II Density

A Density: mass/volume (e.g. kg/m³)
Example: $\rho_{\text{water}} = 10^3 \text{ kg/m}^3$
B Specific gravity ($\rho/\rho_{\text{water}}$)
C Unit weight ($\gamma = \text{weight/volume}$)
D Factors affecting density
   1 Composition
   2 Porosity
   3 Saturation
III Hardness

A Mohs hardness scale

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Talc</td>
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<tr>
<td>2</td>
<td>Gypsum</td>
</tr>
<tr>
<td>3</td>
<td>Calcite</td>
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<tr>
<td>4</td>
<td>Calcite</td>
</tr>
<tr>
<td>4.5</td>
<td>Steel</td>
</tr>
<tr>
<td>5</td>
<td>Apatite, Glass</td>
</tr>
<tr>
<td>6</td>
<td>Orthoclase</td>
</tr>
<tr>
<td>7</td>
<td>Quartz</td>
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<tr>
<td>8</td>
<td>Topaz</td>
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<tr>
<td>9</td>
<td>Corundum</td>
</tr>
<tr>
<td>10</td>
<td>Diamond</td>
</tr>
</tbody>
</table>

B Factors affecting rock hardness

1. Mineralogy (± cement)
2. Weathering: generally decreases rock hardness

IV Stress

A Dimensions: Force/area

B Units: 1 Pa = 1N/m²
   - 1 MPa = 10⁶ N/m² = 145 psi
   - ≈ 10 atm

C Pressure at bottom of a 10-m-deep pool ≈ 0.1 MPa ≈ 1 atmosphere

D Stress as a tensor (quantities with two associated directions)

1. \( \sigma \) acts on a plane normal to the i-direction, and in the j-direction

2. Normal stress acts normal to a surface; shear stress acts parallel to a surface
V Strain

A. Strain measures deformation
B. Elongation
\[ \varepsilon = \left( \frac{L_f - L_0}{L_0} \right) = \frac{\Delta L}{L_0} \]
C. \( \varepsilon \) is dimensionless
D. Poisson's ratio
\[ \nu = -\frac{\varepsilon_2}{\varepsilon_1} \]

from uniaxial stress tests

VI Strength

A. Strength: maximum stress that a rock can withstand
B. Uniaxial compressive strength \( \sim 10 \) uniaxial tensile strength
C. Factors affecting rock strength
   1. Rock type (crystalline vs. clastic) and mineralogy
   2. Weathering: generally decreases rock strength
   3. Discontinuities: these decrease rock strength
   4. Sample size: small samples stronger than large samples; see (3)
VI Strength

C Factors affecting rock strength

1 Rock type (crystalline vs. clastic) and mineralogy; crystalline rocks generally stronger

2 Weathering: generally decreases rock strength

3 Grain-scale fabric

4 Discontinuities: they decrease rock strength

5 Sample size: strength decreases with sample size

VII Elastic Properties

A Stress: strain relations

1 Hooke’s Law of Linear Elasticity (1D)

\[ \sigma_{xx} = E \epsilon_{xx} \]

\(E = \) Young’s modulus

2 Shear stress & shear strain

\[ \sigma_{xy} = 2\mu \epsilon_{xy} \]
VII Elastic Properties

3 Hooke’s Law of Linear Elasticity for isotropic materials (3D)

\[ \varepsilon_{xx} = \frac{\sigma_{xx}}{E} - (\frac{\sigma_{yy} + \sigma_{zz}}{2}(\nu/E)) \]

\[ \varepsilon_{yy} = \frac{\sigma_{yy}}{E} - (\frac{\sigma_{zz} + \sigma_{xx}}{2}(\nu/E)) \]

\[ \varepsilon_{zz} = \frac{\sigma_{zz}}{E} - (\frac{\sigma_{xx} + \sigma_{yy}}{2}(\nu/E)) \]

Summing these, with \( \sigma_{xx} = \sigma_{yy} = \sigma_{zz} = -P \), yields the volumetric dilation (\( \Delta \)) as a function of the pressure (\( P \)) and the bulk modulus (\( K \))

\[ \Delta = \frac{\Delta V}{V_0} = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = \frac{-3P}{E} - \frac{-6P\nu}{E} = [-P]\left[\frac{3(1-2\nu)}{E}\right] \]

C Relationship between elastic properties and seismic wave speeds

The bulk modulus (\( K \)) and shear modulus (\( \mu \)) can be deduced from the compressional wave speed (\( V_p \)) and shear wave speed (\( V_s \)) if the density is known

\[ V_p = \sqrt{\left(\frac{K + \frac{4}{3}\mu}{\rho}\right)} \]

\[ V_s = \sqrt{\frac{\mu}{\rho}} \]

\[ \mu = \frac{E}{2(1+\nu)} \]

\[ K = \left[\frac{3(1-2\nu)}{E}\right] \]
VIII Creep behavior

A Creep: "slow" inelastic deformation at low stress

B Rocks that creep
   1 Ice
   2 Salt

http://en.wikipedia.org/wiki/Salt_glacier


VIII Creep behavior

- WIPP repository for nuclear waste hosted in Salado Formation (salt) near Carlsbad, NM

IX Porosity (n)

A Porosity (n)
\[ n = \text{pore volume} / \text{total volume} \]

B Void ratio (e)
\[ e = \text{void volume} / \text{volume of solids} \]

C Fluids (e.g. air, water, petroleum, natural gas) occupy voids

D Factors affecting porosity
1. Rock type
2. Cementation
3. Weathering
4. Sorting: excellent sorting (or poor grading) \( \Rightarrow \) high porosity

X Hydraulic conductivity (K)

A Darcy’s Law for porous media flow
\[ Q = -K \cdot i \cdot A \]
Discharge = (Hyd. cond) (head gradient) (Area)
\( \text{m}^3/\text{sec} = (\text{m/ sec}) (\text{m/m}) (\text{m}^2) \)

B Hydraulic conductivity: how readily rock, modeled as a continuum, conducts fluid

C Factors affecting hydraulic conductivity
1. Dynamic viscosity and density of fluid
2. Character of rock (“intrinsic permeability”)
   a. Interconnection and apertures of pores
   b. Interconnection and apertures of fractures

\[ i = \text{head gradient} \]
\[ i = \frac{\Delta h}{\Delta L} = \frac{h_2 - h_1}{\Delta L} \]
Mechanical Energy in Flowing Water

- Consider the mechanical energy contained by a small mass of water $m$, volume $V$, and density $p$.
- For steady state, isothermal flow of an incompressible fluid ($p$ is constant).
- (1) Total energy = kinetic energy + elevation potential energy + pressure potential energy.
- (2) Dimension of pressure: (force/area) or energy/volume (i.e. force x distance/volume).
- Pressure measures internal energy in a volume of fluid.
- (3) Total head = Velocity head + elevation head ($H$) + pressure head

\[
E_{\text{total}} = \frac{1}{2} m v^2 + m g H + E_{\text{pressure}}
\]

Dividing through by $V$

\[
\frac{E_{\text{total}}}{V} = \frac{1}{2} \rho v^2 + \rho g H + P
\]

Dividing through by $\rho g$

\[
\frac{E_{\text{total}}}{\rho g V} = \frac{1}{2g} v^2 + \frac{H + P}{\rho g}
\]

Mechanical Energy in Flowing Water

\[
\frac{E_{\text{total}}}{\rho g V} = \frac{1}{2g} v^2 + \frac{H + P}{\rho g}
\]

- Dimensions of hydraulic head: length.
- Hydraulic head: the standing elevation that water rises to in a well.
- Usually the kinetic energy loss is negligible for ground water flow, so the hydraulic head is effectively the elevation head plus the pressure head.
- Water flows from high head (high potential energy) to low head (low potential energy): $Q = -K i A$
- If water flowed from high pressure to low pressure, then water would flow from the bottom of a swimming pool to the top!
XI Chemical stability and reactivity

Calcite or gypsum
The Great Blue Hole, Belize

Sulphides (e.g., pyrite)

http://en.wikipedia.org/wiki/Great_Blue_Hole

http://en.wikipedia.org/wiki/Acid_mine_drainage

XI Chemical stability and reactivity

• Alkali–silica reaction ASR (pozzolanic reaction)
• An acid-base reaction between calcium hydroxide (Portlandite or Ca(OH)$_2$), and silicic acid ($\text{H}_4\text{SiO}_4$ or $\text{Si(OH)}_4$)
• Causes swelling of amorphous (glassy) silica

\[
\text{Ca(OH)}_2 + \text{H}_4\text{SiO}_4 \rightarrow \text{Ca}^{2+} + \text{H}_2\text{SiO}_4^{2-} + 2 \text{H}_2\text{O} \rightarrow \text{CaH}_2\text{SiO}_4 \cdot 2 \text{H}_2\text{O}
\]