Module 2

M2. Basic Constituent Materials in Composites
Learning Units of Module 2

**M2.1** Reinforcements and Matrices for Various types of Composites

**M2.2** Fibers/Reinforcement Matrices

**M2.3** Matrix Materials

**M2.4** Fibre Reinforced Polymer (FRP) Laminated Composites
Materials for Composites

- **Matrices:** – Metals (Cu, Al, Ti, Ni…); **Polymers** (Thermosets, thermoplastics, Elastomers); **Ceramics** (SiC…)
- **Reinforcements:** Fibers (B, C, Glass, Aramids, PE,…); Particles, flakes, ribbons…

**Definitions:**
- **(Macro) composites:** bundles of fibers (scale ~ mm)
- **Micro-composite:** single fiber (or model) composite (scale ~ mm)
- **Nano-composite:** scale of reinforcement is ~ nm
Phases of Composites

- **Matrix Phase:** Polymers, Metals, Ceramics
  Also, continuous phase, surrounds other phase (e.g.: metal, ceramic, or polymer)

- **Reinforcement Phase:** Fibers, Particles, or Flakes
  Also, dispersed phase, discontinuous phase (e.g.: metal, ceramic, or polymer)

  → Interface between matrix and reinforcement

- **Examples:**
  - Jello and cole slaw/mixed fruit
  - Peanut brittle
  - Straw in mud
  - Wood (cellulose fibers in hemicellulose and lignin)
  - Bones (soft protein collagen and hard apatite minerals)
  - Pearlite (ferrite and cementite)
Carbon Nanotubes

Young's modulus of up to several terapascals
Strengths are predicted to be at least 20 GPa

Section of single non-helical shell
Factors in Creating Composites

- Factors in creating composites:
  - Matrix material
  - Reinforcement material

→ control or design properties
Common FRP are composed of fibers and a matrix. Fibers are the reinforcement and the main source of strength while the matrix 'glues' all the fibers together in shape and transfers stresses between the reinforcing fibers. Sometimes, fillers or modifiers might be added to smooth manufacturing process, impart special properties, and/or reduce product cost.
Common fiber reinforcing agents include:

- Aluminum, Aluminum oxide, Aluminum silica
- Asbestos
- Beryllium, Beryllium carbide, Beryllium oxide
- Carbon (Graphite)
- Glass (E-glass, S-glass, D-glass)
- Molybdenum
- Polyamide (Aromatic polyamide, Aramid), e.g., Kevlar 29 and Kevlar 49
- Polyester
- Quartz (Fused silica)
- Steel
- Tantalum
- Titanium
- Tungsten, Tungsten monocarbide
M2.1.2 Matrix of Fiber Reinforced Composites:

Common fiber reinforcing agents include:
- Aluminum, Aluminum oxide, Aluminum silica
- Asbestos
- Beryllium, Beryllium carbide, Beryllium oxide
- Carbon (Graphite)
- Glass (E-glass, S-glass, D-glass)
- Molybdenum
Common Resin Matrix

Common resin materials include:

- Resin Matrix
  - Epoxy
  - Phenolic
  - Polyester
  - Polyurethane
  - Vinyl Ester
Common Metal And Non-Metal Matrix

- Metal Matrix
  - Aluminum
  - Copper
  - Lead
  - Magnesium
  - Nickel
  - Silver
  - Titanium

- Non-Metal Matrix
  - Ceramics
M2.1.3 FRP Composite Constituents

1. Resins (Polymers)
2. Fibers
3. Fiber Reinforcement
4. Fillers
5. Additives
6. Sandwich Panels
7. Adhesives
8. Composite Designs
Primary Function: “To transfer stress between reinforcing fibers and to protect them from mechanical and environmental damage”
Types of Resins

I. Thermoset Resin
   a. Polyester
   b. Vinyl Resin
   c. Epoxy
   d. Phenolic
   e. Polyurethane

II. Thermoplastic
   a. Acetal
   b. Acrylonitrile Butadiene Styrene (ABS)
   c. Nylon
   d. Polyethylene (PE)
   e. Polypropylene (PP)
   f. Polyethylene Terephthalate (PET)
Thermoset Resin: Polyester

Polyesters:
- Phthalic Anhydride (GP)
- Dicyclopentadiene (DCPD) Types
- Isophthalic Acid
- Terephthalic Acid
- Polyethylene Terephthalate (PET)
Primary Function:

- “Carry load along the length of the fiber, provides strength and or stiffness in one direction”.
- Can be oriented to provide properties in directions of primary loads.
Fiber Terminology

SINGLE FILAMENT

STRAND [glass]

TOW [other fibres]

YARN [twisted]

ROVING
A composite material consists of two phases:

- **Primary**
  - Forms the matrix within which the secondary phase is imbedded
  - Any of three basic material types: polymers, metals, or ceramics

- **Secondary**
  - Referred to as the imbedded phase or called the reinforcing agent
  - Serves to strengthen the composite. (fibers, particles, etc.)
  - Can be one of the three basic materials or an element such as carbon or boron
Classification of composite material

• **Metal Matrix Composites (MMCs)**
  – Include mixtures of ceramics and metals, such as cemented carbides and other cermets, as well as aluminum or magnesium reinforced by strong, high stiffness fibers

• **Ceramic Matrix Composites (CMCs)**
  – Least common composite matrix. Aluminum oxid and silicon carbide are materials that can be imbedded with fibers for improved properties, especially in high temperature applications

• **Polymer Matrix Composites (PMCs)**
  – Thermosetting resins are the most widely used polymers in PMCs. Epoxy and polyester are commonly mixed with fiber reinforcement
Continued…

- **Matrix material** serves several functions in the composite:
  - provides the bulk form of the part or product
  - holds the imbedded phase in place
  - shares the load with the secondary phase
The imbedded phase is most commonly one of the following shapes:

- Fibers
- Particles
- Flakes
Fibers

- Diameters range from .0001 in to about .005 in depending on the material.
- Generally circular in cross-section, but can also be in the form of tubular, rectangle, hexagonal.
- Fibers used can be either continuous or discontinuous
  - Continuous fibers – are very long; in theory, they offer a continuous path by which a load can be carried by the composite material
  - Discontinuous fibers – are short lengths
Orientation of fibers is an important consideration.

- **One-dimensional**
  - maximum strength and stiffness are obtained in the direction of the fiber
- **Planar**
  - in the form of two-dimensional woven fabric
- **Random or three-dimensional**
  - the composite material tends to possess isotropic properties
Types of fabrics

Currently, the most common fibers used in composites are glass, graphite (carbon), boron and Kevlar 49.

- Glass – most widely used fiber in polymer composites, the term fiberglass is applied to denote glass fiber-reinforced plastic (GFRP)
  - E-glass – strong and low cost, but modulus is less than other (500,000 psi)
  - S-glass – stiffer and its tensile strength in one of the highest of all fiber materials (650,000 psi). Has about five times the tensile strength of steel and has a density of about one third that of steel
• **Carbon** – are generally a combination of graphite. Graphite has a tensile strength three to five times stronger than steel and has a density that is one-fourth that of steel.

• **Boron** – very high elastic modulus, but its high cost limits its application to aerospace components

• **Ceramics** – Silicon carbide (SiC) and aluminum oxide (Al2O3) are the main fiber materials among ceramics. Both have high elastic moduli and can be used to strengthen low-density, low-modulus metals such as aluminum and magnesium

• **Metal** – Steel filaments, used as reinforcing fiber in plastics
Particles and Flakes

Particles:

• Is an important material form for metals and ceramics range in size from microscopic (less than 1 micron) to macroscopic (greater than 1 micron)
  – In the microscopic size range and proportion of imbedded material of 15% or less, the particles result in strengthening the matrix
  – In the macroscopic size range and proportion of imbedded material of 25% or more, the particles serve to share the load with the matrix material.
  – This form of composite strengthening occurs in cemented carbides, in which tungsten carbide (80%) is held in a cobalt binder.
Flakes

- Basically, two-dimensional particles ranging 0.01 to 1.0 mm in across the flake, with a thickness of 0.001 to 0.005 mm.
Metal Matrix Composites

Common reinforcing phase includes
- Particles of ceramic (commonly called cermets)
- Fibers of various materials, including other metals, ceramics, carbon, and boron

FRMMC – combine the high tensile strength and modulus of elasticity of a fiber with metals of low density, thus achieving good strength-to-weight and modulus-to-weight ratios in the resulting composite material.
Cemented carbides are composed of one or more Carbide compounds bonded in a metallic matrix

Common cemented carbides are based on:
- Tungsten carbide (WC)
- Titanium carbide (TiC)
- Chromium carbide (Cr3C2)
- Tantalum carbide (TaC)
Carbide ceramics constitute the principal ingredient in cemented carbides, typically ranging in content from 80% to 95% of total weight.

Principle metallic binders are:
- Cobalt – used for WC
- Nickel - used TiC and Cr₃C₂
• Cutting tools are the most common application of cemented carbides based on tungsten carbide

• Titanium carbide cermets are used principally for high temperature applications.
  – Nickel is the preferred binder; its oxidation resistance at high temperature is superior to that of cobalt.
  – Used as a cutting tool material for machining steels.
Ceramic Matrix Composites

**Advantage**
- High stiffness
- Hardness
- Hot hardness
- Compressive strength
- Relatively low density

**Disadvantage**
- Low toughness and bulk tensile strength
- Susceptibility to thermal cracking

Ceramic matrix composites represent an attempt to retain the desirable properties of ceramics while compensating for their weakness.
Ceramic materials used as matrices includes:

- Alumina
- Boron carbide
- Boron nitride
- Silicon carbide
- Silicon nitride
- Titanium carbide
Polymer Matrix Composites

The most important of the three classes of synthetic composites. FRP are most closely identified with the term composite.

**FRP**

- A composite material consisting of a polymer matrix imbedded with high-strength fibers.
- Widely used in rubber products such as tires and conveyor belts.
- Principle fiber materials are: glass, carbon, and Kevlar 49 with glass (E-glass) the most common fiber material
Continued…

• Advanced composites – use boron, carbon, Kevlar as the reinforcing fibers with epoxy as the common matrix polymer.
Hybrids:
When two or more fibers materials are combined in the composite.

- **Intraply hybrids** (within) - Alternate strands of different fibers in a single layer or ply.
- **Interply hybrid** (across) – Different plies of different fibers.

• The most widely used form if a laminar structure, made by stacking and bonding thin layers of fiber and polymer until the desired thickness is obtained.
Continued…

Attractive features of FRP:

– high strength-to-weight ratio
– high modulus-to-weight ratio
– low specific gravity
– good fatigue strength
– good corrosion resistance, although polymers are soluble in various chemicals
– low thermal expansion, leading to good dimensional stability
– significant anisotropy in properties
Types of Resins

I. Natural
II. Man-Made
III. Many Varieties Commercially Available
I. Natural Fibers:
   a. Cellulose
   b. Sisal

II. Man-Made Fibers:
   a. Aramid
   b. Boron
   c. Carbon/Graphite
   d. Glass
   e. Nylon
   f. Polyester
   g. Polyethylene
   h. Polypropylene
M2.1.3.3 Fiber Reinforcement

1. Glass
2. Aramid
3. Carbon
1. Glass Fiber Reinforcements
   - E-glass
   - S-glass
   - C-glass
   - ECR-glass
   - AR-glass
2. Aramid (Kevlar) Fiber Reinforcement:

- Superior resistance to damage (energy absorber)
- Good in tension applications (cables, tendons)
- Moderate stiffness
- More expensive than glass
3. Carbon Fiber Reinforcement:
- Good modulus at high temperatures
- Excellent stiffness
- More expensive than glass
- Brittle
- Low electric insulating properties
Carbon fibers are manufactured by treating organic fibers (precursors) with heat and tension, leading to a highly ordered carbon structure. The most commonly used precursors include rayon-base fibers, polyacrylonitrile (PAN), and pitch.

<table>
<thead>
<tr>
<th>Carbon Material</th>
<th>Fiber Diameter (µm)</th>
<th>Tensile modulus (GPa)</th>
<th>Tensile strength (GPa)</th>
<th>Density (g/cm³)</th>
<th>Thermal Expansion Coeff. (10⁻⁶ K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High modulus PAN-based</td>
<td>6 - 8</td>
<td>290 - 590</td>
<td>2.5 - 3.9</td>
<td>1.70 - 1.94</td>
<td>-1.0 to - 1.2</td>
</tr>
<tr>
<td>High strength PAN-based</td>
<td>5 - 8</td>
<td>230 - 295</td>
<td>3.5 - 7.1</td>
<td>1.76 - 1.82</td>
<td>-0.4 to - 1.0</td>
</tr>
<tr>
<td>High modulus Pitch-based</td>
<td>10</td>
<td>520 - 830</td>
<td>2.1 - 2.2</td>
<td>2.03 - 2.18</td>
<td>-1.4</td>
</tr>
</tbody>
</table>

Carbon fibers
Fibrillar model of carbon fibre according to Ruland

Lamellar model of carbon in cross-section

Model of skin-core organization in type I carbon fibres
PAN-based

Pitch-based
Fig. 2.4. Typical transverse microstructures of ex-pitch fibers showing radial, random, onion-skin and quasi-onion-skin structures [Hamada et al. 1987a, 1987b]
Fig. 3.27a-d. SEM photographs showing the morphology change on the surface and the cross section of benzene-derived filaments at different heat treatment temperatures: (a) as-deposited (1000°C); (b) 2200°C; (c) 3000°C; (d) 3500°C [Yoshida et al. 1985]
High-modulus high-strength organic fibers

• Theoretical estimates for covalently bonded organics show strength of 20-50 GPa (or more) and modulus of 200 - 300 GPa
• Serious processing problems
• New fibers developed since the early 1970s: high axial molecular orientation, highly planar, highly aromatic molecules
• Major fibers: Kevlar (polyaramid); Spectra (PE); polybenzoxazole (PBO) and polybenzothiazole (PBT).
Aramid (aromatic polyamide) fibers = poly(paraphenylene terephthalamide)

• Kevlar behaves as a nematic liquid crystal in the melt which can be spun

• Prepared by solution polycondensation of p-phenylene diamine and terephthaloyl chloride at low temperatures. The fiber is spun by extrusion of a solution of the polymer in a suitable solvent (for example, sulphuric acid) followed by stretching and thermal annealing treatment
### The Aramid fiber family

<table>
<thead>
<tr>
<th></th>
<th>Twaron (Akzo)</th>
<th>Twaron HM</th>
<th>Kevlar 29</th>
<th>Kevlar 49</th>
<th>Kevlar 149</th>
<th>HM-50 (Teijin)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density, g/cm³</strong></td>
<td>1.44</td>
<td>1.45</td>
<td>1.44</td>
<td>1.44</td>
<td>1.47</td>
<td>1.39</td>
</tr>
<tr>
<td><strong>Tensile strength, GPa</strong></td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Tensile modulus, GPa</strong></td>
<td>80</td>
<td>125</td>
<td>62</td>
<td>124</td>
<td>186</td>
<td>74</td>
</tr>
<tr>
<td><strong>Tensile strain, %</strong></td>
<td>3.3</td>
<td>2.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.9</td>
<td>4.2</td>
</tr>
<tr>
<td><strong>Coefficient of thermal expansion, 10⁻⁶oC</strong></td>
<td></td>
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<tr>
<td><strong>Longitudinal:</strong></td>
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<tr>
<td>0 to 100 °C</td>
<td>...</td>
<td>...</td>
<td>-2.0</td>
<td>...</td>
<td>--</td>
<td>...</td>
</tr>
<tr>
<td><strong>Radial:</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 100 °C</td>
<td>...</td>
<td>...</td>
<td>59</td>
<td>...</td>
<td>--</td>
<td>...</td>
</tr>
</tbody>
</table>
Schematic representation of structure formation during spinning, contrasting PPT and PET behavior

- Liquid crystal
  - Nematic structure
  - Low entropy
  - Solution
  - Extrusion
  - Solid state

- Conventional (PET)
  - Random coil
  - High entropy

- Extended chain structure
  - High chain continuity
  - High mechanical properties

- Folded chain structure
  - Low chain continuity
  - Low mechanical properties
Kevlar fibers

Schematic diagram of Kevlar® 49 fiber showing the radially arranged pleated sheets
Kevlar - High flexibility but poor compressive performance

Also low shear performance, moisture-sensitive, UV-sensitive
Kevlar/epoxy

Note the fibrillar structure of the fiber
Kevlar fiber

• Little creep only
• Excellent temperature resistance (does not melt, decomposes at ~500°C)
• Linear stress-strain curve until failure
• Low density : 1.44
• Negative CTE
• Fiber diameter = 11.9 micron
• Fiber strength variability
UHMWPE

• UHMWPE (Spectra or Dyneema) are highly anisotropic fibers

• Even higher specific properties than Kevlar because of lower density (0.98 g/cc)

• Limited to use below 120°C

• Creep problems; weak interfaces

• Applications - ballistic impact-resistant structures
UHMWPE (Spectra) - high flexibility and toughness, poor interfacial bonding
Flexibility, compressibility, and limit performance of fibers

Kevlar

Spectra
M2.1.3.3.1 Reinforcement Types

1. Rovings (Continuous)
2. Chopped strand
3. Mat:
   - Chopped strand
   - Continuous strand
4. Woven roving
5. Stitched
6. Braided
7. Unidirectional
8. Veil
M2.1.3.3.2 Reinforcement Forms:

- Woven Roving:
  - aka – Crimped
  - Plain
  - Satin
  - Twill
  - Basket
M2.1.3.3.2 Reinforcement Forms:

- **Woven Roving:**
  - aka – Crimped
  - Plain
  - Satin
  - Twill
  - Basket
M2.1.3.4 Fillers/Additives/Modifies

**Filler Types:**
1. Calcium Carbonate
2. Clay
3. Talc
4. Aluminum Trihydrate
5. Silica
6. Micro Spheres
7. Mica
M2.1.3.4.1 Types of Additives

- Catalysts & Promoter
- Inhibitors
- Release Agent
- Pigments
- UV Absorber
- Fire Retardancy
The primary functions of the additives (modifiers, fillers) are to reduce cost, improve workability, and/or impart desired properties.

- **Cost Reduction:**
  - Low cost to weight ratio, may fill up to 40% (65% in some cases) of the total weight

- **Workability Improvement:**
  - Reduce shrinkage
  - Help air release
  - Decrease viscosity
  - Control emission
  - Reduce coefficient of friction on surfaces
  - Seal molds and/or guide resin flows
  - Initiate and/or speed up or slow down curing process
Property Enhancement:

- Improve electric conductivity
- Improve fire resistance
- Improve corrosion resistance
- Improve ultraviolet resistance
- Improve surface toughness
- Stabilize heat transfer
- Reduce tendency of static electric charge
- Add desired colors
M2.1.3.4.3 Common materials used as additives include:

- **Filler Materials:**
  - Feldspar
  - Glass microspheres
  - Glass flakes
  - Glass fibers, milled
  - Mica
  - Silica
  - Talc
  - Wollastonite
  - Other microsphere products
Modifier Materials:

- Organic peroxide, e.g., methylethylketone peroxide (MEKP)
- Benzoyl peroxide
- Tertiary butyl catechol (TBC)
- Dimethylaniline (DMA)
- Zinc stearate, waxes, silicones
- Fumed silica, clays
M2.2.1 Introduction to Fibres
Mainly, the following different types of fibers namely,
- glass fibers,
- silicon carbide fibers,
- high silica and quartz fibers,
- alumina fibers,
- metal fibers and wires,
- graphite fibers,
- boron fibers, aramid fibers and multi phase fibers are used.

Among the glass fibers, it is again classified into E-glass, S-glass, A-glass, R-glass etc.
Fibres have better stiffness and strength compared to *bulk* materials

- Atomic or molecular alignment (Carbon, Aramid)
- Removal of flaws and cracks (Glass)
- Strain hardening (Metals)
Fig. 2.3: Electron microscope lattice fringe image of a thin fragment of a Type I carbon fibre illustrating layer plane disorder. (From D. J. Johnson.)
<table>
<thead>
<tr>
<th>Fibre</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>High strength, low cost</td>
<td>Low stiffness</td>
</tr>
<tr>
<td>Aramid</td>
<td>High tensile strength, low</td>
<td>Low compressive strength, moisture absorption</td>
</tr>
<tr>
<td></td>
<td>density</td>
<td></td>
</tr>
<tr>
<td>Boron</td>
<td>High stiffness, high</td>
<td>High cost</td>
</tr>
<tr>
<td></td>
<td>compressive strength</td>
<td></td>
</tr>
<tr>
<td>‘HS’ carbon</td>
<td>High strength, high</td>
<td>Moderately high cost</td>
</tr>
<tr>
<td></td>
<td>stiffness</td>
<td></td>
</tr>
<tr>
<td>‘HM’ carbon</td>
<td>Very high stiffness</td>
<td>Low strength, high cost</td>
</tr>
<tr>
<td>Ceramic</td>
<td>High stiffness, high usage</td>
<td>Low strength, high cost</td>
</tr>
<tr>
<td></td>
<td>nature</td>
<td></td>
</tr>
</tbody>
</table>
Types of Natural Fibre

- Bast fibres (flax, hemp, jute, kenaf…)
  - wood core surrounded by stem containing cellulose filaments

- Leaf fibres (sisal, banana, palm)

- Seed fibres (cotton, coconut (coir), kapok)
Examples of Natural Composites
### Polymer Matrix Composite combinations

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass</td>
<td>Epoxy</td>
</tr>
<tr>
<td>S-glass</td>
<td>Polyimide</td>
</tr>
<tr>
<td>Carbon (graphite)</td>
<td>Polyester</td>
</tr>
<tr>
<td>Aramid (e.g., Kevlar)</td>
<td>Thermoplastics (PA, PS, PEEK…)</td>
</tr>
<tr>
<td>Boron</td>
<td></td>
</tr>
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</table>
# Ceramic Matrix Composite combinations

<table>
<thead>
<tr>
<th><strong>Fibre</strong></th>
<th><strong>Matrix</strong></th>
</tr>
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<tbody>
<tr>
<td>SiC</td>
<td>SiC</td>
</tr>
<tr>
<td>Alumina</td>
<td>Alumina</td>
</tr>
<tr>
<td>SiN</td>
<td>Glass-ceramic</td>
</tr>
<tr>
<td></td>
<td>SiN</td>
</tr>
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</table>
## Metal Matrix Composite combinations

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boron</td>
<td>Aluminium</td>
</tr>
<tr>
<td>Borsic</td>
<td>Magnesium</td>
</tr>
<tr>
<td>Carbon (graphite)</td>
<td>Titanium</td>
</tr>
<tr>
<td>SiC</td>
<td>Copper</td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td></td>
</tr>
</tbody>
</table>
## Some Typical Polymer Composite properties

<table>
<thead>
<tr>
<th>Fibre</th>
<th>CSM glass</th>
<th>Woven glass</th>
<th>Filament-wound UD glass</th>
<th>Woven aramid</th>
<th>UD aramid</th>
<th>UD HS carbon</th>
<th>UD HM carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin</td>
<td>Polyester</td>
<td>Polyester</td>
<td>Polyester</td>
<td>Polyester</td>
<td>Epoxy</td>
<td>Epoxy</td>
<td>Epoxy</td>
</tr>
<tr>
<td>$V_f$</td>
<td>17%</td>
<td>32%</td>
<td>44%</td>
<td>48%</td>
<td>60%</td>
<td>63%</td>
<td>60%</td>
</tr>
<tr>
<td>SG</td>
<td>1.46</td>
<td>1.7</td>
<td>1.83</td>
<td>1.3</td>
<td>1.35</td>
<td>1.6</td>
<td>1.6</td>
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<tr>
<td>Tensile strength (MPa)</td>
<td>110</td>
<td>220</td>
<td>650</td>
<td>390</td>
<td>1380</td>
<td>2280</td>
<td>1260</td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>8</td>
<td>14</td>
<td>30</td>
<td>24</td>
<td>76</td>
<td>142</td>
<td>200</td>
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<tr>
<td>Tensile elongation (%)</td>
<td>1.6</td>
<td>1.7</td>
<td>1.9</td>
<td>1.8</td>
<td>1.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Compress</td>
<td>150</td>
<td>230</td>
<td>800</td>
<td>86</td>
<td>276</td>
<td>1440</td>
<td>840</td>
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</table>
Addition of properties:

GLASS + POLYESTER = GRP
(Strength) (Chemical resistance) (Strength and chemical resistance)

Unique properties:

GLASS + POLYESTER = GRP
(Brittle) (Brittle) (Tough!)
<table>
<thead>
<tr>
<th>Advanced Composites</th>
<th>Vs</th>
<th>Reinforced Plastics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace, defence, F1…</td>
<td></td>
<td>Marine, building…</td>
</tr>
<tr>
<td>Highly stressed</td>
<td></td>
<td>Lightly stressed</td>
</tr>
<tr>
<td>Glass, carbon, aramid fibres</td>
<td></td>
<td>Glass (random and woven)</td>
</tr>
<tr>
<td>Honeycomb cores</td>
<td></td>
<td>Foam cores</td>
</tr>
<tr>
<td>Epoxy, bismaleimide…</td>
<td></td>
<td>Polyester, vinyl-ester…</td>
</tr>
<tr>
<td>Prepregs</td>
<td></td>
<td>Wet resins</td>
</tr>
<tr>
<td>Vacuum bag/oven/autoclave</td>
<td></td>
<td>Hand lay up, room temperature cure</td>
</tr>
<tr>
<td>Highly tested and qualified materials</td>
<td></td>
<td>Limited range of lower performance materials</td>
</tr>
</tbody>
</table>
### Approximate comparative materials data

from J Quinn, *Composites Design Manual*

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative cost</th>
<th>Density</th>
<th>Tensile strength</th>
<th>Tensile modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSM E-glass/UP</td>
<td>1.6</td>
<td>1.61</td>
<td>100</td>
<td>7</td>
</tr>
<tr>
<td>woven E-glass/UP</td>
<td>2.1</td>
<td>1.85</td>
<td>250</td>
<td>15</td>
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<tr>
<td>CSM E-glass/VE</td>
<td>3</td>
<td>1.5</td>
<td>120</td>
<td>8</td>
</tr>
<tr>
<td>E-glass pultrusion/VE</td>
<td>2.6</td>
<td>1.8</td>
<td>330</td>
<td>17</td>
</tr>
<tr>
<td>E-glass pultrusion/UP</td>
<td>1.6</td>
<td>1.8</td>
<td>300</td>
<td>17</td>
</tr>
<tr>
<td>UD carbon/epoxy</td>
<td>23</td>
<td>1.56</td>
<td>1200</td>
<td>140</td>
</tr>
<tr>
<td>UD carbon/VE</td>
<td>20</td>
<td>1.53</td>
<td>1100</td>
<td>140</td>
</tr>
<tr>
<td>QI carbon/VE</td>
<td>20</td>
<td>1.55</td>
<td>450</td>
<td>55</td>
</tr>
<tr>
<td>DMC</td>
<td>1.7</td>
<td>1.9</td>
<td>52</td>
<td>8</td>
</tr>
<tr>
<td>SMC</td>
<td>2</td>
<td>1.84</td>
<td>70</td>
<td>12</td>
</tr>
<tr>
<td>mild steel</td>
<td>0.45</td>
<td>7.8</td>
<td>275</td>
<td>205</td>
</tr>
<tr>
<td>6063 aluminium alloy</td>
<td>1.1</td>
<td>2.8</td>
<td>240</td>
<td>69</td>
</tr>
<tr>
<td>softwood</td>
<td>0.29</td>
<td>0.48</td>
<td>80</td>
<td>12</td>
</tr>
<tr>
<td>plywood</td>
<td>0.32</td>
<td>0.54</td>
<td>90</td>
<td>14</td>
</tr>
</tbody>
</table>
M2.3.2 General types of Matrix Materials

• In general, following types of matrix materials are available:
  – Thermosetting material;
  – Thermoplastic material;
  – Carbon;
  – Metals;
  – Ceramics;
  – Glass Matrix.
## Differences between Thermosets & thermoplastics

<table>
<thead>
<tr>
<th>Thermosets</th>
<th>Thermoplastics</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Resin cost is low.</td>
<td>• Resin cost is slightly higher.</td>
</tr>
<tr>
<td>• Thermosets exhibit moderate shrinkage.</td>
<td>• Shrinkage of thermoplastics is low</td>
</tr>
<tr>
<td>• Interlaminar fracture toughness</td>
<td>• Interlaminar fracture toughness is high.</td>
</tr>
<tr>
<td>is low.</td>
<td></td>
</tr>
<tr>
<td>• Thermosets exhibit good resistance</td>
<td>• Thermoplastics exhibit poor resistance to fluids</td>
</tr>
<tr>
<td>to fluids and solvents.</td>
<td>and solvents.</td>
</tr>
<tr>
<td>• Composite mechanical properties</td>
<td>• Composite mechanical properties are good.</td>
</tr>
<tr>
<td>are good.</td>
<td></td>
</tr>
<tr>
<td>• Prepregability characteristics</td>
<td>• Prepregability characteristics are poor.</td>
</tr>
<tr>
<td>are excellent.</td>
<td></td>
</tr>
<tr>
<td>• Prepreg shelf life and out time</td>
<td>• Prepreg shelf life and out time are excellent.</td>
</tr>
<tr>
<td>are poor.</td>
<td></td>
</tr>
<tr>
<td>Thermosets</td>
<td>Thermoplastics</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>• Phenolics &amp; Cyanate ester</td>
<td>• Polypropylene</td>
</tr>
<tr>
<td>• Polyesters &amp; Vinyl esters</td>
<td>• Nylon (Polyamide)</td>
</tr>
<tr>
<td>• Polyimides</td>
<td>• Poly-ether-imide (PEI)</td>
</tr>
<tr>
<td>• Epoxies</td>
<td>• Poly-ether-sulphone (PES)</td>
</tr>
<tr>
<td>• Bismaleimide (BMI)</td>
<td>• Poly-ether-ether-ketone (PEEK)</td>
</tr>
</tbody>
</table>
Advantages of Thermoset Resin

- Adhesion to fibres and to resin;
- No by-products formed during cure;
- Low shrinkage during cure;
- High or low strength and flexibility;
- Resistance to solvents and chemicals;
- Resistance to creep and fatigue;
- Wide range of curative options;
- Adjustable curing rate;
- Good electrical properties.
Disadvantages of Thermoset Resin

- Resins and curatives are somewhat toxic in uncured form;
- Moisture absorption resulting into change in dimensions and physical properties;
- Limited to about 200°C (392°F) upper temperature use;
- Difficult to combine toughness and high temperature resistance;
- High thermal coefficient of expansion;
- High degree of smoke liberation in a fire;
- May be sensitive to ultraviolet light degradation;
- Slow curing.
Additives and Modifiers

Additive used in thermoset and thermoplastic composites exhibits the following properties:

- **Low shrink/low profile:** When parts with smooth surfaces are required, a special thermoplastic resin, which moderates resin shrinkage, can be added to thermoset resins.

- **Fire resistance:** Combustion resistance is improved by proper choice of resin, use of fillers or flame retardant additives. Included in this category are materials containing antimony trioxide, bromine, chlorine, borate and phosphorus.

- **Air release:** Most laminating resins, gel coats and other polyester resins might entrap air during processing and application. This can cause air voids and improper fibre wet-out. Air release additives are used to reduce such air entrapment and to enhance fibre wet-out.
• **Emission control:** In open mold applications, styrene emission suppressants are used to lower emissions for air quality compliance.

• **Viscosity control:** In many composite types, it is critical to have a low, workable viscosity during production. Lower viscosity in such filled systems is usually achieved by use of wetting and dispersing additives. These additives facilitate the wet-out and dispersion of fillers resulting in lower viscosity.

• **Electrical conductivity:** Most composites do not conduct electricity. It is possible to obtain a degree of electrical conductivity by the addition of metal, carbon particles or conductive fibres. Electromagnetic interference shielding can be achieved by incorporating conductive materials.

• **Toughness:** Toughness can be enhanced by the addition of reinforcements. It can also be improved by special additives such as certain rubber or other elastomeric materials.
• **Antioxidants:** Plastics are sometimes modified with antioxidants, which retard or inhibit polymer oxidation and the resulting degradation of the polymer.

• **Antistatic agents:** Antistatic agents are added to polymers to reduce their tendency to attract electrical charge. Control of static electricity is essential in processing and handling operation of certain plastics, as well as in finished products. Static charges on plastics can produce shocks, present fire hazard and attract dust. The effect of static charge in computer/data processing applications, for example, is particularly detrimental.

• **Foaming agents:** Foaming agents are added to polymers during processing to form minute cells throughout the resin. Foamed plastics exhibit lower density, decrease material costs, improves electrical and thermal insulation, increase strength to weight ratio and reduce shrinkage and part warping.
Continued….

• **Plasticizers:** Plasticizers are added to compounds to improve processing characteristics and offer a wide range of physical and mechanical properties. Slip and blocking agents - They provide surface lubrication. This results in reduced coefficient of friction on part surfaces and enhances release of parts from the mold.

• **Heat stabilizers:** They are used in thermoplastic resins to inhibit polymer degradation that results from exposure to heat.

• **Ultraviolet Stabilizers:** Both thermoset and thermoplastic composites use special materials which are added to prevent loss of gloss, crazing, chalking, discoloration, changes in electrical characteristics, embitterment and disintegration due to ultraviolet (UV) radiation. Additives, which protect composites by absorbing the UV, are called ultraviolet absorbers. Materials, which protect the polymer in some other manner, are known as ultraviolet stabilizers.
M2.4 Fibre Reinforced Polymer (FRP) Laminated Composites

- **Ply Orientation definition:** The ply orientation symbol is shown in Figure below. It designates the tape fibre direction or the warp direction, as applicable.
M2.4.2.1 Criteria used during Ply Orientation

Following criteria should be used during ply orientation:

• Attention to ply orientation on strength controlled laminates can prevent matrix and stiffness degradation. The 0° ply orientation is used to carry the longitudinal loading, the 90° ply orientation is suited to the transverse loading and the ±45° ply orientation is for shear loading.

• In order to minimize the in-plane shear, place the ±45° and -45° plies together; the in-plane shear is carried as tension and compression in the 45° plies.

• To minimize warpage and interlaminar shear within a laminate, maintain the symmetry about the centre line of the laminate.
• Stress orientation can be minimized by proper designing or by stepped laminate thickness changes.

• The placement of specific ply orientations can influence the buckling strength and damage tolerance. The outer ply orientations influence the laminate bending characteristics more than plies placed at or near the laminate bending characteristics more than the plies placed at or near the neutral axis.
Laminate lay-up code must be able to specify the following:

- The orientation of each ply relative to the reference axis;
- Number of plies, with orientation;
- Exact geometric sequence of plies;
- Adjacent plies oriented at angles equal in magnitude but opposite in sign, appropriate positive or negative signs should be assigned.
M2.4.4.1 Total Lay-up code

<table>
<thead>
<tr>
<th>Laminate Lay-up</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 45°</td>
<td>[45/0/-60_2/30]_T</td>
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<tr>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>-60°</td>
<td></td>
</tr>
<tr>
<td>-60°</td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td></td>
</tr>
<tr>
<td>• 45°</td>
<td>[±45/-30/+30/0]_T</td>
</tr>
<tr>
<td>-45°</td>
<td></td>
</tr>
<tr>
<td>-30°</td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td></td>
</tr>
</tbody>
</table>
M2.4.4.1 Symmetric Lay-up code

<table>
<thead>
<tr>
<th>Laminate Lay-up</th>
<th>Code</th>
</tr>
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<tbody>
<tr>
<td>90°</td>
<td>[90/0]_S</td>
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<td>0°</td>
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<td>90°</td>
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<tr>
<td>45°</td>
<td>[0/45/90/90]_S</td>
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<td></td>
</tr>
<tr>
<td>45°</td>
<td></td>
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## M2.4.4.3 Hybrid Laminate Code

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<th>Laminate Lay-up</th>
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<tbody>
<tr>
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<td>$[0_B/\pm45_{GR}/90_{GR}]_S$</td>
</tr>
<tr>
<td>$45^\circ_{GR}$</td>
<td></td>
</tr>
<tr>
<td>$-45^\circ_{GR}$</td>
<td></td>
</tr>
<tr>
<td>$90^\circ_{GR}$</td>
<td></td>
</tr>
<tr>
<td>$90^\circ_{GR}$</td>
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<tr>
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<tr>
<td>$-45^\circ_{GR}$</td>
<td></td>
</tr>
<tr>
<td>$0^\circ_B$</td>
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M2.4.4.4 Quasi Symmetric Lay-up Code

<table>
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<td>45°</td>
<td>[45/0/90]$_{2S}$</td>
</tr>
<tr>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>-45°</td>
<td></td>
</tr>
<tr>
<td>Laminate Lay-up</td>
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</tr>
<tr>
<td>----------------</td>
<td>--------------</td>
</tr>
<tr>
<td>45°</td>
<td>[45/0/90]_{2S}</td>
</tr>
<tr>
<td>0°</td>
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</tr>
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