Deformation and failure in limestone surrounding the Andra Underground Research Laboratory at Bure (East of France)

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Outline

I. Studied material

II. Experimental data: effect of water and effect of stylolites on mechanical strength

III. Micro-mechanical interpretation
Limestones surrounding the Bure URL

(Gunzburger et Cornet, 2007)
# Material properties

<table>
<thead>
<tr>
<th></th>
<th>Oxfordian</th>
<th>Dogger</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Depth (m)</strong></td>
<td>159 – 310</td>
<td>719 – 748</td>
</tr>
<tr>
<td><strong>Composition</strong></td>
<td>&gt;95% calcite</td>
<td></td>
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<tr>
<td><strong>Porosity (%)</strong></td>
<td>7 – 18</td>
<td>2 – 6</td>
</tr>
<tr>
<td><strong>Vp (km/s)</strong></td>
<td>4 – 6</td>
<td>6 – 7</td>
</tr>
<tr>
<td><strong>BET (m²/g)</strong></td>
<td>0.8 – 1.15</td>
<td>X</td>
</tr>
<tr>
<td><strong>E (GPa)</strong></td>
<td>17 – 36</td>
<td>36 – 70</td>
</tr>
<tr>
<td><strong>ν</strong></td>
<td>0.35</td>
<td>0.37</td>
</tr>
</tbody>
</table>
Experimental procedure

- **Uniaxial** $\sigma_2 = \sigma_3 = 0$
- **Triaxial** $\sigma_1 > \sigma_2 = \sigma_3$
- Room temperature
- Strain rate $= 10^{-5}\, s^{-1}$
- Samples size $= 20\times40\, mm$
- Dry and wet experiments with or without (intact) stylolite
Selected data (1/3)

- Weakening effect of water
- Brittle/ductile transition between 20 and 40 MPa
Selected data (2/3)

**Dogger (D1) - 729 m - \( \phi = 6\% \)**

- Differential stress, \( \sigma_{1} - \sigma_{3} \) (MPa)
- Axial strain, \( \varepsilon_{ax} \) (%)

**Dogger (D1) - 719 m - \( \phi = 6\% \)**

- Differential stress, \( \sigma_{1} - \sigma_{3} \) (MPa)
- Differential stress change, \( \Delta \phi \) (%)

- Water = weaker + Stylo = stronger
- Brittle
- Ductile behavior not reached
Selected data (3/3)

Oxfordian - Stylolite orientation

- O2 - 20%
- O3 - 18%
- O5 - 15%
- O6 - 8%

Dogger (D1) - Stylolite orientation

- Dry
- Wet

Oxfordian = no effect
Dogger = weaker \(\Rightarrow\) porosity? Microstructure?
Dry and wet UCS: Sammis and Ashby’s pore–emanated cracking model (1986)

- Pore emanated crack (Vajdova et al., 2010)
- Elastic medium with circular pores of radius r
- Propagation of wing cracks to a distance $\ell$ with crack interactions

(Sammis and Ashby, 1986)
Sammis and Ashby’s pore-emanated cracking model (2/2)

- Sammis and Ashby (1986): Triaxial case
  \[ K_1 = -L^{1/2}\left\{\frac{1.1(1 - 2.1\lambda)}{(1 + L)^{3.3}} - \lambda\right\}\sigma_1\sqrt{\pi a} + K_1' = \frac{\sqrt{2}}{\pi}\sigma_1\sqrt{\pi a}(L + 1)^{1/2} \left(1 - \frac{8}{\pi} f_A\lambda (L + 1)^3\right) \left(1 - \frac{2}{\pi} f_A\lambda (L + 1)^3\right)^{1/2}. \]
  where \( \lambda = \sigma_3/\sigma_1 \)

- Sammis and Ashby (1986): Uniaxial case
  external loading + crack interaction
  \[ \sigma(L) = \frac{K_{IC}}{\sqrt{\pi r}} \left[\frac{1.1\sqrt{L}}{(1 + L)^{3.3}} + \frac{\sqrt{2}}{\pi} \sqrt{\Phi(1 + L)}\right]^{-1}. \]
  where \( L = \ell/r \)

- Zhu et al. (2010): \( d\sigma/dL = 0 \)
  => Analytic approximation

\[ \sigma_u = \frac{1.325}{\Phi 0.414} \frac{K_{IC}}{\sqrt{\pi r}} \]
Application to limestones

- Zhu et al., 2010:
  - 2 families
  - $K_{IC}^{\text{calcite}} = 0.2 \text{ MPa.m}^{1/2}$
  - $r_M = 2 - 10 \mu\text{m}$
  - $r_A = 26 - 500 \mu\text{m}$

- This study:
  - Intermediate
  - Pore radius
  - $r = 10 - 26 \mu\text{m}$
Microstructure (1/2)

- Allochemical limestones with a wide range of grain size
- No crack porosity
Absence of macropores but microporosity at the periphery of grains and in the cement

- This study – O3 – 18%
- (Ji et al., 2011 – Indiana – 16%)
Effect of stylolites – dry tests

- Dogger = stronger
- Oxfordian = weaker
Preliminary microstructural observations

- Cracks parallel to $\sigma_1$
- Complex interaction between stylolite and induced damage
Conclusions

- Bure limestones have a mechanical strength intermediate to micritic and allochemical ones

- Weakening effect of water $\Rightarrow$ reduction of $K_{IC}$

- Effect of stylolites not obvious for Dogger horizon but weakening for Oxfordian layer $\Rightarrow$ stress concentrator?

- No effect of stylolite orientation in dry conditions $\Rightarrow$ stylolite $\neq$ plane of weakness