2.2 FIBERS

2.2.1 ARAMID FIBERS[504-513]

Names: aramid fiber, poly(p-phenylene terephthalamide)		**CAS #**: 26125-61-1
Chemical formula: $(C_{14}H_{10}N_2O_2)_n$	**Functionality**: NH, COOH, H	
PHYSICAL PROPERTIES		
Density, g/cm^3: 1.44-1.45	**Decomposition temp.**, °C: 500	**Melting point**, °C:
Hot air shrinkage, %: 0.1	**Loss on ignition**, %: 0.2-0.3	**Specific heat**, kJ/kg·K: 1.42
Thermal conductivity, W/K·m: 0.04-0.05	**Thermal expansion coefficient**, 1/K: -3.5×10^{-6}	
Tensile strength, MPa: 2500	**Residual strength**, 48 h @200°C in %: 90	
Elongation, %: 2-3%		
CHEMICAL PROPERTIES		
Chemical resistance: low resistance to strong acids and alkalis but substantially better than E-glass[507]		
Adsorbed moisture, %: 5-8		
MORPHOLOGY		
Fiber length, mm: 1-6	**Amount of sizing**, %: 4-6	**Aspect ratio**: 100-500
Filament diameter, μm: 5-18	**Filament count**, dtex: 1.7	**Specific surface area**, m^2/g: 0.2
MANUFACTURERS & BRAND NAMES: Akzo Nobel Aramid Products, Inc., Conyers, GA, USA Twaron 1010, 1055, 1488 - chopped aramid fiber Twaron 5000, 5010, 5011 - powders with average particle sizes of 450, 110, 55 μm, respectively Composite Particles, Inc., Allentown, PA, USA Vistamer KF - aramid fiber which has surface activated by a patented reactive gas process DuPont, Wilmington, DE, USA Kevlar 29, 49, 149 - Kevlar 149 has lower moisture absorption		
MAJOR PRODUCT APPLICATIONS: composites, wear resistant machine parts, automotive parts, office equipment parts, electrical devices, pumps, brake pads		
MAJOR POLYMER APPLICATIONS: POM, PA, PC, PBT, epoxy, phenoxy, vinyl ester, fluoropolymers		

Aramid fiber have been in use for a long time to improve wear resistance of plastic parts. Aramid fiber is superior to other wear resistant additives due to its easier dispersion and minimal effect on mechanical properties of filled materials. Incorporation of fibers increases the impact strength of composites.[506] Further improvements in mechanical properties can be obtained by applying technology developed by Composite Particles, Inc. in which the surface is modified with OH and COOH groups. The presence of these groups was found to increase adhesion to many polymers. The degree of modification should be carefully controlled because the mechanical strength of the fiber and the performance of its composite may be adversely affected.[507]

The high moisture absorption of aramid fibers is their biggest disadvantage. It was reported in the literature that moisture absorption by epoxy laminates degrades their mechanical properties.[504,510] Hygroscopic fibers provide an easy route for moisture ingress. The addition of aramid fibers to epoxy and phenolic composites slightly improves their flame resistance and decreases smoke formation.[505]

2.2.2 CARBON FIBERS[514-547]

Names: carbon fiber, graphite fiber | **CAS #**: 7440-44-0

Chemical formula: C | **Functionality**: OH, COOH, NH

Chemical composition: C - 84.3-95.7%, 97-99% (pitch-based), oxygen - 3-7%; sizing agents: epoxy, polyamide (1.3-7%)

PHYSICAL PROPERTIES

Density, g/cm^3: 1.76-1.99, 1.9-2.25 (pitch-based) | **Mohs hardness**: 0.5-1

Linear expansion coefficient, 1/K: -0.1x10^{-6}, -1.45x10^{-6} (pitch-based) | **Specific heat**, kJ/kg·K: 0.71

Thermal conductivity, W/K·m: 9-100, 25-1000 (pitch-based fiber), 400 (pure copper), 540 (pitch-based carbon fiber 40/epoxy 60 composite)

Maximum temperature of use, ^{o}C: 1300 | **Young modulus**, GPa: 230-390

Tensile strength, MPa: 3000-5500, 1400-3700 (pitch-based) | **Elongation**, %: 0.4-2

Tensile modulus, GPa: 230-500, 160-980 (pitch-based) | **Coefficient of friction**: 0.1-0.14

OPTICAL & ELECTRICAL PROPERTIES

Color: black

Resistivity, Ω-cm: 3.3x10^{-2}-1.5x10^{-3}, 10^{-5} (hollow graphite fibrils), 1-3x10^{-4} (pitch-based fiber)

MORPHOLOGY

Fiber length, μm: 40-160 (milled), 6000 (chopped), 1-10 (hollow graphite fibrils), 3-50,000 (pitch-based)

Filament count: 500-12,000 | **Micropores**, cm^3/g: 0.058 | **Pore diameter**, nm: 0.02-0.05

Filament diameter, μm: 4-7 (carbon fiber), 0.01 (hollow graphite fibrils), 10-13 (pitch-based)

Aspect ratio: 6-30 (milled); 860 (chopped), 100-1000 (hollow graphite fibrils)

Specific surface area, m^2/g: 0.27-0.98, 250-300 (nanofibers[521]), 0.4-0.7 (pitch-based)

MANUFACTURERS & BRAND NAMES:

Amoco Performance Products, Inc., Alpharetta, GA, USA
- ThermalGraph DKA X (0.2 mm), CKD X (50 mm), DKE X (0.003-0.005 mm), DKD X (0.2 mm) - pitch-based thermally conductive fibers which have 50% higher longitudinal conductivity than copper. The filament diameter is 10 μm for all fibers and their length is given in parentheses. DKD has higher tensile modulus than DKA.
- Thornel VMX-11, VMX-12 - granulated pitch-based fillers for injection molding to enhance electric and thermal conductivity, frictional characteristics and dimensional stability
- Thornel K-1100 2K - fiber which has thermal conductivity 2-3 higher than copper and 4-5 times higher than aluminum
- T300, T650 - PAN-based carbon fibers

Asahi Chemical Industry, Tokyo, Japan

Courtauld Ltd., UK
- Courtelle HM, HT

Hercules Aerospace Espana S.A., Spain
- AS

Hyperion Catalysis International, Cambridge, MA, USA
- Hollow carbon fibrils

continued on the next page

MANUFACTURERS & BRAND NAMES:
Toho Rayon Co., Ltd., Tokyo, Japan affiliated with Toho US and Tenax, Germany
Besfight HTA-C6- S, SR, SRS, N, NR, NRS, E - chopped fiber (S, E - epoxy sizing, N - polyamide sizing)
Besfight HTA-CMF- 0040 OH, 0160-E, 0160-OH - milled fiber
Besfight pellet - S-1002C-00, S-1002G-00, L-1002C, L-1002G-00 (PA-66), S-1230C-00, 1230G-00 (POM)
Besfight Prepreg - 100 series (epoxy modified), 300 series (bismaleimide modified)
Toray Industries
Celion G30

MAJOR PRODUCT APPLICATIONS: personal computers, aircraft, rockets, satellites, automation equipment, electrical and electronics parts, mechanical parts, medical instruments, fishing rods, golf clubs, tennis rackets, brake pads, composites, mufflers, surface preparation for electrostatic painting

MAJOR POLYMER APPLICATIONS: PP, PE, PA, PC, PBT, PEEK, PS, epoxy, polyurethane

The following properties of carbon fibers are exploited in their applications: high tensile strength and modulus, good fatigue resistance and wear lubricity, low density (lower than metal), low linear thermal expansion coefficient, good dimensional stability, heat resistance, electric conductivity, ability to shield electromagnetic waves, x-ray penetrability, good chemical stability and excellent resistance to acids, alkalis, and many solvents. This list shows that carbon fibers have a high potential use in high performance materials. Total world production of carbon fibers is estimated 9,590 tons. North America consumes 40% of total production, Europe and Japan 21% each and the remaining countries 18%. The largest use is in aircraft industry followed by sport and leisure equipment and industrial equipment. Carbon fiber is produced from polyacrylonitrile fiber, rayon or pitch filaments which undergo preoxidation, carbonization and surface treatment. Surface oxidized carbon fibers are also produced to increase adhesion are produced. Also, prepregs are manufactured with various resins (mostly epoxy and bismaleimide) to aid in the incorporation of carbon fibers. Figure 2.77 shows micrograph of the cross-section of carbon fiber which can be compared with Figure 2.38 which shows this fiber coated with nickel.

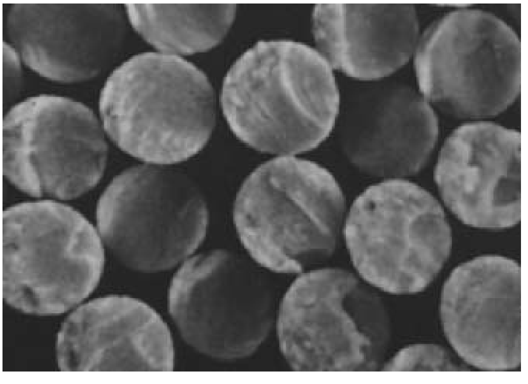

Figure 2.77. Micrograph of Besfight carbon fiber. *Courtesy of Toho Rayon Co., Ltd., Tokyo, Japan.*

The conditions of carbonization have impact on properties of carbon fibers and their price. The least expensive carbon fibers manufactured from PAN are produced by rapid heating under tension from the initial orientation temperature of 300°C to 1000°C. This process produces low modulus fibers. High strength fibers are heated to 1500°C and the high modulus fiber to 2200°C under argon. These various conditions result in graphite crystals with different structures which affects the mechanical performance of fibers. In the coal-tar or petroleum pitch processes, the initial material is polymerized by heat which helps to remove low molecular weight volatile components. The resultant nematic liquid crystal, or mesophase, is oriented during the spinning operation to form fibers. The third raw material – rayon is used less often because of the environmental impact of the precursor material.[546]

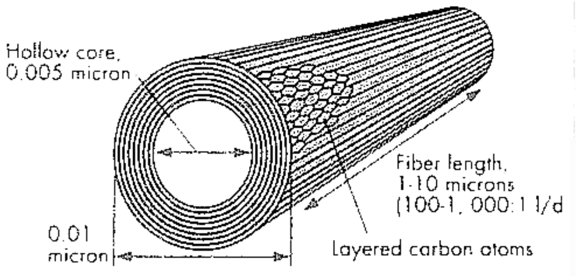

Figure 2.78. A structure of hollow carbon fibers. *Courtesy of Hyperion Catalysis International, Cambridge, MA, USA.*

Hyperion Catalysis International developed a new technology to produce hollow carbon fibrils. The patented technology produces hollow fibrils of very small diameter in a catalytic process using ethylene gas as the raw material. The fibril structure is given in Figure 2.78. The striking feature of these fibrils is their very small diameter. Typically, with these fibrils, seven times less material is required to obtain a conductivity equivalent to products filled with PAN-based carbon fibers and 3 times less than products filled with steel fibers. This performance is due to the high elasticity of these fibers which lowers breakage and allows the fibers to form entangled structures within the body of the plastic material. Efforts are

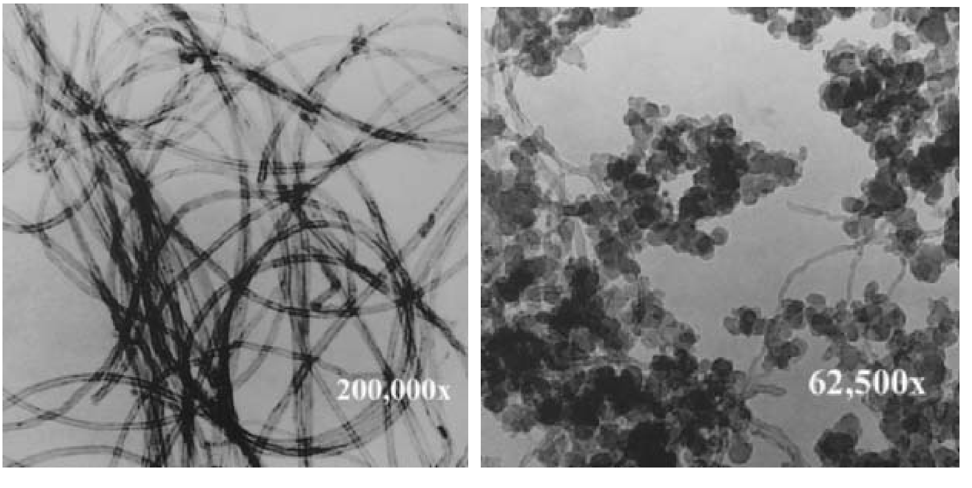

Figure 2.79. Hollow graphite fibrils (left) and fibrils mixed with carbon black (right). *Courtesy of Hyperion Catalysis International, Cambridge, MA, USA.*

being made to simplify the electrostatic painting of parts filled with carbon fibers for automotive and other applications.

Figure 2.79 shows graphite fibrils alone and in comparison with particles of carbon black. Carbon black particles have larger diameter than these hollow tubes.

2.2.3 CELLULOSE FIBERS[548-553]

Name: cellulose fiber	**CAS #**: 9004-34-6
Chemical formula: $(C_6H_{10}O_5)_n$	**Functionality**: OH or from modification
Chemical composition: cellulose content - 45-99.6%	
Trace elements: Pb - 10 ppm, As - 1 ppm	

PHYSICAL PROPERTIES

Density, g/cm^3: 1-1.1	**Char point**, ^{o}C: 290	**Loss on ignition**, %: 0.3-25
Maximum temperature of use, ^{o}C: 200		

CHEMICAL PROPERTIES

Moisture content, %: 2-10	**Adsorbed moisture**, %: 420-1000	**Ash content**, %: 0.13-0.4
pH of water suspension: 4-9	**Water solubility**, %: 1.5	

OPTICAL PROPERTIES

Color: white, gray, brown	**Brightness**: 86-89

MORPHOLOGY

Pore size: 100 Å (only polymers which have molecular weight less than 10,000 can enter pores)	
Fiber length, μm: 22-290	**Oil absorption**, g/100 g: 300-1000
Specific surface area, m^2/g: 1 (dry state), 100-200 (accessible to water in wet state)	
Sieve analysis: residue on 200 mesh sieve - traces-60%	**Fiber diameter**, μm: 5-30

MANUFACTURERS & BRAND NAMES:

Cellulose Filler Factory Corporation, Chestertown, MD, USA affiliate of Cellulose-Füllstoff-Fabrik, Mönchengladbach, Germany
- Technocel 1003/5, 1004, 1004/5, 1004/10, 1004/15, 2004, 202, 40, 90, 150, 180, 200, 300, 750, 2500- recycled and virgin fibers for industrial applications. Fibers differ is color, purity, and particle sizes
- Topcel - products for asphalt reinforcement
- Diacel 40, 90, 150, 200 - pulp for filtration industry (with number increasing particle size increases)
- Sanacel 40, 90, 150, 200, - fibers for cosmetic and pharmaceutical applications
- Qualicel 40, 90, 150, 200, - vegetable fiber for food applications

Fiber Sales & Development Corporation, St. Louis, MO, USA
- Solca-Floc 1016, 10, 20, 40, 60, 100, 200, 300 - fibers of different length manufactured from purified cellulose

Interfibe Corporation, Solon, OH, USA
- White fibers - Gel-Cel W10, W30, W50, 5FT
- Gray fibers - 185, 230, ETF, JMC, JMM, FT, GC66
- Treated fibers - 200, 205, WFP, FTP
- Gel-Cel fibers - 10, 20, 30 - fibers obtained by Jet Process developed to improve uniformity of fibers, modify their morphology, and improve their anti-settling characteristics

MAJOR PRODUCT APPLICATIONS: filtration, ceramics, foams, floor tiles, shoe soles, paints, food, building products, welding electrodes, gaskets, stucco, EIFS, asbestos alternative, sealants, roof coatings, athletic surface coatings, crack fillers and sealers, brake pads, clutches, pavement, artificial leather, electrical components, automotive components, household appliances, mastics, putties, patching compounds, grouts

MAJOR POLYMER APPLICATIONS: alkyd, polyurethane, acrylic, rubber, melamine resins, phenoxy, polyester, PE, PP, PVC, NBR

Cellulose fibers offer many valuable properties but the most important characteristic is that they are natural in origin. They are safe to use, non-polluting, and energy efficient. These qualities are the major reasons for the growing interest in these fibers. Technical cellulose fibers are produced by recycling of newsprint, magazines, and other paper products. There are also numerous industrial applications for these fibers which exploit their chemical functionality (reactivity) for crosslinking, their ability to retain water and their hydrogen bonding capability for improvement of rheological properties. The shape of fiber helps to prevent cracking, reduce shrinkage, increase green strength, and reinforce materials.

Cellulose content varies. Virgin fibers produced from wood pulp contain 99.6% cellulose and are white. Fibers manufactured from reclaimed materials contain 75% and are gray or brown. Cellulose fibers (especially virgin materials) have a complex morphological structure which facilitates reinforcement (Figure 2.80).

Figure 2.81 shows the fiber surface at a high magnification. The accessability of the fiber surface to interaction with the matrix depends on the differences in fiber morphology relative to the method of their manufacture. The choice of hydrophilic or hydrophobic grades improves their dispersion in different matrices and readily accessible functional groups allow the use fibers to double as reactive crosslinkers.

Figure 2.80. The morphology of cellulose fibers. *Courtesy of Cellulose Filler Factory Corporation, Chestertown, MD, USA.*

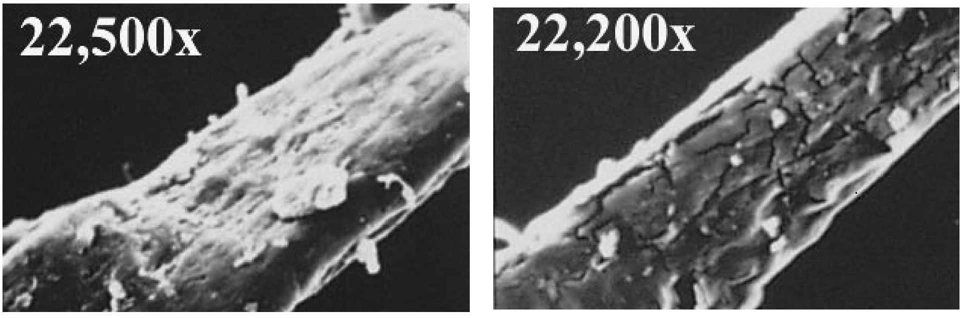

Figure 2.81. SEM micrograph of cellulose fiber, Interfibe WF (left), Interfibe 231 (right). *Courtesy of Interfibe Corporation, Solon, OH, USA.*

2.2.4 GLASS FIBERS[554-565]

Name: glass fibers		**CAS #**: 65997-17-3
Chemical formula: variable	**Functionality**: OH unless modified	
Chemical composition: SiO_2 - 52.5-55.5%, CaO - 21-24%, Al_2O_3 - 14-14.5%, B_2O_3 - 5-8.6%, sizing 0-3%		
PHYSICAL PROPERTIES		
Density, g/cm^3: 2.52-2.68	**Mohs hardness**: 6-6.5	**Softening point**, ^{o}C: 830-920
Thermal conductivity, W/K·m: 1	**Specific heat**, kJ/kg·K: 0.83	
Young modulus, MPa: 70,000	**Poisson ratio**: 0.22	**Coefficient of friction**: 0.9-1
Tensile strength, GPa: 3.1-3.8	**Elastic modulus**, GPa: 76-81	**Elongation**, %: 4.5-4.9
CHEMICAL PROPERTIES		
Moisture content, %: 0.1-3	**Adsorbed moisture**, %: 0.3	**pH of water suspension**: 5-10
OPTICAL & ELECTRICAL PROPERTIES		
Refractive index: 1.55-1.56	**Color**: white	**Loss tangent**: 0.001
Dielectric constant: 5.8-6.1	**Volume resistivity**, Ω-cm: 10^{13}-10^{16}	
MORPHOLOGY		
Fiber length, μm: 50-350 (milled grades), 4000-13,000 (chopped grades)		
Aspect ratio: 3-800	**Filament diameter**, μm: 15.8	

MANUFACTURERS & BRAND NAMES:

Evans Clay Company, McIntyre, GA, USA

FG 500, 700, 800

Owens Corning, Toledo, OH, USA

Fiberglas - 731 line (cationic size), 737 line (silane) 739 line (no sizing agent) - milled fibers produced in each line in different length sizes but the same filament diameter (15.8 μm) made out of E-glass

Fiberglas 405 - chopped strands made out of E-glass in 1/8, 3/16, 1/4, and ½ lengths for polyester, epoxy and phenolics

Cratec 144A (PP), 408A (PBT, POM, SMA, ABS, SAN, PS, PC, PP), 415A (PE & PC below 15 wt% loading), 489A (products which require FDA approval), 497A (PPS, PPO, PVC, PSF, phenoxy) - chopped glass fiber grades optimized for application in polymers listed in parentheses. All grades have the same fiber length (4 mm) and are produced from E-glass

continued on the next page

MANUFACTURERS & BRAND NAMES:
PPG Industries, Inc., Fiber Products, Pittsburgh, PA, USA

Chop Vantage 3535 (PA), 3540 (PA, PET, ABS, SAN), 3563 (PET), 3640 (PA-66, PA-46), 3660 (PA), 3763 (PBT, PC), 3793 PBT, ABS, SAN, SMA, PC, PPS, PEI, PES, PEEK), 8016 (chopped strand, mat applications) - chopped fibers with different silane treatment designed for the selected polymers listed in parentheses. Filament diameter is 10 μm and length 3.2 or 4.5 mm.

DeltaChop 3796 (PPS, PEI, PES, PEEK), 8610 (paper, ceramics), 8810 (asbestos replacement in friction applications) - chopped strand of ultrafine fibers with proprietary sizing having filament diameter of 6.5μm and length varying from 3 to 38 mm. The fibers are used in applications listed in parentheses.

MaxiChop 3242 (PP), 3298 (PP), 3617 (PA), 3662 (PA), 3707 (PC), 3762 (PBT, PC), 3790 (PBT, ABS, SAN, SMA, PC), 8018 (non-woven, papers, felts)- chopped strand of fibers with silane sizing having filament diameter of 13 μm (except for 3617 and 3707 which have filament diameter of 17 μm) length for most grades is 3.2 mm except for 3790 (3.2 and 4.8) and 8018 (3 to 38 mm). The fibers are used in applications listed in parentheses.

Type 3075 (bulk molding compounds, BMC), 3156 (thermosets, such as phenoxy, epoxy, polyester, etc.) - chopped strand of 13 and 10 μm silane sized filaments, respectively, cut to the length in a range from 3.2 to 12.8 mm

8239 - wet chopped strand for wet laid mat (diameter - 16 μm, length - 6-32 mm)

MAJOR PRODUCT APPLICATIONS: electrical connectors, automotive components, automotive fascia, automotive seals, gaskets and bearings, aerospace components, friction products, putty compounds, adhesives

MAJOR POLYMER APPLICATIONS: polyester, epoxy, phenoxy, polyurethanes, PTFE, PP, PE, PBT, POM, SMA, ABS, SAN, PS, PC, PES, PEI, PPS, PPO, PVC, PSF, phenoxy

Glass fibers are produced by two methods, milling and chopping. The milled fibers are milled using a hammer mill which results in a relatively broad (but consistent) length distribution. The diameter depends on the filament diameter manufactured for milling process. The chopped fibers are produced by chopping a bundle of glass filaments to a precise length. The length of chopped fibers is substantially larger than that of the milled fibers. In both cases, fibers may or may not contain sizing or surface modification. If sizing is applied, it is optimized for a certain type or types of polymers. Owen Corning milled fibers are produced with a variety of size coatings for different polymers. Cationic sized milled fiber is suggested for polyester epoxy, phenolic and thermoplastics. Silane modified grades are for urethanes and thermoplastics, and glass fiber without any sizing agent is suggested for use in PTFE and thermoplastics.

Glass fibers are extensively used by industry because of their reinforcing effect, and the improvements they produce in thermal properties such as a reduction in thermal expansion and an increase in heat deflection temperature. The most challenging tasks of fiber application include the incorporation process which must be designed to prevent breakage, improve matrix fiber adhesion, prevent fiber corrosion in some environments, and develop proper fiber orientation.

2.2.5 OTHER FIBERS

Numerous fibrous products are used as fillers in plastics materials. Fibers are generally divided into natural and man-made fibers. The natural fibers belong to three groups: vegetable, animal, and mineral fibers. Natural mineral fibers were discussed above in separate sections. The vegetable fibers group is divided into hair fibers (cotton, kapok), bast fibers (flax, hant, jute, ramie) and hard fibers (sisal, hanequen, coir). A typical feature of vegetable fiber is the high cellulose content (65-85%). Other building blocks of vegetable fibers include hemicellulose (5-15%), and lignin (2-15%). In addition to vegetable fibers there is a growing interest in utilization of various waste wood products such as paper and construction wood waste which constitute a significant portion of municipal waste. The properties of wood fibers and cellulose fibers discussed above (Sections 2.1.58 and 2.2.3) show that these materials offer very good properties and are likely to be studied in the future with a growing interest.

Current research indicates that there is a growing interest in natural fibers. Natural fibers from jute were tested in thermosetting and thermoplastic resins.[566-568] Lignin fillers were used in phenol-formaldehyde,[569] SBR, SBS, and SIS[570] and PE[571] with good results. The opportunities for applications of natural fibers in industrial products have been the subject of recent reviews.[572,573] Cellulose whiskers with a high reinforcing value were obtained from wheat straw.[574,575] Wood fibers were found applicable to such diverse materials as polypropylene parts,[576] foams,[577] and polymer blends.[578] The interest in this research is inspired by availability, biological degradability, low cost, and chemical reactivity of these products which can be easily modified by chemical methods. Fibers of animal origin are less important although small amounts are used in adhesives and sealants.

Metal fibers form another group of important materials due to the growing interest in conductive materials.[579-581] Some of these fibers were discussed together with metal powders, flakes and metal coated minerals in Section 2.1.40.

There is also an interest in application of synthetic fibers.[582,583] Two directions are common: surface modification and development of fibers with special morphology. The controlled composition of synthetic fibers gives opportunities to regulate their surface properties to meet specific requirements giving the product formulator new tools to make product improvement. Synthetic fibers can be produced in variety of shapes and sizes which can be tailored to specific applications in new products. Ultra small fibers, some hollow, with a wide variety of surface morphologies can be produced economically to meet specific requirements of a wide variety of high technology products.

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