Powder Pressing: used for both clay and non-clay compositions.

- Powder (plus binder) compacted by pressure in a mold
  - Uniaxial compression - compacted in single direction
  - Isostatic (hydrostatic) compression - pressure applied by fluid - powder in rubber envelope
  - Hot pressing - pressure + heat
Sintering

Sintering occurs during firing of a piece that has been powder pressed

-- powder particles coalesce and reduction of pore size

Aluminum oxide powder:

-- sintered at 1700°C for 6 minutes.

Adapted from Fig. 13.16, Callister & Rethwisch 8e.

Adapted from Fig. 13.17, Callister & Rethwisch 8e. (Fig. 13.17 is from W.D. Kingery, H.K. Bowen, and D.R. Uhlmann, Introduction to Ceramics, 2nd ed., John Wiley and Sons, Inc., 1976, p. 483.)
Eq. 12.9

\[ E = E_0 (1 - 1.9P + 0.9P^2) \]

- modulus w/ zero voids

\[ \sqrt{\sigma} = \sigma_0 E \]

- strength at zero porosity

Chapter 12 - 40
Problem 12.47

Given: \( E_{\text{BeO}} = 310 \text{ GPa} \)
\( \rho = 5\% \)

Find: a) \( E_0 \)  
   b) \( E_{\text{BeO}} \)
\( \rho = 10\% \)

\[
\begin{align*}
a) \quad E_0 & = \frac{E}{1 - 1.7\rho + 0.7\rho^2} = \frac{310 \text{ GPa}}{1 - (1.7)(0.05) + 0.9(0.05)^2} = 342 \text{ GPa} \\
b) \quad E & = (342 \text{ GPa}) \left[ 1 - (1.7)(0.10) + 0.9(0.10)^2 \right] = 280 \text{ GPa}
\end{align*}
\]
Prob. 12.50  

Given:  

\[
\begin{array}{ccc}
\sigma (\text{MPa}) & 100 & 0.05 \\
\sigma_0 & 50 & 0.20 \\
\end{array}
\]

Find:  
a) Strength

\[
\sigma_0 e^{-np}
\]

b) Strength for \( p = 0.10 \)

\[
\sigma = \sigma_0 e^{-np}
\]

\[a) \quad \ln \sigma = \ln \sigma_0 - np\]

\[
\begin{align*}
\ln (100 \text{ MPa}) &= \ln \sigma_0 - (0.05)n \quad \Rightarrow 1 \\
\ln (50 \text{ MPa}) &= \ln \sigma_0 - (0.20)n \quad \Rightarrow 2 \\
\end{align*}
\]

Solving for \( n + \sigma_0 \Rightarrow n = 4.62 \) and \( \sigma_0 = 126 \text{ MPa} \)

\[b) \quad \sigma = (126 \text{ MPa}) \exp \left[ -(4.62)(0.10) \right] = 79.4 \text{ MPa} \]
CERAMIC PROPERTIES AND THEIR ENGINEERING EXPLOITATION

• High strength:weight ratio
• High strength at high temperature
• Low thermal conductivity
• High oxidation resistance
• High hardness
• High electrical resistivity
STRENGTH TO DENSITY RATIOS
STRENGTH AT HIGH TEMPERATURE

Ceramics hold their strength at high temperatures better than metals due to:

- slow diffusion
- immobility of dislocations
- strong bonding
LOW THERMAL CONDUCTIVITY

Materials conduct heat by electron motion, phonons, and electromagnetic radiation. In ceramics, electron motion is near zero, and their porosity can be made high to make thermal conductivity low.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>3000</td>
</tr>
<tr>
<td>Silver</td>
<td>425</td>
</tr>
<tr>
<td>Steel</td>
<td>52</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>39</td>
</tr>
<tr>
<td>ZrO$_2$</td>
<td>3</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>1.4</td>
</tr>
<tr>
<td>High-porosity SiO$_2$</td>
<td>~0.1 (varies)</td>
</tr>
</tbody>
</table>
Oxides do not react with air at high temperatures because they are already fully oxidized.
### HIGH HARDNESS

Hardness correlates well with bond strength. Ceramic bond strengths can be very high.

<table>
<thead>
<tr>
<th>Material</th>
<th>Microhardness (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>70 to 100</td>
</tr>
<tr>
<td>Cubic-BN</td>
<td>45 to 50</td>
</tr>
<tr>
<td>$\text{B}_4\text{C}$</td>
<td>40</td>
</tr>
<tr>
<td>$\text{AlMgB}_{14}\text{-TiB}_2$</td>
<td>36 to 45</td>
</tr>
<tr>
<td>WC</td>
<td>22</td>
</tr>
<tr>
<td>Tempered martensite</td>
<td>4 to 7</td>
</tr>
</tbody>
</table>
Most ceramics have essentially all electrons fully bound to one location (no “free” electrons).

<table>
<thead>
<tr>
<th>Material</th>
<th>Electrical Resistivity at 20°C (Ω-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1.7 (10^{-8})</td>
</tr>
<tr>
<td>Graphite</td>
<td>7.0 (10^{-6})</td>
</tr>
<tr>
<td>(\text{ZrO}_2)</td>
<td>(~10^{10})</td>
</tr>
<tr>
<td>Fused (\text{SiO}_2)</td>
<td>(~10^{18})</td>
</tr>
</tbody>
</table>
AMORPHOUS SILICA (GLASS)

(Na acts as network modifier)

World glass production:
120 million tons/year
APPLICATION: CRUCIBLE LININGS

- Oxidation resistance

- Low thermal conductivity

Refractory-lined crucibles are essential in steel-making
APPLICATION: SPACE SHUTTLE TILES

- High-strength to weight ratio
- High strength at high temperature
- Low thermal conductivity

(But, unfortunately, low fracture toughness)
ABRASIVE WATER JET CUTTING/MACHINING

- Units can cut almost any material.
- Garnet \((\text{Ca}_3\text{Al}_2\text{(SiO}_4)_3\)) is most often used abrasive (hardness ~15 GPa).
- Wear in mixing nozzle degrades cutting accuracy.
- Water pressure is typically 380 MPa (55,000 psi); higher pressures would accelerate cutting, but nozzle and orifice wear become excessive.
APPLICATION: ABRASIVE WATER JET CUTTING/MACHINING

- Fastest growing cutting technology in past 10 years
- Severe wear problems must be overcome in the orifice and mixing tube components.
- Orifice (sapphire), mixing tube (B₄C, Si₃N₄, WC-Co)
- Operating life only 40 to 120 hours ($250 each)
ABRASIVE WATER JET CUTTING/MACHINING

- Ames Lab AlMgB_{14} + TiB_2 composite shows erosive wear resistance superior to conventional materials.
- Trials in mixing tube nozzles scheduled for underway.
- If successful, pressures can be raised above 380 MPa, accelerating cutting and lowering costs.

Variation in abrasive wear rate with applied load:

<table>
<thead>
<tr>
<th>Load, N</th>
<th>WC/Co</th>
<th>cubic BN</th>
<th>Ames baseline boride</th>
<th>Ames boride + TiB2 #1</th>
<th>Ames boride + TiB2 #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
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<tr>
<td>15</td>
<td></td>
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<td>20</td>
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<tr>
<td>25</td>
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</tbody>
</table>

Wear rate, micro-gram/m
Cement is a mixture of CaO, SiO$_2$, Al$_2$O$_3$, MgO, CaSO$_4$, and Fe$_2$O$_3$ dried and finely powdered.

Mixed with sand and water, it forms mortar.

Mixed with gravel, sand, and water, it forms concrete.

World cement production: 2 billion tons/year
APPLICATION: TURBOCHARGER IMPELLERS

- High-strength to weight ratio
- High strength at high temperature
- Low thermal conductivity
- High oxidation resistance
APPLICATION: CERAMIC ENGINES

- High-strength to weight ratio
- High hardness and wear resistance
- High oxidation resistance
- Low thermal conductivity
- Low coefficients of thermal expansion
- High elastic modulus
• The principal drawback of ceramic materials for many structural applications is their low fracture toughness in tension and in impact loading.

• Partially-stabilized ZrO\textsubscript{2} can be heat-treated to raise $K_{IC}$ to 8 to 12 MPa·√m (ceramics are usually 1 to 5 MPa·√m).
Transformation-toughened zirconia (TTZ) has a two-phase microstructure: tetragonal precipitates in a cubic matrix.

Near crack tips, the tetragonal phase (6.1 g/cm³) transforms to a monoclinic phase (5.6 g/cm³) that occupies more space, inducing a compressive stress in the surrounding material that retards further crack propagation.
TRANSFORMATION TO MONOCLINIC PHASE “PINCHES SHUT” AN EXPANDING CRACK
MAKING TTZ

1. Sinter at 1800°C (all cubic)

2. Cool to 20°C (metastable: all cubic)

3. Hold at 1400°C to form tetragonal ppts. in cubic matrix

4. Cool to 20°C (metastable cubic + tetragonal)
Dies for fabricating Al cans are often made of TTZ. They cost 4 times more than steel dies, but wear so much longer that they save money overall.