Ceramic Biomaterials

Lecture #17
Ceramics

- Refractory (maintain shape and composition at high temperatures)
- Polycrystalline
- Nonductile virtually zero creep at room temperatures
- Usually inorganic
  - Silicates
  - Metallic oxides
  - Carbides
  - Refractory hydrides, sulfides, and selenides

- Low heat conductivity
- Hard
  - Moh scale
    - Diamond 10
    - Talc 1
  - Alumina (Al₂O₃) 9
  - Quartz (SiO₂) 8
  - Apatite (Ca₅P₃O₁₂F) 5
Traditional Uses of Ceramics

- In form of pottery, used for thousands of years
- Until recently use was limited
  - Brittle
  - Susceptible to notching and microcracking
  - Low tensile strength (but high compressive strength)
  - Low impact resistance
Bioceramics

- Augment or replace various body parts – especially bone
- Dental crowns
  - Relative inertness to body fluids
  - High compressive strength
  - Aesthetically pleasing appearance
- Carbons
  - Blood interfacing applications – heart valves
  - Tendons and ligaments
Desired Properties of Bioceramics

- Nontoxic
- Noncarcinogenic
- Nonallergenic
- Biocompatible
- Functional for its lifetime in the host

Ceramics must meet or exceed these requirements to be termed a bioceramic
Nonabsorbable (Relatively Bioinert) Bioceramics

- Pyrolytic carbon-coated devices
- Dense and nonporous aluminum oxides
- Porous aluminum oxides
- Zirconia ceramics
- Dense hydroxyapatites
- Calcium aluminates
Uses of Bioinert Bioceramics

- Reconstruction of acetabular cavities
- Bone plates and screws
- Ceramic-ceramic composites
- Ceramic-polymer composites
- Femoral heads
- Middle ear ossicles (small bones in the ear, *malleus*, *incus*, and *stapes* – hammer, anvil, and stirrup)
- Reconstruction of orbital rims
- Total and partial hips
- Sterilization tubes
- Ventilation tubes
- Cardiovascular repair
Alumina (Al$_2$O$_3$)

- **Source:** bauxite and corundum
- **Calcination of alumina trihydrate**
- **Natural alumina is either sapphire or ruby, depending on impurities present**
- **Good wear properties**
- **Used in orthopedics for over 25 years – joint replacement, total hip prosthesis**

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Composition (weight%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$</td>
<td>99.6</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>0.12</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>0.03</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Chemical composition of Calcinated Alumina
Zirconi (ZrO$_2$)

- Derived from zircon
  - ZrSiO$_4$
  - Y$_2$O$_3$ used for stabilization
- Good wear and friction properties but not quite as good as alumina

<table>
<thead>
<tr>
<th>Property</th>
<th>Alumina</th>
<th>Zirconia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (GPa)</td>
<td>380</td>
<td>190</td>
</tr>
<tr>
<td>Flexural strength (GPa)</td>
<td>&gt;0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Hardness, Mohs</td>
<td>9</td>
<td>6.5</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>3.8-3.9</td>
<td>5.95</td>
</tr>
<tr>
<td>Grain size (µm)</td>
<td>4.0</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Physical properties of alumina and zirconia
Carbons

- Diamond
- Graphite
- Noncrystalline glassy carbon
- Quasicrystalline pyrolytic carbon
## Properties of Various Types of Carbon

<table>
<thead>
<tr>
<th>Property</th>
<th>Graphite</th>
<th>Glassy</th>
<th>Pyrolytic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>1.5-1.9</td>
<td>1.5</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>Elastic Modulus (GPa)</td>
<td>24</td>
<td>24</td>
<td>28</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>138</td>
<td>172</td>
<td>517</td>
</tr>
<tr>
<td>Toughness (N•m/cm³)</td>
<td>6.3</td>
<td>0.6</td>
<td>4.8</td>
</tr>
</tbody>
</table>
Strength and Modulus vs. Density for Pyrolytic Carbon

- Fracture Stress vs. Density
- Elastic Modulus vs. Density
Biodegradable or Resorbable Ceramics

- Plaster of Paris used as a bone substitute – 1892
- Biodegradable substitutes – 1969
  - Replaced by endogenous tissue
  - Almost all are variations on calcium phosphate
Examples of Biodegradable/Resorbable Bioceramics

- Al-Ca-P oxides
- Glass fibers and their composites
- Corals
- Calcium sulfates, incl. Plaster of Paris
- Fe^{+++}-Ca-P oxides
- Hydroxyapatites
- Tricalcium Phosphate
- Zn-Ca-P oxides
- Zn-SO_4^-Ca-P oxides
Use of Biodegradable/Resorbable Bioceramics

- Drug delivery devices
- Repair of bone damaged by disease or trauma
- Filling space vaced by screws, donor bone, excised tumors, and disead bone loss
- Repairing and fusion of spinal and lumbo-sacral vertebrae
- Repairing herniated discs
- Repairing maxillofacial and dental defects
- Hydroxyapatite ocular implants
Calcium Phosphate

- Artificial bone
- Implants
- Solid or porous coatings
- May be crystallized into hydroxyapatite
  - $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$
- Mechanical properties vary greatly

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (GPa)</td>
<td>4.0-117</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>294</td>
</tr>
<tr>
<td>Bending strength (MPa)</td>
<td>147</td>
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<tr>
<td>Hardness (GPa)</td>
<td>3.43</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.27</td>
</tr>
<tr>
<td>Density (theoretical, g/cm$^3$)</td>
<td>3.16</td>
</tr>
</tbody>
</table>

Physical properties of calcium phosphate
Hydroxyapatite

- Excellent biocompatibility
- Forms direct chemical bond with hard tissue
- On implant, new compact bone forms within 4-8 weeks
Aluminum-Calcium-Phosphate (ALCAP) Ceramics

- Developed in 1980
- Unique
  - Tailor where resorption takes place

FIGURE 2.8 Scanning electron micrograph (1000x) of sintered porous ALCAP
Corraline

- Any of various red algae of the family Corallinaceae whose fronds are covered with calcareous deposits
- Main component – calcium carbonate – gradually resorbed
- Can be converted to hydroxyapatite
- Repair traumatized bone, replace diseased bone, correct bone defects
Tricalcium Phosphate (TCP) ceramics

- Correct peridontal defects
- Augment bony contours
- Ceramic matrix drug delivery systems
- More soluble than synthetic hydroxyapatite
- Good bone ingrowth
Zinc-Calcium Phosphorous Oxide (ZCAP) Ceramics

- Zn, essential for human metabolism
- Component of >30 metalloenzymes
- May be involved in wound healing
- Repair bone
- Deliver drugs
Zinc-Sulfate-Calcium-Phosphate Oxide (ZSCAP) Ceramics

- Formed from zinc oxide, zinc sulfate, calcium oxide, and phosphorous pentoxide
- Set and harden on contact with blood
- Repair bone defects
Ferric-Calcium-Phosphorous Oxide (FECAP) Ceramics

- Sets and hardens on contact with water
- Complete resorption within 60 days
- Patients with anemia

FIGURE 2.12  Scanning electron micrograph (1000x) of a set and hardened FECAP-α-ketoglutaric acid composite. Plate-shaped FECAP particles have been aggregated by the acid.
Bioactive or Surface Reactive Ceramics

- Surface reactive ceramics, upon implant form strong bonds with adjacent tissue
  - Bioglas and Cervital™
  - Dense and nonporous glasses
  - Hydroxyapatite
- Coating of metal prostheses
Uses of Surface-Reactive Ceramics

- Coating metal prostheses
- Reconstruction of dental defects
- Filling space voided by screws *etc.*
- Bone plates and screws

- Middle ear ossicles
- Lengthening of rami – vertical part of jaw
- Correcting periodontal defects
- Tooth replacement
Glass

- **Bioglas®**
  - SiO$_2$ (42.1% - mol %)
  - CaO (29.0%)
  - Na$_2$O (26.3%)
  - P$_2$O$_5$ (2.6%)

- **Ceravital®**
  - SiO$_2$ (40-50% - weight %)
  - CaO (30-35%)
  - Na$_2$O (5-10%)
  - P$_2$O$_5$ (10-15%)
  - MgO (2.5-5%)
  - K$_2$O (0.5-3%)