	
Carbon (pitch based)								
High-modulus types (HM)	Thornel, Grafil,	6–9		250–400	500–800			
High-strength types (HS)	Fiber G Magnamite	9–12		124–200	250–400			
High-modulus types (HM)	Pyrofil,	6–7		160–260	300–500			
High-strength types (HS)	Torayca,...	7–9		110–165	200–300	2.2	4	

<sup>a</sup> st = stable fiber, fi = filament, hd = highly drawn, an = annealed, ap = antipilling.

Table 6. Thermal properties of fibers

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Fiber shrinkage in water of 95 °C, %		Specific heat capa- city [67], J g <sup>-1</sup> K <sup>-1</sup>	Thermal conductivity, W m <sup>-1</sup> K <sup>-1</sup>	Glass transition temperature, °C	Melting temperature (decomposition temperature), °C	Heat resistance in air up to <i>t</i> , °C
			drawn	thermoset					
<b>Natural fibers</b>									
Cotton		st			1.3	0.3–0.5	(400)		120
Wool		st			1.3–1.6	0.2–0.4	45 [90]		120
Silk		fi			1.4	0.2–0.4	40–50	(170–180)	120
Flax		st			1.4	0.3			
<b>Regenerate cellulose</b>									
Viscose rayon, Viscose, Modal	Evlan, Fibro, Sarille,...	st/fi	0.5–10 <sup>b</sup>		1.3–1.5	0.3–0.6	(175–190)		120
Cuprammonium rayon	Asahi Bemberg, Bemberg	st/fi	0.5–10 <sup>b</sup>		1.4		(175–205)		120
Cellulose acetate	Arnell, Celco, Diel,	st/fi	5–20		1.3–1.5	0.3	255		120
Cellulose triacetate	Estron, Silene, Tricel,...	st/fi	5–20	0.7	1.5	0.3	170–180 [68]	300	130
<b>Polycondensate fibers</b>									
Nylon 6 (PA 6)	Perlon, Acelon,	st	8–15	0.5–1.5	1.5–1.8		80–85 (dry)	215–220	120
	Amilan, Anso,	fi	8–15	1–5	1.5–1.8	0.2–0.3	≈ 20 (3.7 % water)	215–220	120
Nylon 66 (PA 66)	Caprolan, Grilon,...	hd	8–15		1.5–1.8	0.4	90–95 (dry)	215–220	120–150
	Nylon, Antron,	st	8–15	0.5–1.5	1.5		90–95 (dry)	255–260	120
	Cantrac, Meryl,	fi	8–15	1–5	1.5	0.2–0.3	≈ 30 (3.7 % water)	255–260	120
	Timbrelle, Ultron,...	hd	8–15		1.5	0.4	255–260	255–260	120–150





Table 6. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Fiber shrinkage in water of 95 °C, %		Specific heat capacity J g <sup>-1</sup> K <sup>-1</sup>	Thermal conductivity, W m <sup>-1</sup> K <sup>-1</sup>	Glass transition temperature, °C	Melting temperature (decomposition temperature), °C	Heat resistance in air up to <i>t</i> , °C
			drawn	thermoset					
<b>Polymerizate fibers</b>									
Polyethylene (HD-PE) (HM – HD – PE: $M_r > 10^6$ )	Hiralon, Vegon,	fi	5 – 10		1.4 – 2.0	0.2 – 0.4	– 20 to – 30	124 – 138	70 – 90
	Spectra 1000	hd				10 – 38 [84], [85]	– 20 to – 30	124 – 138	
Polypropylene (PP)	Herculon, Meraklon	st/fi	0 – 5		1.6	0.2 – 0.3		160 – 175	≈ 120
	Dralon T	fi/st	14 – 16 (20 – 40 °C)		1.2 – 2.5	0.2	≈ 95 (dry) 85 – 95 (dry); 50 – 60 (wet)	≈ 320 (> 250)	140 140
Copolymerizates with PAN ≥ 85 %	Dolan, Dralon	st	0.5 – 5		1.2 – 1.5	0.2	85 – 95 (dry); 50 – 60 (wet)	(> 250)	140
	Euroacril, Leacril, Kanekalon, SEF,...	fi st	≈ 1 0.2 – 5				85 – 95	(≈ 170)	≈ 120
Modacrylies (50 – 84 % PAN)									
	Poly(vinyl chloride) (PVC) atactic syndiotactic [61]	st/fi st st	20 – 30	0 2 – 3	0.8 – 0.9	0.16 – 0.17	70 – 90 90 – 100 75 – 90	(160 – 200) (160 – 200)	< 65 140
Poly(vinyl alcohol) (PVA)									
Polytetrafluoroethylene (PTFE)									
Poly(phenylene sulfide) (PPS) Melamine resin fiber	Gore-Tex Fibers	st/fi			1.0 – 1.1	0.23	75 – 130	(240 – 260)	(water vapor: 120)
	Procon, Ryton, ... Basofil	st/fi st	≈ 16				127 – 130 85 – 95	327 – 342 [72] 270 – 290	180 190 – 200 200 – 220

<sup>a</sup> st = stable fiber, fi = filament, hd = highly drawn, an = annealed, ap = antipilling;

<sup>b</sup> Depending on fiber type;

<sup>c</sup> High-shrinkage (HS) fiber.

Table 7. Thermal and electrical properties of inorganic fibers

Fiber name	Trade name	Fiber diameter, $\mu\text{m}$	Specific heat capacity [67], $\text{Jg}^{-1}\text{K}^{-1}$	Thermal conductivity, $\text{Wm}^{-1}\text{K}^{-1}$	Heat resistance in air up to, $^{\circ}\text{C}$	Fire Limiting Oxygen Index (LOI), %	Melting temperature (Glass transition $T_g$ ), $^{\circ}\text{C}$	Specific electrical resistance, $\Omega\text{cm}$
Textile glass	Gevetex, Fiberglass	5–15	$\approx 0.75$	$\approx 0.8$	300–400		$(600 \lesssim T_g \lesssim 700)$	$10^{12} - 10^{15}$
E-Glass	E-Fiber, Enkafort	5–15	$\approx 0.75$	$\approx 0.8$	300–400		$(600 \lesssim T_g \lesssim 700)$	$10^{12} - 10^{15}$
Aluminum silicate	Nextel 312	17			1200–1300		1800	
(e.g., $3\text{Al}_2\text{O}_3$ $\cdot 2\text{SiO}_2 \cdot \text{B}_2\text{O}_3$ )	Nextel 440				1200–1300		1800	
	Nextel 480				1200			
$\beta$ -Silicon carbide	Nicalon (Nippon Carbon)	5–20		12	> 800		2700	
	FP (DuPont)	20			900			
	Saffil, Safimax (ICI)	3–3.2			1000		1750	
Silica ( $\text{SiO}_2$ )	Silica (Akzo)	9–10			1000–1100		1400–1450	
Steel (20% Cr, 7% Ni)	Bekinox	filaments	0.46	15				
Carbon (pitch based)								
High-modulus types (HM)	Thornel, Grafil,	6–9			300 (-500)			$0.7 \times 10^{-4}$
High-strength types (HS)	Fiber G,...	9–12			300 (-500)			$> 10^{-3}$
Carbon (PAN based)								
High-modulus types (HM)	Magnamite, Pyrofil,	6–7		60–115 [73]	300 (-500)	> 60	3600	$\approx 10^{-3}$
High-strength types (HS)	Torayca,...	7–9	0.7	15–20 [73]	300 (-500)	> 60	$\approx 1.5 \times 10^{-3}$	

Table 8. Electrical resistance, ironing temperature, water absorption and solubility of fibers

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Specific electrical resistance, <sup>b</sup> Ω cm	Ironing temperature, °C	Water absorption at 21 °C, 65 % R.H., <sup>d</sup> %	Water retention [74], %	Solubility in selected solvents <sup>c</sup>
<b>Natural fibers</b>							
Cotton		st	$10^6 - 10^8$	180–220	7–11	40–50	concentrated H <sub>2</sub> SO <sub>4</sub> , Cuoxam-solution
Wool		st	$10^8 - 10^{11}$	160–170	15–17	40–45	conc. inorg. acids, conc. KOH
Silk		fi	$10^9 - 10^{10}$	140–165	9–11	40–45	conc. inorg. acids, conc. KOH, conc. HCO <sub>2</sub> H
Flax		st		215–240	8–10	50–55	concentrated H <sub>2</sub> SO <sub>4</sub>
<b>Regenerate cellulose</b>							
Viscose rayon	Evlan, Fibro, Sarille,...	st/fi	$10^6 - 10^7$	150–180	12–14	85–120	conc. inorg. acids
Cuprammonium rayon	Asahi Bemberg, Bemberg,...	st/fi	$\approx 10^7 - 10^8$	150–180	11–12	100–125	conc. inorg. acids
Cellulose acetate	Amel, Celco, Diecl	st/fi	$10^9 - 10^{12}$	180	6–7	20–28	conc. inorg. acids, acetone, dioxane, phenols
Cellulose triacetate	Estron, Silene, Tricel,...	st/fi	$\approx 10^{14}$	220–250	2–5	10–18	conc. inorg. acids, acetone, dioxane, phenols
NMMO Fiber	Lyocell, Tencel,...	st/fi		150		65–70	N-methylmorpholine oxide (NMMO)
<b>Polycondensate fibers</b>							
Nylon 6 (PA 6)	Perlon, Acelon,	st		150	3.5–4.5	10–15	conc. inorg. acids, phenols
	Amilan, Anso,	fi	$10^9 - 10^{11}$	150	3.5–4.5	10–15	conc. inorg. acids, phenols
	Caprolan, Grilon,...	hd		150	3.5–4.5	9–11	conc. inorg. acids, phenols
Nylon 66 (PA 66)	Nylon, Antron,	st		180–200	3.5–4.5	10–15	conc. inorg. acids, phenols
	Cantrice, Meryl,	fi	$10^9 - 10^{11}$	180–200	3.5–4.5	10–15	conc. inorg. acids, phenols
	Timbrelle, Ultron,...	hd		180–200	3–4	9–11	conc. inorg. acids, phenols
<b>Aramids</b>							
Poly( <i>m</i> -phenyleneisophthalamide)	Nomex, Conex	fi			4.5–5	12–17	polar org. solvents and solutes (LiCl, CaCl <sub>2</sub> ), conc. H <sub>2</sub> SO <sub>4</sub>
	Kevlar 29, Twaron,	fi			2–3	7	conc. H <sub>2</sub> SO <sub>4</sub>
Poly( <i>p</i> -phenyleneterephthalamide) (PPTA)	Kevlar 49, Kevlar 149, Twaron	fi/an	$10^{15}$		2–3	7	conc. H <sub>2</sub> SO <sub>4</sub>
	Kevlar 981, Twaron	fi/hd			2–3	7	conc. H <sub>2</sub> SO <sub>4</sub>
Poly(ethylene terephthalate) (PET)	Kevlar Hp	fi			2–3	7	conc. H <sub>2</sub> SO <sub>4</sub>
	Dacron, Diolen,	st		150–200	0.3–0.4	3–5	conc. H <sub>2</sub> SO <sub>4</sub> , conc. KOH, phenols, tetrachloroethane
	Fortrel, Grilene,	fi	$10^{11} - 10^{14}$	150–200	0.2–0.5	3–5	conc. H <sub>2</sub> SO <sub>4</sub> , conc. KOH, phenols, tetrachloroethane
Poly(1,4-dimethylene cyclohexane terephthalate) (PDCT) [59]	Terylene, Trevira,...	hd		150–200	0.2–0.4	3–5	conc. H <sub>2</sub> SO <sub>4</sub> , conc. KOH, phenols, tetrachloroethane
	Kodel	st		$\approx 200$	0.2		conc. H <sub>2</sub> SO <sub>4</sub> , conc. KOH, phenols, tetrachloroethane

Table 8. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Specific electrical resistance, <sup>b</sup> $\Omega$ cm	Ironing temperature, <sup>c</sup> °C	Water absorption at 21 °C, 65 % R.H., <sup>d</sup> %	Water retention [74], %	Solubility in selected solvents <sup>c</sup>
Polyarylate	Ekonol [60], Vectran	fi			0		NMP + CaCl <sub>2</sub> conc. H <sub>2</sub> SO <sub>4</sub>
Poly(ether ether ketone) (PEEK)	Zyex	fi			6–8		
Novolak	Kynol, Phylene, Novoloid,...						
Poly(amide imide) (PAI)	Kermel	st/fi			3		polar org. solvents (DMA, NMP)
Poly(ether imide) (PEI)		fi		150–180	0.25–1.25	7–11	dichloromethane
Polyurethane elastomers (spandex)	Dorlastan, Lycra, ...				0.5–1.5		noncross-linked fibers: DMA, DMF, HMPA, conc. inorg. acids (decomp.)
<b>Polymerizate fibers</b>							
Polyethylene (HD-PE)	Hiralon, Végon, Spectra,...	fi	$10^{13} - 10^{17}$		0	0	conc. H <sub>2</sub> SO <sub>4</sub> , benzene, chlorinated hydrocarbons
Polypropylene (PP)	Herculon, Meraklon, ...	st/fi	$> 10^{13}$	130	0	0	conc. H <sub>2</sub> SO <sub>4</sub> , toluene, chlorinated hydrocarbons
Polyacrylonitrile (PAN)	e.g., Dralon T	fi/st	$\approx 10^{14}$	150–180	$\approx 1$	4–6	conc. inorg. acids, DMA, DMF, DMS, ethylene carbonate, conc. ZnCl <sub>2</sub> or NaSCN solutions
Copolymerizates with PAN $\geq 85$ %	Dolan, Dralon, ...	st/fi	$10^8 - 10^{14}$	150–180	1–1.5	5–12	conc. inorg. acids, DMA, DMF, DMS, ethylene carbonate, conc. ZnCl <sub>2</sub> or NaSCN solutions
Modacrylics (50–84 % PAN)	Kanekalon, SEF, ...	st	$10^{12} - 10^{13}$		0.4–3	10–20	conc. H <sub>2</sub> SO <sub>4</sub> , DMF, acetone, phenol, cyclohexanone
Poly(vinyl chloride) (PVC)	Clevyl, Rhovyl	st/fi	$10^{12} - 10^{14}$		0–0.2	4–6	conc. H <sub>2</sub> SO <sub>4</sub> , chlorinated hydrocarbons, dioxane, cyclohexanone, DMF
atactic					0	4–6	conc. H <sub>2</sub> SO <sub>4</sub> , chlorinated hydrocarbons, dioxane, cyclohexanone, DMF
syndiotactic [61]		st	$10^{12} - 10^{14}$				

Table 8. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Specific electrical resistance, <sup>b</sup> $\Omega$ cm	Ironing temperature, °C	Water absorption at 21 °C, 65% R.H., <sup>d</sup> %	Water retention [74], %	Solubility in selected solvents <sup>c</sup>
Poly(vinyl alcohol) (PVA)	Kuralon, Mewlon,...	st/fi			3.5–5	25–35	
Poly(tetrafluoroethylene) (PTFE)	Gore-Tex Fibers,...	st/fi	> 10 <sup>14</sup>		0		conc. inorg. acids, phenols, DMF
Poly(phenylene sulfide) (PPS)	Procon, Rylton,...	st/fi			≈ 0.03–0.25 (< 0.6)		perfluorinated solvents > 300 °C < 200 °C no solvent
Melamine resin fiber	Basofil	st			9		
<b>Inorganic fibers</b>							
Textile glass	Gevetex, Fiberglas	st/fi	10 <sup>12</sup> – 10 <sup>15</sup>		0.1	0	hydrofluoric acid
E glass	E-Fiber, Enkafort	fi	10 <sup>12</sup> – 10 <sup>15</sup>		0.1	0	hydrofluoric acid
Aluminum silicate	Nextel 312	st			≈ 0	0	hydrofluoric acid
(e.g., 3 Al <sub>2</sub> O <sub>3</sub> · 2 SiO <sub>2</sub> · B <sub>2</sub> O <sub>3</sub> )	Nextel 440	st			≈ 0	0	hydrofluoric acid
Steel (20% Cr, 7% Ni)	Bekinox	fi	0.7 × 10 <sup>-4</sup>		0		(attacked by halogenated solvents)

<sup>a</sup> st = staple fiber, fi = filament, hd = highly drawn, an = annealed, ap = antipilling;

<sup>b</sup> of fibers without additives or special finishes;

<sup>c</sup> DMA = dimethylacetamide, DMF = dimethylformamide, DMS = dimethyl sulfoxide, HMPA = hexamethylphosphoramide, NMP = *N*-methyl pyrrolidone;

<sup>d</sup> R.H. = relative humidity.

Table 9. Resistance of fibers<sup>c</sup>

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Heat (air) up to <i>t</i> , °C	Light/Weather <sup>b</sup>		Biological influence <sup>c</sup>		Chemicals <sup>c</sup>		Fire
				Residual tenacity, %	Residual tenacity, %	Micro- organisms [57], [58], [75], [76]	Insects	Residual tenacity, %	Residual tenacity, %	
<b>Natural fibers</b>										
Cotton		st	120	20–30/0–20		–	(+)	60–80/0–20	80–100/80–100	19–20
Wool		st	120	0–20/0–20		–	–	90–100/selective	selective	25–28
Silk		fi	120	0–20/0–20		(+)	(+)	lower than wool	selective	
Flax		st		0–20/0–20		bleached (+)		more resistant than cotton	lower than cotton	
<b>Regenerate cellulose</b>										
Viscose rayon, Viscose Modal	Evlan, Fibro, Sarlite,...	st/fi	120	0–30/0		–	–	similar to cotton		19–20
Cuprammonium rayon	Asahi Bemberg, Bemberg	st/fi	120	0–30/0		–	–	similar to cotton		19–20
Cellulose acetate (CA)	Arnell, Celco, Dicel,	st/fi	120	20–45/0–25		(+)	–	60–100/selective	0–20/20–60 NaOH	18–19
Cellulose triacetate	Estron, Silene, Tricel,...	st/fi	130	20–45/0–25		(+)	–	60–100/selective	better than CA	18–19
NMMO Fiber	Lyocell, Tencel	st/fi	150			similar to cotton		similar to cotton		similar to cotton
<b>Polycondensate fibers</b>										
Nylon 6 (PA 6)	Perlon, Acelon,	st	120	20–30/5–15		(+)	+	90–100/90–100	90–100/90–100	20–21.5
	Amilan, Anso,	fi	120	20–30/5–15		(+)	+	90–100/90–100	90–100/90–100	20–21.5
	Caprolan, Grilon,...	hd	120–150	20–30/5–15		(+)	+	90–100/90–100	90–100/90–100	20–21.5
Nylon 66 (PA 66)	Nylon, Antron,	st	120	20–30/5–15		(+)	+	90–100/90–100	90–100/90–100	20–21.5
	Cantrece, Meryl,	fi	120	20–30/5–15		(+)	+	90–100/90–100	90–100/90–100	20–21.5
	Timbrelle, Ultron,...	hd	120–150	20–30/5–15		(+)	+	90–100/90–100	90–100/90–100	20–21.5

Table 9. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Heat (air) up to <i>t</i> , °C	Light/weather <sup>b</sup>		Biological influence <sup>c</sup>		Chemicals <sup>c</sup>		Fire limiting oxygen index (LOI), %
				Residual tenacity, %	Residual tenacity, %	Micro- organisms [57], [58], [75], [76]	Insects	Residual tenacity, %	After 1000 h at 20 °C/10 h at 100 °C dilute acid dilute alkali	
<i>Aramids</i>										
Poly( <i>m</i> -phenyleneisophthalamide)	Nomex, Conex	fi	180–200	/50	+			80–100/80–100	90–100/90–100	26–30
Poly( <i>p</i> -phenylene-terephthalamide) (PPTA)	Kevlar 29, Twaron,	fi	180–200	65–80/ after 16 weeks	+			+	+	
	Kevlar 49, Twaron,	fi/an	180–200	65–80/ after 16 weeks	+			+	+	29–31
	Kevlar 149,	fi/hd	180–200	65–80/ after 16 weeks	+			+	+	29–31
	Kevlar 981, Twaron,	fi	180–200	65–80/ after 16 weeks	+			+	+	29–31
Poly(ethylene terephthalate) (PET)	Kevlar Hp	fi	180–200							
	Dacron, Diolen,	st	120–150	60–80/5–15	+			90–100/90–100	90–100/90–100	20–22
	Fortrel, Grilene,	ap	120–150	60–80/5–15	+			90–100/90–100	90–100/90–100	20–22
	Terylene, Serene,	fi	120–150	60–80/5–15	+			90–100/90–100	90–100/90–100	20–22
	Trevira,...	hd	150–160	60–80/5–15	+			90–100/90–100	90–100/90–100	20–22
	Trewira 810,...813	st/fi	120							
Poly(butylene terephthalate) (PBT)										
Poly(1,4-dimethylene cyclohexane terephthalate) (PDCT) [59]	Kodel	st	≈ 200		+			70–80/HCl	50–70 Na <sub>2</sub> CO <sub>3</sub> solution	
Polyarylate	Vectran, Ekonol [60]	fi	180–260							36
Poly(ether ether ketone) (PEEK)	Zyex	fi	200–250					+ / 96 99/23-74 selective	- / 95	30–35
Polyimide (PI)	P 84	st/fi	260					≥ 80	(+)	36–38
Novolak	Kynol, Phylene, Novoloid	st	200					+	-	30–39



Table 9. (Continued)

Fiber name/polymer	Trade names	Fiber type <sup>a</sup>	Heat (air) up to $t_r$ , °C	Light/weather <sup>b</sup>		Biological influence <sup>c</sup>		Chemicals <sup>c</sup>		Fire
				Residual tenacity, %	Residual tenacity, %	Micro- organisms [57], [58], [75], [76]	Insects	Residual tenacity, %	limiting	
Poly(amide imide) (PAI)	Kermel	st	250	-						
Poly(ether imide) (PEI)		st/fi	160–170	+						
Polyurethane elastomers (spandex)	Dorlastan, Lycra,...	fi	120	0/0	+	+				oxygen index (LOI), %
								(+)		31–32
								95–100/ 85–100/		33
								selective; polyether more resistant than polyester		
<b>Polymerizate fibers</b>										
Polyethylene (HD)-PE	Hiralon, Vegon,...	fi	70–90	+						
(HM-HD-PE; $\bar{M}_r$ > 10 <sup>6</sup> )	Spectra 1000	hd	80–90	+						
Polypropylene (PP)	Herculon, Meraklon,...	st/fi	≈ 120	0/0						
Polyacrylonitrile (PAN)	e.g., Dralon T	fi/st	140	60–80/50–60						
Copolymerizates with PAN ≥ 85 %	Dolan, Dralon	st/fi	140	60–80/50–60						
Modacrylics (50–84 % PAN)	Euroacril, Leatril,...									
	Kanekalon, SEF,...	st	120	lower than PAN	+					
Poly(vinyl chloride)										
atactic	Clevyl, Rhovyl,...	st/fi	< 65	60–90/						
syndiotactic [61]		st								
Poly(vinyl alcohol) (PVA)	Kuralon, Mewlon, Solvron, Vilon,...	st	140 (water vapor: 120)							
		fi	140 (water vapor: 120)	+(+)						
(HM: $\bar{M}_r$ > 10 <sup>6</sup> )		hd	140 (water vapor: 120)							
Poly(tetrafluoroethylene) (PTFE)	Gore-Tex Fibers,...	st/fi	180							
Poly(phenylene sulfide) (PPS)	Procon, Ryton,...	st/fi	190–200	-						
Melamine resin fiber	Basofil	st	200–220							

<sup>a</sup> st = staple fiber, fi = filament, hd = highly drawn, an = annealed ap = antipilling;

<sup>b</sup> no UV stabilizers added, one-year exposure in Florida;

<sup>c</sup> + resistant, (+) moderately resistant, — not resistant.

Table 10. Dyeing behavior of fibers

Fiber name/polymer	Trade name	Dyes
<b>Natural fibers</b>		
Cotton		substantive
Wool		anionic
Silk		anionic, cationic, substantive, reactive, vat
<b>Regenerate cellulose</b>		
Viscose rayon	Evlan, Fibro,...	substantive
Cuprammonium rayon	Asahi Bemberg,...	substantive
Cellulose acetate	Arnel, Celco, Dichel,	substantive, disperse
Cellulose triacetate	Estron, Silene, Tricel,...	substantive, disperse
NMMO fiber	Lyocell, Tencel,...	substantive, reactive
<b>Polycondensate fibers</b>		
Nylon 6	Perlon, Capron, Grilon,...	anionic, metal-complex disperse
Nylon 66	Nylon, Antron, Ultron,...	anionic, metal-complex, disperse
Poly( <i>m</i> -phenyleneisophthalamide) (aramid)	Nomex	cationic plus carrier, high-temperature conditions
Poly(ethylene terephthalate)	Dacron, Diolen,...	disperse plus carrier, high-temperature conditions
Poly(1,4-dimethylenecyclohexane)	Kodel	disperse plus carrier, high-temperature conditions
Poly(butylene terephthalate)	Trevira 810,..813	disperse
Novolak	Kynol,...	disperse
Poly(ether imide)		disperse
Polyurethane elastomers	Dorlastan, Lycra	anionic
<b>Polymerizate fibers</b>		
Polypropylene	Herculon, Meraklon,...	disperse
Polyacrylonitrile	Dralon, Dolan,...	cationic, disperse
Modacrylics	Kanekalon, SEF,...	cationic, disperse
Poly(vinyl chloride)	Clevyl, Rhovyl,...	disperse
Poly(phenylene sulfide)	Procon, Ryton	disperse

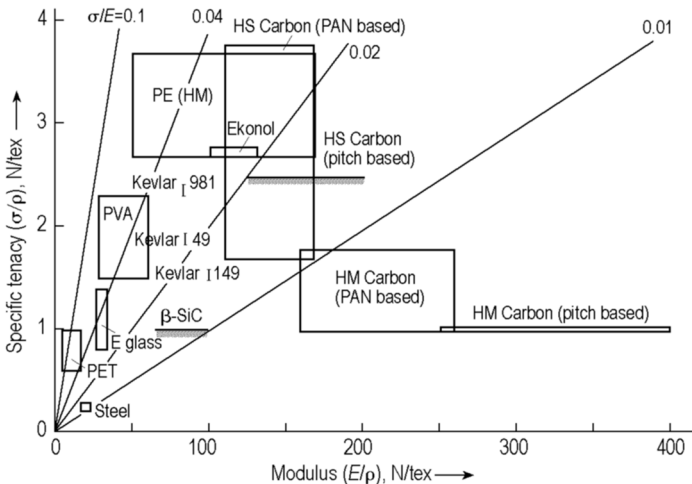
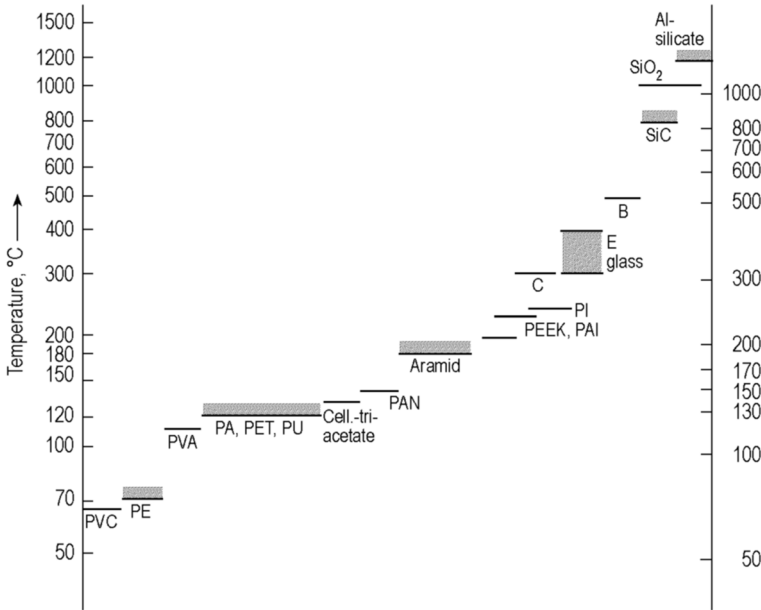


Figure 8. Specific tenacity ( $\sigma/\rho$ ) and modulus ( $E/\rho$ ) of high-performance fibers ( $\rho$ =density)



**Figure 9.** Highest temperatures for fiber application without significant loss in tenacity

Values for fiber elongation, fiber shrinkage, and relative properties such as wet tenacity, loop tenacity and other parameters are expressed as percent. If properties such as fiber resistance to light, weather, chemicals, or organisms cannot be expressed numerically, they are characterized in a simplified qualitative manner in Table 9. In individual cases, the respective conditions and the type of attack (e.g., by certain kinds of pests [57], [58]) are such that widely differing results can be expected.

Some promising fibers that are still being developed have also been included, in particular, high-performance fibers made from high molecular mass poly(vinyl alcohol), the thermoresistant PEEK, PAI, PI (see Fig. 9, and the polyarylate “Ekonol,” an example of a thermotropic polymer [59]. Among the inorganic fibers, apart from carbon and glass, the properties of silicon carbide, and ceramic fibers have been included. Figure 8 shows the ranges of Young’s moduli and tenacities of presently known high-performance fibers used mainly for reinforcing organic resins.

Although fibers are highly anisotropic compared with other materials and therefore especially strong in the axial direction their Young’s modulus is always inferior to the theoretical

(crystal) modulus. The ratio of fiber to crystal modulus attains about 0.1 for textile commodity fibers, 0.3 for high-performance fibers (e.g., from HM-HDPE), especially those with extended chain structure, and as high as 0.8 for the LC polymer Kevlar 149 with unfolded, oriented PPTA molecules. The deficit of the fiber modulus is a consequence of incompletely uncoiled and disentangled macromolecules in as-spun and drawn fibers. The mechanical response of fibers is controlled by the fraction of taut tie molecules connecting neighboring crystallites. This fraction can be estimated from measurements of the elastic modulus by using a simple rheological model or other methods to be about 0.05–0.1 for drawn fibers [83].

Compressibility and lateral compliance increase with increasing fiber anisotropy (on drawing) and this is undesirable for reinforcing fibers (e.g., Kevlar or carbon fibers) in composites. In some cases thermal aftertreatment of such high-performance fibers allows a compromise to be found between the desired compressibility and lower tenacity (see also compressive strength of fibers in Table 4).

The applicability of industrial fibers at higher temperatures (see Tables 6 and 7) is of current

interest. Figure 9 reviews the thermal long-term stability in air.

This compilation of important data is by no means complete. For further information, see → Fibers, 4. Synthetic Organic and → Fibers, 5. Synthetic Inorganic.

## 9. References

### General References

1. H. Batzer (ed.): *Polymere Werkstoffe*, Thieme Verlag, Stuttgart 1986.
2. R. Bauer, H. J. Koslowski: *Chemiefaser-Lexikon*, 10th ed. Deutscher Fachverlag, Frankfurt 1993.
3. J. Brandrup, (ed.): *Polymer Handbook*, 2nd ed., Interscience, New York 1976.
4. R. M. Brown, (ed.): *Cellulose and Other Natural Polymer Systems*, Plenum Publishing, New York 1982.
5. M. E. Carter: *Essential Fiber Chemistry*, Dekker, New York 1971.
6. J. G. Cook: *Handbook of Textile Fibres*, Merrow, Watford 1968.
7. H. Driesch: *Welche Chemiefaser ist das*, Franckh, Stuttgart 1962.
8. A. A. Dembeck: *Guidebook to Man-made Textile Fibres and Textured Yarns of the World*, 3rd ed. The United Piece Dyed Works, New York 1969.
9. H. Doehner (ed.): *Wollkunde*, Parey, Berlin 1964.
10. H. F. Mark (ed.): *Encyclopedia of Polymer Science and Technology*, "Plastics, resins, rubbers, fibres," Wiley-Interscience, New York 1967.
11. B. Falkai (ed.): *Synthesefasern*, Verlag Chemie, Weinheim 1981.
12. F. Fourné (ed.): "Herstellung und Verarbeitung," *Synthetische Fasern*, Wissenschaftl. Verlags GmbH, Stuttgart 1964.
13. B. C. Gaswami, J. G. Martindale, F. L. Scardino: *Textile Yarns*, Wiley-Interscience, New York 1977.
14. M. Grayson (ed.): *Encyclopedia of Textiles, Fibers, and Nonwoven Fabrics*, Wiley-Interscience, New York 1984.
15. F. Happey: *Applied Fibre Science*, Academic Press, London 1979.
16. H. W. Haudek, E. Viti: *Textilfasern*, Bondi, Wien 1980.
17. *High polymers*, a Series of Monographs on the Chemistry, Physics and Technology of High Polymeric Substances, Interscience, New York.
18. Internat. Baumwoll-Inst. (ed.): *Handbuch der Baumwollstoffe*, Frankfurt 1983.
19. H. Klare: *Geschichte der Chemiefaserforschung*, Akademie Verlag, Berlin 1985.
20. P.-A. Koch, (ed.): *Großes Textil-Lexikon*, Deutsche Verlagsanstalt, Stuttgart 1966.
21. H. A. Krässig, J. Lenz, H. F. Mark: *Fiber Technology*, Dekker, New York 1984.
22. R. Vieweg, G. W. Becker (ed.): *Kunststoff-Handbuch*, Hanser Verlag, München 1965.
23. P. Lennox-Kerr: *The World Fibres Book*, The Textile Trade Press, Manchester, 1972.
24. M. Lewin, S. B. Sello (ed.): *Handbook of Fiber Science and Technology*, Dekker, New York 1983.
25. W. Loy: *Chemiefaserstoffe*, Schiele und Schön, Berlin 1978.
26. J. A. Maclaren, B. Milligan: *Wool Science*, Science Press, Marrickville 1981.
27. H. F. Mark (ed.): *Man-made Fibers, Science and Technology*, Interscience, New York 1968.
28. R. Meredith: *Elastomeric Fibres*, Merrow, Watford 1971.
29. B. E. Messerli (ed.): *Seide*, Textilwerkstattverlag Hannover, 1986.
30. L. Miles: *Cotton*, Wayland, Have 1980.
31. R. Moncrieff: *Man-made-Fibres*, 4th ed., Heywood, London 1966.
32. J. S. Robinson (ed.): *Fiber-forming Polymers*, Noyes Data Corp., Park Ridge 1980.
33. J. S. Robinson (ed.): *Spinning, Extruding and Processing of Fibers*, Noyes Data Corp., Park Ridge 1980.
34. J. S. Robinson (ed.): *Manufacture of Yarns and Fabrics from Synthetic Fibers*, Noyes Data Corp., Park Ridge 1980.
35. W. J. Roff: *Fibres, Films, Plastics and Rubbers*, Butterworths, London 1971.
36. Z. A. Rogovin: *Chemiefasern*, Thieme Verlag, Stuttgart 1982.
37. H. E. Schiecke: *Wolle als textiler Rohstoff*, Schiele und Schön, Berlin 1979.
38. K. A. Schmidt: *Technologie textiler Glasfasern*, Zechner, Speyer 1964.
39. *Textil-Fakten: Markt- und Strukturdaten der Textil- und Bekleidungsirtschaft*, Deutscher Fachverlag, Frankfurt 1983.
40. *Textile Faserstoffe*, Fachbuchverlag, Leipzig 1967.
41. C. A. Tisdell: *Economics of Fibre Markets*, Univ. New Castle, New Castle, Austr. 1977.

42. E. Wagner: *Die textilen Rohstoffe*, 6th ed., Spohr, Wuppertal 1981.
43. A. Ziabicki: *Fundamentals of Fibre Formation*, Wiley Interscience, New York 1976.
44. A. Ziabicki: *High Speed Fibre Spinning*, Wiley Interscience, New York 1985.
45. F. Schultze-Gebhardt, "Survey of the Most Important Properties of High-Performance Fibers and their Technical Use," *Chemiefasern/Textilind.* **43** (1993) T 194–196, E 135.
- Specific References
46. P.-A. Koch (ed.): *Großes Textil-Lexikon*, Deutsche Verlagsanstalt, Stuttgart 1966.
47. H. Batzer, (ed.): *Polymere Werkstoffe*, Thieme Verlag, Stuttgart 1986.
48. H. Staudinger et al., *Phys. Chem.* **126** (1927) 3.
49. G. Henrici-Olivé, S. Olivé, *Adv. Polym. Sci.* **51** (1983) 1.
50. K.-H. Umbach, *Chemiefasern/Textilind.* **33** (1983) 85, 136, 204.
51. *Chemiefasern/Textilind.* **37** (1987) 182.
52. J. D. Geerdes: *World Fibre Production, Trends and Outlook*, Internat. Conference on Man Made Fibres, Beijing, Nov. 1985.
53. P.-A. Koch: *Faserstoff-Tabellen*, Konradin-Verlag Kohlhammer GmbH, Stuttgart 1968, 1977, 1979.
54. E. Kleinhansl, J. Mavely: *Denkendorfer Fasertafeln 1986*, Textilpraxis int., Leinfelden-Echterdingen 1986.
55. F. Schultze-Gebhardt: "Mechanische Eigenschaften," in B. von Falkai (ed.): *Synthesefasern*, Verlag Chemie, Weinheim 1981, p. 64.
56. DIN 53 835 (1975).
57. W. Kerner-Gang, H. Kühne in G. Schreyer (ed.): *Konstruieren mit Kunststoffen*, Hanser Verlag, München 1972.
58. H. Kühne, *TPI Text. Prax. Int.* **29** (1974) 57; **30** (1975) 598, 718.
59. E. V. Martin, H. Busch, *Angew. Chem.* **74** (1962) 624.
60. Sumitomo Chem. Com., US 4 503 005, 1983 (K. Ueno, H. Sugimoto, K. Hayatsu).
61. C. Mazzolini: *The Development of a New Fibre from Syndiotactic Polyvinylchloride*, 2nd Shirley International Seminar, Manchester 1970.
62. DIN 53 843 (1976).
63. DIN 53 842 (1976).
64. R. Meredith, *J. Text. Inst., Trans.* **45** (1954) T 489. N. Adams, *J. Text. Inst., Trans.* **47** (1956) T 530. I. D. Owen, *J. Text. Inst., Trans.* **56** (1965) T 329.
65. C. L. Choy, W. P. Leung, *J. Polym. Sci. Polym. Phys. Ed.* **23** (1985) 1759–1780.
66. P. A. Koch, G. Feier, B. Hoffmann: "Untersuchungen über die Quersprödigkeit neuer Synthesefasern," *Forschungsber. Landes Nordrhein-Westf.* no. 2299, Westdeutscher Verlag, Opladen 1973.
67. W. Götze, F. Winkler, *Faserforsch. Textiltech.* **18** (1967) 119, 385.
68. K. E. Perepelkin, *Faserforsch. Textiltech.* **25** (1974) 251.
69. G. W. Urbanczyk, G. Michalak, *J. Appl. Polym. Sci.* **32** (1986) 3841–3846.
70. H. Hespe, E. Meisert, U. Eisele, L. Morbitzer, W. Goyert, *Kolloid Z. Z. Polym.* **250** (1972) 797. D. J. Hourston, R. Meredith, *J. Appl. Polym. Sci.* **17** (1973) 3259.
71. G. Hinrichsen, *Angew. Makromol. Chem.* **20** (1971) 121.
72. R. L. McGee, J. R. Collier, *Polym. Eng. Sci.* **26** (1986) 239–242.
73. H. Böder, D. Gölden, P. Rose, H. Würmseher: "Kohlenstofffasern – Herstellung, Eigenschaften, Verwendung," *Z. Werkstofftech.* **11** (1980) 275.
74. DIN 53 814 (1974).
75. I. A. Ermilova, L. N. Alekseeva, I. I. Šamolina, V. A. Chochlova, *Sowj. Beiträge Faserforsch. Textiltech.* **19** (1982) 274–276.
76. Y. L. Hsieh, D. A. Timm, J. Merry, *Textile Res. J.* **57** (1987) 20–28.
77. G. Wu, J.-D. Jiang, P. A. Tucker, J. A. Cuculo, *J. Polym. Sci.: B: Polym. Phys.* **34** (1996) 2035–2047.
78. F. Schultze-Gebhardt, *Chemiefasern/Textilind.* **43** (1993) 432–433, E 66, E 68.
79. *Chem. Fibers Int* **46** (1996) 230. Econom. Fiber Bureau, Washington: Fiber Organon, Washington 1996.
80. T. F. N. Johnson, *Chem. Fibers Int.* **46** (1996) 280, 282–284, 286.
81. S. R. Allen, *J. Mater. Sci.* **28** (1993) 853–859.
82. G. J. Hayes, D. D. Edle, J. M. Kennedy, *J. Mater. Sci.* **28** (1993) 3347–3257.
83. M. Miwa et al., *J. Mater. Sci.* **31** (1996) 499–506.
84. F. Schultze-Gebhardt, *Acta Polym.* **41** (1990) 512–513, *Chemiefasern/Textilind.* **40** (1990) T 56, T 58, E 49–E 50.
85. B. Poulaert et al., *Polym. Commun.* **31** (1990) 48–51.
86. C. L. Choy, Y. Fei, T. G. Xi, *J. Appl. Polym. Sci.* **31** (1993) 365–370.

87. D. T. Grubb, L. W. Jelinski, *Macromolecules* **30** (1997) 2860–2867.
88. W. Albrecht, M. Reintjes, B. Wulfhorst:  
“Lyocell-Fasern, Faserstoff-Tabellen nach  
P.-A. Koch, 1. Ausg. 1997,” *Melliand*  
*Textilber.* **78** (1997) 575–581.
89. H. Blumberg, *Chem. Fibers Int.* **47** (1997)  
36–41.
90. J. M. Kure et al., *Textile Res. J.* **67** (1997)  
18–22.