3. Composite materials

(1) introduction

composite material – a material system composed of a suitably arranged mixture or combination of two or more micro- or macro-constituents with an interface separating them that differ in form and chemical composition and are essentially insoluble in each other

• every material is composite at one or the other level
• properties of composite materials can be superior to its individual components
• examples: fiber-reinforced plastics, concrete, asphalt, wood, bone
(2) fibers for reinforced-plastic composite materials
three main types of synthetic fibers to reinforce plastic materials: glass, carbon, aramid fibers
(a) glass fibers for reinforcing plastic resins
  • favorable properties: high strength-weight ratio, good dimensional stability, good temperature, moisture and corrosion resistance and low cost
  • E glass – a lime-aluminum-borosilicate glass with zero or low Na and K levels
    composition: 52~56% SiO$_2$, 12~16% Al$_2$O$_3$, 16~25% CaO and 8~13% B$_2$O$_3$
    tensile strength: 3.44 GPa
    tensile modulus: 72.3 GPa
  • S glass – has high strength-to-weight ratio, primarily used for military and aerospace application
    composition: 65% SiO$_2$, 25% Al$_2$O$_3$ and 10% MgO
    tensile strength: 4.48 GPa
    tensile modulus: 85.4 GPa
• production of glass fibers – produced by drawing monofilaments from a furnace and gathering them to form a strand, strands are held together with resinous binder

properties: tensile strength and modulus are lower than carbon and aramid fibers, higher elongation and density
• low cost and hence commonly used

<table>
<thead>
<tr>
<th>Property</th>
<th>Glass (E)</th>
<th>Carbon (HT)</th>
<th>Aramid (Kevlar 49)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, ksi (MPa)</td>
<td>450 (3100)</td>
<td>500 (3450)</td>
<td>525 (3600)</td>
</tr>
<tr>
<td>Tensile modulus, Msi (GPa)</td>
<td>11.0 (76)</td>
<td>33 (228)</td>
<td>19 (131)</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td>4.5</td>
<td>1.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Density (g/cm²)</td>
<td>2.54</td>
<td>1.8</td>
<td>1.44</td>
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</tbody>
</table>
(b) carbon fibers for reinforced plastics

- light weight, very high strength and high stiffness
- produced from polyacrylonitrile (PAN) and pitch

![Diagram](image)

**stabilization**: PAN fibers are stretched and oxidized in air at about 200°C

**carbonization**: stabilized carbon fibers are heated in inert atmosphere at 1000-1500°C which results in elimination of O, H and N resulting in increase of strength

**graphitization**: carried out at 1800°C and increases modulus of elasticity at the expense of strength

- tensile strength: 3.1~4.45 GPa
- tensile modulus: 193-241 GPa
- density: 1~7.2 g/cm³
- 7-10 micrometer in diameter
(c) aramid fibers for reinforcing plastic resins
  • aramid – aromatic polyamide fibers
    trade name is Kevlar

- Kevlar 29: low density, high strength, and used for ropes and cables
- Kevlar 49: low density, high strength and modulus and used for aerospace and auto applications
- hydrogen bonds bond fiber together
- aromatic ring gives high rigidity and causes polymers to have rodlike structure
- used where resistance to fatigue, high strength and light weight is important
(d) comparison of mechanical properties

- carbon fibers provide best combination of high strength, high stiffness, low density
- comparison shows outstanding strength-to-weight and stiffness-to-weight of carbon and aramid (Kevlar 49) fiber

- due to favorable properties, carbon and aramid fiber reinforced composites have replaced steel and aluminum in aerospace applications
(3) fiber-reinforced-plastic composite materials
(a) matrix materials
• polyester and epoxy resins are the two important matrix materials
• polyester resins is cheaper than epoxy resins
  applications: boat hulls, auto and aircraft applications
• epoxy resins have good strength, low shrinkage
  commonly used matrix materials for carbon and aramid-fiber composite

(b) fiber-reinforced-plastic composite materials
(i) fiberglass-reinforced polyester resins
• higher the wt% of glass, stronger the reinforced plastic is
• nonparallel alignment of glass fibers reduces strength

<table>
<thead>
<tr>
<th>Table 12.2</th>
<th>Some properties of unfilled cast polyester and epoxy resins</th>
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<tbody>
<tr>
<td></td>
<td>Polyester</td>
</tr>
<tr>
<td>Tensile strength, ksi (MPa)</td>
<td>6–13 (40–90)</td>
</tr>
<tr>
<td>Tensile modulus of elasticity, Msi (GPa)</td>
<td>0.30–0.64 (2.0–4.4)</td>
</tr>
<tr>
<td>Flexural yield strength, ksi (MPa)</td>
<td>8.5–23 (60–160)</td>
</tr>
<tr>
<td>Impact strength (notched-bar Izod test) ft · lb/in. (J/m) of notch</td>
<td>0.2–0.4 (10.6–21.2)</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.10–1.46</td>
</tr>
</tbody>
</table>
(ii) carbon fiber reinforced epoxy resins
- carbon fiber contributes to rigidity and strength while epoxy matrix contributes to impact strength
- polyimides, polyphenylene sulfides are also used
- exceptional fatigue properties

<table>
<thead>
<tr>
<th>Table 12.3 Some mechanical properties of fiberglass-polyester composites</th>
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<tbody>
<tr>
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<tr>
<td><strong>Woven cloth</strong></td>
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<tr>
<td><strong>Chopped roving</strong></td>
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<tr>
<td><strong>Sheet-molding compound</strong></td>
</tr>
<tr>
<td>Tensile strength, ksi (MPa)</td>
</tr>
<tr>
<td>30–50</td>
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<tr>
<td>(206–344)</td>
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<tr>
<td>15–30</td>
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<tr>
<td>(103–206)</td>
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<tr>
<td>8–20</td>
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<tr>
<td>(55–138)</td>
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<tr>
<td>Tensile modulus of elasticity, Msi (GPa)</td>
</tr>
<tr>
<td>1.5–4.5</td>
</tr>
<tr>
<td>(103–310)</td>
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<tr>
<td>0.80–2.0</td>
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<tr>
<td>(55–138)</td>
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<tr>
<td>Impact strength</td>
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<tr>
<td>5.0–30</td>
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<tr>
<td>(267–1600)</td>
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<tr>
<td>2.0–20.0</td>
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<tr>
<td>(107–1070)</td>
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<tr>
<td>7.0–22.0</td>
</tr>
<tr>
<td>(374–1175)</td>
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<tr>
<td>notched bar, Izod ft¹·lb/in. (J/m) of notch</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
</tr>
<tr>
<td>1.5–2.1</td>
</tr>
<tr>
<td>1.35–2.30</td>
</tr>
<tr>
<td>1.65–2.0</td>
</tr>
</tbody>
</table>
• carbon fiber epoxy material is laminated to meet strength requirements

![Carbon Fiber Composite](image)

five-layer, bidirectional composite

![Composite Diagram](image)

**Table 12.4** Some typical mechanical properties of a commercial unidirectional composite laminate of carbon fibers (62% by volume) and epoxy resin

<table>
<thead>
<tr>
<th>Properties</th>
<th>Longitudinal (0°)</th>
<th>Transverse (90°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, ksi (MPa)</td>
<td>270 (1860)</td>
<td>9.4 (65)</td>
</tr>
<tr>
<td>Tensile modulus of</td>
<td>21 (145)</td>
<td>1.36 (9.4)</td>
</tr>
<tr>
<td>elasticity, Msi (GPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate tensile strain (%)</td>
<td>1.2</td>
<td>0.70</td>
</tr>
</tbody>
</table>

ex. a unidirectional Kevlar 49 fiber-epoxy composite contains 60 vol% of Kevlar 49 and 40 vol% of epoxy resin, what is the density of the composite? (density: Kevlar 49, 1.48 Mg/m³; epoxy, 1.20 Mg/m³)

1 m³ composite material

mass of Kevlar 49 = (0.6 m³)(1.48 Mg/m³) = 0.888 Mg

mass of epoxy = (0.4 m³)(1.20 Mg/m³) = 0.48 Mg

density = (0.888 + 0.48) Mg/ 1 m³ = 1.37 Mg/m³
engineering stress

\[ \sigma = \frac{F}{A_0} \]  
(average uniaxial tensile force)

(Original cross-sectional area)

Units of stress are psi or N/m² (Pascals)

engineering strain

\[ \varepsilon = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0} \]  
(change in length)

(Original length)

Units of strain are in/in or m/m

Modulus of elasticity (E): stress and strain are linearly related in the elastic region. (Hooke's law)

\[ E = \frac{\sigma}{\varepsilon} \]
(c) equation for elastic modulus of lamellar composite

**Isostrain condition** – stress on composite causes uniform strain on all composite layers

\[ P_c = P_f + P_m \]

- \( P_c \): load on composite
- \( P_f \): load on fibers
- \( P_m \): load on matrix

\[ \sigma = \frac{P}{A} \]
\[ \sigma_c A_c = \sigma_f A_f + \sigma_m A_m \]

since length of layers are equal

\[ \sigma_c V_c = \sigma_f V_f + \sigma_m V_m \]

where \( V_c, V_f \) and \( V_m \) are volume fractions

\( (V_c = 1) \)

since strains \( \varepsilon_c = \varepsilon_f = \varepsilon_m \)

\[ \frac{\sigma_c}{\varepsilon_c} = \frac{\sigma_f V_f}{\varepsilon_f} + \frac{\sigma_m V_m}{\varepsilon_m} \]

\[ E_c = E_f V_f + E_m V_m \]

rule of mixture of binary composites
loads on fiber and matrix regions of a lamellar composite structure loaded under isostrain condition
since $\sigma = E\varepsilon$ and $\varepsilon_f = \varepsilon_m$

\[
\frac{P_f}{P_m} = \frac{\sigma_f A_f}{\sigma_m A_m} = \frac{E_f}{E_m} \frac{\varepsilon_f A_f}{\varepsilon_m A_m} = \frac{E_f A_f}{E_m A_m} = \frac{E_f V_f}{E_m V_m}
\]

$P_c = P_f + P_m$

from above two equations, load on each of fiber and matrix regions can be determined if values of $E_f$, $E_m$, $V_f$, $V_m$ and $P_c$ are known

ex. calculate (a) the modulus of elasticity, (b) the tensile strength, and (c) the fraction of the load carried by the fiber for the following composite material stressed under isostrain conditions, the composite composed of 60 vol% E-glass fibers ($E_f = 10.5 \times 10^6$ psi, $\sigma_f = 350,000$ psi) and 40 vol% harden epoxy resin ($E_m = 0.45 \times 10^6$ psi, $\sigma_m = 9,000$ psi)

(a) $E_c = E_f V_f + E_m V_m$

$= (10.5 \times 10^6 \text{ psi})(0.60) + (0.45 \times 10^6 \text{ psi})(0.40)$

$= 6.48 \times 10^6$ psi
(b) \[ \sigma_c = \sigma_f V_f + \sigma_m V_m \]
\[ = (350000 \text{ psi})(0.6) + (9000 \text{ psi})(0.4) \]
\[ = 214,000 \text{ psi} \]

(c) \[ \frac{P_f}{P_c} = \frac{E_f V_f}{E_f V_f + E_m V_m} = \frac{6.30 \times 10^6 \text{ psi}}{6.48 \times 10^6 \text{ psi}} = 0.97 \]

**Isostress condition** – stress on the composite structure produces an equal stress condition on all the layers

\[ \sigma_c = \sigma_f = \sigma_m \]

Total strain \[ \varepsilon_c = \varepsilon_f + \varepsilon_m \]

Assuming no change in area

\[ \varepsilon_c = \varepsilon_f V_f + \varepsilon_m V_m \]

Assuming Hook’s law is valid under loading

\[ \varepsilon_c = \frac{\sigma}{E_c} \quad \varepsilon_f = \frac{\sigma}{E_f} \quad \varepsilon_m = \frac{\sigma}{E_m} \]

Therefore

\[ \frac{\sigma}{E_c} = \frac{\sigma V_f}{E_f} + \frac{\sigma V_m}{E_m} \]

Dividing by \( \sigma \)

\[ \frac{1}{E_c} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \]
rearranging

\[
\frac{1}{E_c} = \frac{V_f E_m}{E_f E_m} + \frac{V_m E_f}{E_m E_f}
\]

or

\[
E_c = \frac{E_f E_m}{V_f E_m + V_m E_f}
\]

- higher modulus values are obtained with isostrain loading for equal volume of fibers

**Example:** calculate the modulus of elasticity for a composite consisting of 60 vol% of E-glass fiber \((E_f = 10.5 \times 10^6 \text{ psi})\) and 40 vol% epoxy resin \((E_m = 0.45 \times 10^6 \text{ psi})\) when stressed under isostress condition

\[
E_c = \frac{E_f E_m}{V_f E_m + V_m E_f} = \frac{(10.5 \times 10^6 \text{ psi})(0.45 \times 10^6 \text{ psi})}{(0.6)(10.5 \times 10^6 \text{ psi})+(0.4)(0.45 \times 10^6 \text{ psi})}
\]

\[= 1.06 \times 10^6 \text{ psi}\]
(4) open-mold process for fiber-reinforced-plastic composite materials

(a) **hand lay-up process**
- gel coat is applied to open mold
- fiberglass reinforcement is placed in the mold
- base resin mixed with catalysts is applied by pouring brushing or spraying

(b) **spray-up process**
continuous strand roving is fed by chopper and spray gun and chopped roving and catalyst resin is deposited in the mold
(c) **vacuum bag-autoclave process**
used to produce high-performance laminates
usually of fiber-reinforced epoxy system
• long thin sheet or prepeg carbon-fiber epoxy material is laid on the table
• the sheet is cut and laminate is constructed
• laminate is put in vacuum bag to remove
entrapped air and cured in autoclave
carbon-fiber epoxy composite is usually
heated at 190°C at a pressure of 100 psi

(d) **filament winding process**
produces extremely high tensile strengths
• fiber reinforcement is fed through resin bath
and wound around suitable mandrel

• mandrel is cured and molded part is stripped
from mandrel
(5) closed-mold process for fiber-reinforced-plastic composite materials
(a) compression and injection molding
same as in polymers except that the fiber reinforcement is mixed with resin
(b) sheet molding compound (SMC) process
highly automated continuous-molding process
• continuous strand fiberglass roving is chopped in about 2 in. and deposited on a layer of resin-filler paste
• another layer of paste is deposited on first layer to form a continuous sandwich
• sandwich is compacted and rolled into rolls

• the rolled up sheet is stored in a maturation room for 1~4 days
• the sheets are cut into proper size and pressed in hot mold (149°C) to form final product efficient, quick, good quality and uniformity

(c) continuous-pultrusion process
continuous strand fibers are impregnated in resin bath, fed into heated steel die and drawn used to produce beams, channels, and pipes
(6) concrete

- an engineering material used for structural construction
- advantage – can be cast, economical, fire resistant, durable, able to be fabricated on site, aesthetic appearance
- disadvantage – low tensile strength, low ductility and shrinkable.
- concrete is a ceramic composite composed of coarse granular material (aggregate) embedded in a hard matrix of cement paste (binder)
- concrete : 7~15% Portland cement, 14~21% water, 0.5~ 8% air, 24~30% fine aggregate and 31~51% coarse aggregate

(a) Portland cement

- basic raw materials – lime CaO, silica SiO$_2$, alumina Al$_2$O$_3$ and iron oxide Fe$_2$O$_3$
- production – raw materials are crushed, ground and proportional for desired composition and blended mixture is fed into rotary kiln and heated to 1400~1650°C and then cooled and pulverized
chemical composition:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Chemical formula</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricalcium silicate</td>
<td>$3\text{CaO} \cdot \text{SiO}_2$</td>
<td>$C_3S$</td>
</tr>
<tr>
<td>Dicalcium silicate</td>
<td>$2\text{CaO} \cdot \text{SiO}_2$</td>
<td>$C_2S$</td>
</tr>
<tr>
<td>Tricalcium aluminate</td>
<td>$3\text{CaO} \cdot \text{Al}_2\text{O}_3$</td>
<td>$C_3A$</td>
</tr>
<tr>
<td>Tetracalcium aluminoferrite</td>
<td>$4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$</td>
<td>$C_4AF$</td>
</tr>
</tbody>
</table>

- types of Portland cements differ by composition:
  - **type I**: a general-purpose cement used when high sulfate attack from soil and water, and high temperature are absent. Examples: sidewalks, buildings, bridges
  - **type II**: used in case of moderate sulfate attack as in case of drainage structure
  - **type III**: early strength type for quick use
  - **type IV**: low-heat-of-hydration type and used when rate and heat generated must be minimized
  - **type V**: used for heavy sulfate attack as in case of groundwater with high sulfate

<table>
<thead>
<tr>
<th>Table 12.5 Typical compound compositions of portland cement</th>
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<tbody>
<tr>
<td><strong>Cement type</strong></td>
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<tr>
<td>-----------------</td>
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<tr>
<td></td>
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<tr>
<td>Ordinary</td>
</tr>
<tr>
<td>Moderate heat of hydration,</td>
</tr>
<tr>
<td>moderate sulfate resistance</td>
</tr>
<tr>
<td>Rapid hardening</td>
</tr>
<tr>
<td>Low heat of hydration</td>
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<tr>
<td>Sulfate-resistant</td>
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</tbody>
</table>
• hardening of Portland cement
tricalcium silicate and dicalcium silicate constitute 75% of Portland cement
hydration reactions:
\[ 2C_3S + H_2O \rightarrow C_3S_2 \cdot 3H_2O + 3Ca(OH)_2 \]
\[ 2C_2S + 4H_2O \rightarrow C_3S_2 \cdot 3H_2O + Ca(OH)_2 \]
• tricalcium silicate hydrate \(C_3S\) is responsible for early strength
• dicalcium silicate hydrate \(C_2S\) is mainly responsible for strength increases beyond one week
• most of compressive strength is developed in 28 days
• strengthening might continue for years
(b) water, aggregates and air

- drinking and non-drinking water can be used. non-drinking water should be tested for level of impurities
- aggregates make up 60~80% of concrete volume
  fine aggregates consist of sand particles up to 6 mm and coarse aggregates are the rocks retained on a no.16 sieve (1.18 mm opening)
- air-entrained concretes are produced to improve the resistance to freezing and thawing
  air entraining agents contain surface-active agents to form extremely small air bubbles

(c) compressive strength

- compressive strength is higher than tensile strength and depends on settled time
- compressive strength depends on water-to-cement ratio, high water content reduces compressive strength
- air entrainment improves workability and hence water content can be reduced
(d) proportioning concrete mixture facts to be considered for designing concrete mixture:
• workability
• strength and durability
• economy of production

cement : water : fine aggregate : coarse aggregate : air volume ratio

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<tbody>
<tr>
<td>1</td>
<td>15%</td>
<td>18%</td>
<td>8%</td>
<td>28%</td>
<td>31%</td>
</tr>
<tr>
<td>2</td>
<td>7%</td>
<td>14%</td>
<td>4%</td>
<td>24%</td>
<td>51%</td>
</tr>
<tr>
<td>3</td>
<td>15%</td>
<td>21%</td>
<td>3%</td>
<td>30%</td>
<td>31%</td>
</tr>
<tr>
<td>4</td>
<td>7%</td>
<td>16%</td>
<td>$\frac{1}{5}$%</td>
<td>25$\frac{1}{5}$%</td>
<td>51%</td>
</tr>
</tbody>
</table>

Air-entrained concrete

Non-air-entrained concrete

Water/cement ratio

Compressive strength (psi)

Compressive strength (MPa)
(e) reinforced and prestressed concrete

- steel reinforcements are used to improve tensile properties as in bending – reinforced concrete

- compressive stress are induced to improve tensile properties by introducing tensioned reinforcements (tendons)

- pretensioned concrete – the tendon is first stretched and concrete is poured on the tendon

- posttensioned concrete – steel reinforcements are used to improve tensile properties as in bending
(7) asphalt and asphalt mixes
• asphalt is a *bitumen* – a hydrocarbon with other elements: 80~85% C, 9~10% H, 2~8% O, 0.5~7% S and traces of impurities
• obtained primarily from *petroleum refining* but also from rocks (rock asphalt) and surface deposits (lake asphalt)
• asphalt mix – *asphalt* (as bituminous binder) + *aggregates*
• used primarily for paving roads, roofing, construction
• angular aggregate bonds better with asphalt and produces better skid resistance on pavements
• the most stable asphalt mix – a dense-packed angular aggregate with just enough asphalt to coat aggregate particles
(8) wood
naturally occurring composite material that consists of a complex array of cellulose cells and a polymeric substance (lignin) and other organic compounds
(a) macrostructure of wood
• nonhomogenous structure and the strength is highly anisotropic
• layers in the cross section of tree:
  (a) outer bark – dry tissue, provides protection
  (b) inner bark – moist and soft, carries food
  (c) cambium layer – forms wood and bark cells
  (d) sapwood – food storage and carrying sap
  (e) heartwood – provides strength
  (f) pith – soft tissue at the center
  (g) wood rays
• trees are classified into two major groups:
  softwoods (gymnosperms) – seed is exposed, retains its leaves (evergreen) and physically soft
  examples: fir, spruce, pine and cedar
  hardwoods (angiosperms) – seeds are covered, sheds leaves annually (deciduous), physically hard
  examples: oak, elm, maple and cherry
• annual growth rings – in temperate climates, new layer of wood is formed around tree stem
  each ring has two subrings:
  latewood (summer) and earlywood (spring)

• axes of symmetry:
  longitudinal axis (parallel to stem)
  radial axis (perpendicular to ring)
  tangential axis (parallel to rings)
(b) microstructure of softwoods

- **tracheids** – long thin walled tubular cells and constitute 90% of volume, 3~5 mm long and 20~80 micrometers in diameter
- earlywood cells have larger diameter and larger lumen than latewood cells
- wood rays run from bark to center of the tree
(c) microstructure of hardwoods
- **vessels** – thin walled structure made up of vessel
- elements and are large than tracheids
- **ring porous trees** – vessels formed in earlywood are larger than in latewood
- **diffuse porous trees** – vessels formed are of same diameter
- **fibers** – elongated cells, 0.7~3 mm length and 20 μm in diameter provide support
- rays are larger than those in softwoods
(d) cell-wall ultrastructure

- **primary wall** – initial wall formed during cell division

- **secondary wall** – forms in concentric layers after primary wall reaches its full size

**Principal constituents of wood cell:**

- **cellulose** – makes 45~50% of solid material linear polymer of glucose units \((n = 5,000\sim 10,000)\)

- **hemicellulose** – makes 20~25% of solid branched amorphous molecule \((n = 150\sim 200)\)

- **lignin** – makes 20~30 wt% of solid formed from phenolic units
(e) properties of wood

• moisture content – water occurs in wood as absorbed in fiber walls or in cell fiber lumen

\[
\text{wood moisture content (wt\%) } = \frac{\text{wt of water in sample}}{\text{wt of dry wood sample}} \times 100
\]

ex. a piece of wood containing moisture weights 165.3 g and after oven drying to a constant weight 147.5 g. what is its % moisture content?

\[
\frac{165.3 - 147.5}{147.5} \times 100\% = 12.1\%
\]

average moisture content
150% for sapwood and 60% for heartwood in softwood, about 80% in hardwood

• mechanical strength
  • softwoods are physically soft and hardwoods are physically hard
  • compressive strength parallel to the grain is 10 times higher than that perpendicular to the grain
  • wood in green condition is weaker than kiln- dried wood
• **shrinkage**
  - greenwood shrinks as moisture eliminated and causes distortion of the wood
  - shrinkage is more in **transverse direction** (10~15%) than in longitudinal direction (0.1%)
(9) sandwich structure

• composite materials are also made by sandwiching a core material between two thin outer layers

• **honeycomb sandwich** – fabricated by adhesively bonding aluminum alloy face sheets to aluminum alloy honeycomb core sections stiff, rigid strong and used in aerospace applications

![](honeycomb.png)

• **clad metal structure** – metal core and thin outer layer of other metal are bonded by hot rolling

e.g.: 10 cent and 25 cent coins have cladding of Cu -25% Ni alloy over less expensive Cu core

![](clad.png)
(10) metal-matrix composites (MMCs) 
three main types of MMCs:
(a) **continuous fiber reinforced MMCs**
continuous fibers are reinforced in metal matrix
• used in aerospace, auto industry and sports equipments
• aluminum alloy-boron fiber composite
boron fiber is made by chemical vapor deposition of boron on tungsten substrate, boron fibers are hot pressed between aluminum foils

• addition of 51 vol% B, tensile strength of Al 6061 increases from 310 to 1417 GPa and tensile modulus increases from 69 to 231 GPa
• other continuous fibers have been used: SiC, alumina, tungsten fibers
(b) **particulate reinforced MMCs**
irregular shaped alumina and silicon carbide particulate (3~200 μm) are used
particulate is mixed into molten aluminum and cast into ingots or billets
- Al 6061 + 20% SiC tensile strength can be increased from 310 to 496 MPa, tensile modulus increased from 69 to 103 GPa

(c) **discontinuous fiber reinforced MMCs**
needlelike SiC whiskers (1~3 μm diameter, 20~200 μm in length) are mixed with metal powder
mixture is consolidated by hot pressing and then forged or extruded into desired shapes

---

**Table 12.7 Mechanical properties of metal-matrix composite materials**

<table>
<thead>
<tr>
<th></th>
<th>Tensile strength (MPa)</th>
<th>Tensile strength (ksi)</th>
<th>Elastic modulus (GPa)</th>
<th>Elastic modulus (Msi)</th>
<th>Strain to failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Continuous-fiber MMCs:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al 2024-T6 (45% B) (axial)</td>
<td>1458</td>
<td>211</td>
<td>220</td>
<td>32</td>
<td>0.810</td>
</tr>
<tr>
<td>Al 6061-T6 (51% B) (axial)</td>
<td>1417</td>
<td>205</td>
<td>231</td>
<td>33.6</td>
<td>0.735</td>
</tr>
<tr>
<td>Al 6061-T6 (47% SiC) (axial)</td>
<td>1462</td>
<td>212</td>
<td>204</td>
<td>29.6</td>
<td>0.89</td>
</tr>
<tr>
<td><strong>Discontinuous-fiber MMCs:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al 2124-T6 (20% SiC)</td>
<td>650</td>
<td>94</td>
<td>127</td>
<td>18.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Al 6061-T6 (20% SiC)</td>
<td>480</td>
<td>70</td>
<td>115</td>
<td>17.7</td>
<td>5</td>
</tr>
<tr>
<td><strong>Particulate MMCs:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al 2124 (20% SiC)</td>
<td>552</td>
<td>80</td>
<td>103</td>
<td>15</td>
<td>7.0</td>
</tr>
<tr>
<td>Al 6061 (20% SiC)</td>
<td>496</td>
<td>72</td>
<td>103</td>
<td>15</td>
<td>5.5</td>
</tr>
<tr>
<td><strong>No reinforcement:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al 2124-F</td>
<td>455</td>
<td>66</td>
<td>71</td>
<td>10.3</td>
<td>9</td>
</tr>
<tr>
<td>Al 6061-F</td>
<td>310</td>
<td>45</td>
<td>68.9</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>
- Al alloy 6061 + SiC whisker tensile strength can be increased from 310 to 480 MPa and tensile modulus increased form 69 to 115 GPa
- Ex. a metal-matrix composite is made from a B fiber-reinforced Al alloy. W wire (r = 10 μm) is first coated with B to give a final radius of 75 μm. Al alloy is then bonded around the B fibers, giving a volume fraction of 0.65 for Al alloy. calculate the effective tensile elastic modulus of this composite under isostrain condition (\(E_W = 410\) GPa, \(E_B = 379\) GPa, \(E_{Al} = 68.9\) GPa)

\[
f_w = \frac{\pi(10 \, \mu\text{m})^2}{\pi(75 \, \mu\text{m})^2} \times 0.35 = 0.0062
\]

\[
f_B = 0.35 - 0.0062 = 0.344 \quad f_{Al} = 0.65
\]

\[
E_c = f_w E_W + f_B E_B + f_{Al} E_{Al}
\]

\[
= 0.0062 \times 410 + 0.344 \times 379 + 0.65 \times 68.9 = 178\ \text{GPa}
\]
(11) ceramic-matrix composites (CMCs) three main types of CMCs:
(a) continuous fiber reinforced CMCs
• SiC and Al₂O₃ fibers are used for CMCs
• SiC fibers are woven into mat and SiC impregnated into fibrous mat by chemical vapor deposition
• SiC fibers can be encapsulated by a glass ceramic
• used in heat exchanger tube and thermal protection system
(b) discontinuous (whisker) and particulate reinforced CMCs
• significantly increases fracture toughness

| Table 12.8 Mechanical properties of SiC whisker reinforced ceramic-matrix composites at room temperature |
|---------------------------------|--------|-------------------|----------------------|
| Matrix | SiC whisker content (vol %) | Flexural strength | Fracture toughness |
|        |       | MPa   | ksi   | MPa√m | ksi√in. |
| Si₃N₄  | 0      | 400–650 | 60–95 | 5–7 | 4.6–6.4 |
|        | 10     | 400–500 | 60–75 | 6.5–9.5 | 5.9–8.6 |
|        | 30     | 350–450 | 50–65 | 7.5–10 | 6.8–9.1 |
| Al₂O₃  | 0      | …     | …     | 4.5 | 4.1 |
|        | 10     | 400–510 | 57–73 | 7.1 | 6.5 |
|        | 20     | 520–790 | 75–115 | 7.5–9.0 | 6.8–8.2 |

• toughness of the CMCs is believed to be resulted from reinforcing fibers interfering with crack propagation in the ceramics
toughening mechanism:

- **crack deflection** – upon encountering the reinforcement, crack is deflected making propagation more meandering
- **crack bridging** – fibers bridge the crack and help to keep the cracks together
- **fiber pullout** – friction caused by pulling out the fiber from matrix results in higher toughness

ex. a CMC is made with continuous SiC fiber embedded in a glass ceramic matrix
calculate the tensile elastic modulus of the composite under isostrain condition

\[
f_{SiC} = \frac{\pi (50)^2}{(80)^2} = 0.307 \quad f_{GC} = 0.693
\]

\[
E_c = f_{GC}E_{GC} + f_{SiC}E_{SiC} \\
= (0.307)(350) + (0.693)(94) = 172 \text{ GPa}
\]
(11) bone – natural composite material
a mixture of organic and inorganic materials
• inorganic component: hydroxyapatite (HA) $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$, platelike 20~80 nm long and 2~5 nm thick
  60~70 wt% of dry bone
• organic component: collagen, a protein
  fibrous, tough, flexible and high inextensible
  25~30 wt% of dry bone
• about 5% water
• two distinct types of tissues:
cortical protein (compact)  cancellous protein (tabecular)