Fibers Classifications and Properties

1- Advantages of Polymer Composites
Polymer composites make the largest and most diverse use of composites due to ease of fabrication, low cost and good properties. Also, they have:
• High specific strength properties (20-40% weight savings)
• Ability to fabricate directional mechanical properties
• Outstanding corrosion resistance
• Excellent Fatigue and fracture resistance
• Lower tooling cost alternatives
• Lower thermal expansion properties
• Simplification of manufacturing by parts integration
• Potential for rapid process cycles
• Ability to meet stringent dimensional stability requirements

Glass-fiber reinforced composites (GFRC) are strong, corrosion resistant and lightweight, but not very stiff and cannot be used at high temperatures. Applications include auto and boat bodies, aircraft components. Carbon-fiber reinforced composites (CFRC) use carbon fibers, which have the highest specific module (module divided by weight). CFRC are strong, inert, allow high temperature use. Applications include fishing rods, golf clubs, aircraft components.

2. Fiber reinforcement
Fibers are pliable hair-like substances, built up by long chains of basic molecules. Fibres are very small in diameter in relation to their length. Long continuous strands of fibers are called filaments. The only natural filament fibre is silk from butterflies or spiders. Fibre’s properties depend strongly on both the external and internal fibre structure as well as the chemical composition. Properties therefore vary significantly. Crystalline areas give tensile strength, stiffness and stability, while amorphous areas are weaker but more movable. The fibers can be individual strands as thin as a human hair or they can be multiple fibers braided in the form of a yarn (or tow).

2.1. Choosing fibers
The fibers in advanced composites are usually non-metallic in nature, consisting of such materials as glass, carbon, silicon carbide, alumina, boron or Kevlar. Other fibers such as spectra and quartz are also available, but these are usually reserved for specialized application. The table below shows some advantages and disadvantages of some fibertypes, while Figure 4.7 shows some properties of some fibers.
Figure 4.8 shows a plot of specific strength vs. specific stiffness of some fibers. High-strength fibers utilized in high-performance composites include carbon, glass, aramid, ultrahigh molecular-weight polyethylene (PE), boron, quartz, ceramic, and hybrid combinations. Continuous bundles (tow or roving) are the basic fiber forms for high-performance composite applications. These forms may be used directly in processes such as filament winding or pultrusion or may be converted into tape, fabric, and other forms.

In high-performance composites, the structural properties of the finished part are derived primarily from the fiber. A fiber-to-matrix ratio of 60:40 or higher is common for both thermoset- and thermoplastic-matrix composites. Desirable properties are not achieved, however, without effective adhesion between fiber and matrix, which requires sufficient saturation with resin (wetout) at the fiber-matrix.

### Table of Fiber Properties

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Advantages</th>
<th>Disadvantages</th>
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</table>
| E-, S-Glass | - High strength  
- Low cost | - Low stiffness  
- Short fatigue life  
- High temp sensitivity |
| Aramid (Kevlar) | - High tensile strength  
- Low density | - Low comp. strength  
- High moisture absorp.  
- High cost |
| Boron | - High stiffness  
- High comp. strength | - Moderate cost |
| Carbon (AS4, T300) | - High strength  
- High stiffness | - Low strength  
- High cost |
| Graphite (pitch) | - Very high stiffness | - Low strength  
- High cost |
| Ceramic (silicon carbide, alumina) | - High stiffness  
- High use temp | - Low strength  
- High cost |
interface. Attention to fiber surface preparation, such as use of a surface finish or coupling agent and selection of a compatible fiber and matrix combination, ensures good adhesion. We will have a closer look at some types of fibers.

2.2. Glass fibers

Glass fibers (GF) are the most widely used reinforcement for plastic and rubber products, and are also the finest (smallest diameter) of all fibers, typically 1 to 4 microns in diameter. Glass fibers, see Figure 4.9, are made of silicon oxide with addition of small amounts of other oxides. Glass fibers are characteristic for their high strength, good temperature and corrosion resistance, and low price. Over 90% in the composite industry is glass fibers. Properties of glass fibers are
bound to the chemical composition of the mixture, but they are also influenced by the spinning way. Usually, they are divided into:

<table>
<thead>
<tr>
<th>Use</th>
<th>Type of glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multipurpose fibers</td>
<td>glass E</td>
</tr>
<tr>
<td>Acid resistant fibers</td>
<td>glass A, C, CR</td>
</tr>
<tr>
<td>Alkali resistant fibers</td>
<td>glass R, S</td>
</tr>
<tr>
<td>High strength fibers</td>
<td>glass R, S</td>
</tr>
<tr>
<td>Fibers with good dielectric properties</td>
<td>glass D</td>
</tr>
</tbody>
</table>

The two types of glass fibers that are most common are the E-glass and S-glass. The first type is the most used, and takes its name from its good electrical properties (no electrical interference in thunderstorms, and no sparks). The second type is very strong (S-glass), stiff, and temperature resistant. They are used as reinforcing materials in many sectors, e.g. automotive and naval industries, sport equipment. S-glass are used for instance in aircraft flooring, helicopter blades etc. Some properties for E- and S- glass are listed in the following table:

<table>
<thead>
<tr>
<th>E-glass</th>
<th>S-glass</th>
</tr>
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<tbody>
<tr>
<td>- softens at $\approx 850^\circ C$</td>
<td>- softens at $\approx 1000^\circ C$</td>
</tr>
<tr>
<td>- most inexpensive fiber</td>
<td>$\approx 30%$ stronger than E-glass</td>
</tr>
<tr>
<td>- most commonly used fiber today</td>
<td>$\approx 15%$ stiffer than E-glass</td>
</tr>
<tr>
<td>- insulators and capacitors</td>
<td>$\approx 3$ times as expensive as E-glass</td>
</tr>
<tr>
<td></td>
<td>- high quality glass fiber</td>
</tr>
<tr>
<td></td>
<td>- high technical purposes</td>
</tr>
</tbody>
</table>

The most widely used composite material is fiberglass in polyester resin, which is commonly referred to as just fiberglass. Fiberglass is light weight, corrosion resistant, economical, easily processed, has good mechanical properties, and has over 50 years
of history. It is the dominant material in industries such as boat building and corrosion equipment, and it plays a major role in industries such as automotive, medical, recreational, and industrial equipment.

Quartz fibers Quartz fibers (SiO2) are very high silica version of glass with much higher mechanical properties and excellent resistance to high temperatures and can be used continuously to 1048.9°C and for short-temperature applications, even to 1248.9°C. They are more expensive than E-glass and S-glass, provide significantly better electromagnetic properties than glass, making them a good choice for parts such as aircraft radomes.

2.3. Carbon fibers
Carbon fibers (CF) appeared on the market in 1960 and are produced of organic fibers (rayon, acrylics etc.) or from remaining of petroleum or tar distillation.

![Figure 4.10: Carbon fibre.](image)

Carbon fibers, see Figure 4.10, are the stiffest and strongest reinforcing fibres for polymer composites, the most used after glass fibres. Made of pure carbon in form of graphite, they have low density and a negative coefficient of longitudinal thermal expansion. Carbon fibres are very expensive and can give galvanic corrosion in contact with metals. They are generally used together with epoxy, where high strength and stiffness are required, i.e. race cars, automotive and space applications, sport equipment.

2.4. Boron fiber
Boron (BF) is a metal known for its exceptional resistance and form. BF is five times as strong and twice as stiff as steel. Boron provides strength, stiffness, light weight and excellent compressive properties, as well as buckling resistance. Use of boron composites ranges from sporting goods, such as fishing rods, golf club shafts, skis and bicycle frames, to aerospace applications such as aircraft empennage.
skins, space shuttle truss members and prefabricated aircraft repair patches. It has a melting point at 2180°C.

2.5. **Ceramic fibers**

Ceramic fibers (CEF) are mostly used as refractory fibers in uses over 1000°C and are characterized by a polycrystalline structure rather than amorphous. Some of the more common ceramic continuous reinforcements include silica, mullite, alumina, carbon, zirconia, and silicon carbide in addition. The more sophisticated kinds of fibers, have a basis of borate, carbide, silicon nitride and borate nitride. They are very expensive fibers because only a small quantity is produced, and they are used in particular fields such as aerospace.

Ceramic fibers offer high to very high temperature resistance but poor impact resistance and relatively poor room-temperature properties. They are often divided into the following two groups:

* **Non-oxide fibers** can be such as Siliconcarbide (SiC), boron nitride (BN), silicon nitride (SiN), aluminium nitride (AlN) and multiphase fibers consisting of silicon, carbon, boron, nitride, titanium, (Si-C-B-N-Ti).

* **Oxide fibers** can be such as aluminium oxide (Al2O3), alumina zirconiumixtures (Al2O3+Zr2O2), yttria-alumina-garnet (YAG), and mullite (3Al2O3-2SiO2). Ceramic fibers of pure Al2O3 in a single crystalline microstructure are called sapphire fibers.

2.6. **Polymer Fibers**

**Aramid fiber (Kevlar)**

Aramids are a family of nylons, including Nomex R° and Kevlar R° (Polyamide -PA). Aramid fibers, see Figure 4.11 are known for their large hardness and resistance to penetration. Thanks to their toughness aramid fibres are used where high impenetrability is required, e.g. bulletproof vests,
bike tires, airplanes wings, and sport equipment. These fibres are not as spread as glass or carbon fibres, mostly because of their cost, high water absorption, and their difficult post-processing.

(References: DuPont (Kevlar R°) Fibers of KEVLARR° consist of long molecular chains produced from poly-paraphenylene terephthalamide). PPTA is the acronym for para-phenylen-terephthalamid.

Polymers are not only used for the matrix, they also make a good reinforcement material in composites. For example, Kevlar is a polymer fibre that is immensely strong and adds toughness to a composite. It is used as the reinforcement in composite products that require lightweight and reliable construction (e.g., structural body parts of an aircraft). Composite materials were not the original use for Kevlar; it was developed to replace steel in radial tires and is now used in bulletproof vests and helmets. Kevlar, and aramid-fiber composite can be used as textile fibers. Applications include bullet-proof vests, tires, brake and clutch linings. Service temperature of Aramid fibre is up to 250°C, and its melting temperature is 426.7°C.

UHMW-PE - Ultra-high molecular weight polyethylene

UHMW, see Figure 4.12, is a polymer material composed of long chains with a very high molecular weight. It even replaced Kevlar R° for making bullet-proof vests! UHMW-PE combines the traditional abrasion and cut resistance of metal alloys with the impact and corrosion resistance of synthetic materials. Tough as a metal, self-lubricating and slippery. UHMW-PE fibres have the tendency to elongate under load (creep). They are extremely low density, and they can float.

Melting-point between 120°C and 150°C. Applications are being developed particularly in the areas of ballistic protection and ropes. The material is inflammable. These fibres have a tensile strength 20 times greater than that of steel, and 40% stronger than aramid. Their free breaking length is around 330 km (steel breaks at 25, glass at 135, carbon at 195 and aramid at 235).
Products: Bullet-proof vest, Cut-resistant gloves, Psychiatric clothing. LCP - Liquid crystal polymer LCP, see Figure 4.13 is a thermoplastic fibre with exceptional strength and rigidity (five times that of steel), and about 15 times the fatigue resistance of aramid. Very good impact resistance. It doesn’t absorb moisture, has very low stretch, it doesn’t creep like UHMW-PE fibre, and has excellent abrasion, wear, and chemical resistance. Its high melting-point (320°C) allows the retention of these properties over broad ranges of temperatures. It is suitable for industrial, electronic, and aerospace applications, as well as for ropes, and sport equipment. Products: Fishing line, High performance rope, Tennis racket.

2.7. Carbon nanotube (CNT) fibers
Strong and versatile carbon nanotubes are finding new applications in improving conventional polymer-based fibers and films. For example, composite fibers made from single-walled carbon nanotubes (SWNTs) and polyacrylonitrile, a carbon fiber precursor, are stronger, stiffer and shrink less than standard fibers. Nanotube-reinforced composites could ultimately provide the foundation for a new class of strong and lightweight fibers with properties such as electrical and thermal conductivity unavailable in current textile fibers.
2.8. **Fiber hybrids**

Fiber hybrids capitalize on the best properties of various fiber types, while reducing raw material costs. Hybrid composites combining carbon/aramid and carbon/glass fibers have been used successfully in ribbed aircraft engine thrust reversers, telescope mirrors, drive shafts for ground transportation and infrastructure column-wrapping systems. For example, in hybrid-fiber flywheels for electric vehicles, the composite components withstand energy forces as high as 2.5 million ft-lb.

2.9. **Spider silk**

Spider silk is a biopolymer fiber and a natural composite, see Figure 4.14 and chapter 4.2. It is 5 times as strong as steel and 2 times as strong as Kevlar. Man-made spider silk has now become a reality. "Spider-goats," (goats that are created having one spider gene added to the 70,000 genes that make a goat a goat) for example, produce an extra protein in their milk that can be spun into man-made spider silk. Spider silk is stronger, by weight, than anything else on earth. The hope was to spin silk from milk - and use the ultra-light material for things like bulletproof vests. It turns out that it takes a lot of goat milk to make just a small bit of silk, so for now the idea of making bulletproof vests out of spider silk has been put aside. Other uses of the material, medical sutures, for example are in progress instead.
3.1. **Aerogel composites**

Aerogel is 99.8% air, and provides 39 times more insulating than the best fiberglass insulation, and is 1,000 times less dense than glass, see Figure 4.15 [http://stardust.jpl.nasa.gov/tech/aerogel.html](http://stardust.jpl.nasa.gov/tech/aerogel.html) where the picture can be found. A cube of 1x1x1 meter of aerogel will only weight three kg. It can also be exposed to temperatures up to 1400°C before it will soften.

Aerogel is not like conventional foams, but is a special porous material with extreme microporosity on a micron scale. It is composed of individual features only a few nanometers in size. These are linked in a highly porous dendritic-like structure. This exotic substance has many unusual properties, such as low thermal conductivity, refractive index and sound speed - in addition to its exceptional ability to capture fast moving dust. Aerogel is made by high temperature and pressure critical-point drying of a gel composed of colloidal silica structural units filled with solvents.

Silica aerogel is just another form of glass. If aerogel is handled roughly, it will break just like glass. However, if care is taken, the material can be handled and shaped effectively. Silica aerogels are inorganic solids, very brittle and usually very low density materials. A collapse of the solid network in the material occurs gradually, spreading the force of impact out over a longer time, and is why they can be very useful as energy absorbing materials.

Aerogels can be added different materials/particles in order to obtain special effect of the materials. For instance can we add metal salts, or other compounds to a sol before gelation. Then we may obtain a deep blue aerogel by adding nickel; while a pale green color appears by adding copper; a black gel contains carbon and iron; and orange aerogel is added iron oxide. It is also possible to obtain a magnetic aerogel by using chemical vapor infiltration to get iron oxide introduced in the material. The aerogel can also be made photoluminescent, which means that it glows-in-the-dark by using a
pigment that absorbs light and emits that energy over a period of time - even after the light source has been removed. The pigment is rechargeable.

### 3.3 Flexible aerogels

In the mid to late 1990’s, Aspen Systems perfected proprietary changes in the formulation, processing and drying of aerogels, reducing drying time to a few hours. Besides a cost effective drying time, the aerogels were also isolated in the form of thin, flexible blankets. The blankets were much more robust than the monoliths and beads, and could also be easily installed like any other flexible batting. These breakthroughs led to the formation of Aspen Aerogels, Inc. in 2001, and the commercialization of aerogel technology for broad use, see for instance the Figure 4.16.

Aspen Aerogels has created a variety of organic and inorganic/organic hybrid aerogel formulations including those made from polydimethylsiloxane/silica, cellulose polyurethane, polyimide, polymethylmethacrylate/silica, and polybutadiene rubber. These materials show enhanced physical and mechanical properties relative to pure silica aerogel.

As shown in the table below, aerogels offer significantly more insulating value per unit of material than other insulations:

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (k) [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerogel</td>
<td>0.012</td>
</tr>
<tr>
<td>Polyurethane foam</td>
<td>0.021</td>
</tr>
<tr>
<td>Polystyrene foam</td>
<td>0.038</td>
</tr>
<tr>
<td>Microporous silica</td>
<td>0.019-0.038</td>
</tr>
<tr>
<td>fiberglass</td>
<td>0.040</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.038</td>
</tr>
<tr>
<td>Perlite</td>
<td>0.040-0.060</td>
</tr>
<tr>
<td>Calcium Silicate</td>
<td>0.047</td>
</tr>
</tbody>
</table>

Figure 4.16: Areas that Aspens flexible aerogels can be used in. The picture is from: [http://www.aerogel.com/markets.htm](http://www.aerogel.com/markets.htm)