Experimental study of mechanical and thermal damage in crystalline hard rock

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December, 3\textsuperscript{rd} 2009
Overview

- Introduction
- Characterization of North African gabbro
- Acoustic emission (AE) monitoring of intact rocks during uniaxial tests
- Damage and rock properties evolution due to mechanical and thermal loadings
- Conclusions
Main objectives of the research

- To study crack propagation and to predict failure of rock subjected to:
  - high pressure
  - high temperature

- To relate to:
  - Acoustic Emission
  - Sonic waves velocity
  - Micro-crack evolution

in order to investigate damage in crystalline intact rock
Failure precursors study in laboratory

- Rock deformation data;
- Acoustic emission (AE) and sonic wave velocity changes;
- Infrared radiation (IR) and thermal anomalies;
- Rock electrical resistivity changes;
- Electromagnetic emissions and anomalies;
- ...

Introduction
Rocks characterization
Conclusions
AE monitoring
T+M damages investigation
Conclusions
Characterization of North African gabbro
Microscopic investigation under polarized light

North African gabbro
Mechanical tests and physical parameters measurements

- **Uniaxial compression tests**
  - Elasticity modulus, $E$
  - Poisson’s ratio, $\nu$
  - Max. uniaxial compressive strength, $\sigma_{c_{\text{max}}}$

- **Brazilian tests**
  - Tensile strength, $\sigma_{c_t}$

- **Triaxial tests**
  - Mohr-Coulomb, $c$, $\phi$
  - Hoek & Brown, $s$ & $m$

- **Sonic wave velocity measurements**
  - Primary elastic wave velocity, $V_p$
  - Shear wave velocity, $V_s$
Specimen preparation and testing equipment

a. Grinding machine
b. Measuring of parallelism
c. Elastic wave measurement
d. Schenck press
e. Close view of specimen after uniaxial test
Uniaxial compression test on North African gabbro

Specimen Ga10

$\sigma_{\text{cmax}} = 225 \text{ MPa}$

$E = 85 \text{ GPa}$

$\nu = 0.20$

$\varepsilon_v = \varepsilon_1 + 2\varepsilon_3$

$\varepsilon_3$

$\varepsilon_1$

Stress [MPa]

Deformations (%)
Brazilian tests on gabbro

Gab1 to Gab6 = ø 70 mm
Gab7 to Gab11 = ø 40 mm

No size effect

σ_t = 11.5 MPa

Conclusions

T+M damages investigation

AE monitoring
Ultra high triaxial compression test by Giga press

Max. capacity of machine; \( \sigma_3 = 650 \text{ MPa} \) and \( \sigma_1 = 2400 \text{ MPa} \)

Giga press and confinement cell (a) photo of the cell of the press (b) (Gabet et al, 2006 with modification)
Triaxial test result on gabbro specimen Ga2(200)

\[ \sigma_3 = 200 \text{ MPa} \]
\[ \sigma_1 = 1480 \text{ MPa} \]
Hoek-Brown and Mohr-Coulomb criteria for gabbro

Mohr-Coulomb: $c = 68 \text{ MPa}$ and $\varphi = 43^\circ$
Hoek and Brown: $s = 1$ and $m = 30$
# Summary of mechanical tests and physical measurements

<table>
<thead>
<tr>
<th>Properties</th>
<th>North African Gabbro</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean values</td>
</tr>
<tr>
<td>$\rho_b$ (g/cm$^3$)</td>
<td>2.90</td>
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<tr>
<td>Porosity (%)</td>
<td>&lt;0.5</td>
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<tr>
<td>$V_p$ (m/s)</td>
<td>6560</td>
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<tr>
<td>$V_s$ (m/s)</td>
<td>4078</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.21</td>
</tr>
<tr>
<td>$E$ [GPa]</td>
<td>88</td>
</tr>
<tr>
<td>$\sigma_{ct}$ [MPa]</td>
<td>11.5</td>
</tr>
<tr>
<td>$\sigma_{cmax}$ [MPa]</td>
<td>226</td>
</tr>
</tbody>
</table>
Acoustic emission (AE) monitoring and deformation data during uniaxial tests on intact rock
Damage evolution and stress – deformation curves

Step I: Cracks closure, $\sigma_{cc}$

Step II: Elasticity, reversible strains, Cracks initiation stress, $\sigma_{ci}$

Step III: Crack damage threshold, maximum contraction, $\sigma_{cd}$

Step IV: Peak strength, failure stress, $\sigma_{cf}$

Step V: Post-failure, strain softening

Monotonic Compression Tests and Typical Thresholds during unconfined compression test
Acoustic emission and related parameters

Frequency ranges over which AE and other associated studies have been conducted (Hardy, 2003)

Main parameters of an acoustic emission hit (Huang et al., 1998)
Comparison of AE records and Stress – Deformation data

Identification of damage thresholds in gabbro specimen Ga10 by AE energy parameter
AE monitoring during Brazilian test on gabbro

Identification of damage thresholds in gabbro specimen Gab1 by AE energy and AE hit parameters
Comparison of AE monitoring and stress – deformation data

- AE monitoring is more accurate than stress-deformation curve to determine damage thresholds,

- AE energy parameter is a more effective parameter than the conventional AE hit number to detect different stages of the rock failure process,
Damage investigations on mechanically and thermally loaded specimens
Different effects of mechanical and thermal changes on rocks

- Stress changes
  - Micro-crack initiation
  - Physical and mechanical properties of rock

- Thermal changes
  - Thermal Healing
  - Chemical reactions
  - Phase transitions
  - Micro-crack initiation
To evaluate the magnitude of damages in both T. & M. methods, we've used,

- Uniaxial compression tests ($\sigma_{\text{cmax}}, E, u, \ldots$),
- Elastic wave velocity measurements ($V_s$ and $V_p$),
- AE monitoring,
- Microscopic investigation.

**Thermal damage:**
Specimens subjected to high temperature

$150^\circ C < T < 1000^\circ C$

**Mechanical damage:**
Specimen subjected to high confining pressure

$\sigma_3 = 650 \text{ MPa}$
$\sigma_1 = 2350 \text{ MPa}$
Ultra high pressure triaxial test on gabbro specimen Ga1(650)

\[ \varepsilon_v = (\varepsilon_1 + 2\varepsilon_3) \]

\[ \sigma_3 = 650 \text{ MPa} \]
\[ \sigma_1 = 2350 \text{ MPa} \]

Mechanical damage investigation

Starting of axial loading

Rocks characterization

Introduction

T+M damages investigation

AE monitoring

Conclusions
Thermal damage investigation

Nominal temperature:
150, 300, 450, 500, 600, 700, 800 and 1000 °C

Heating rate: 100°C/hour

Programmable electrical furnace

- Specimen

10 mm (for microscopic investigations)

80 mm (Sonic wave velocity measurements and uniaxial compression test)
Uniaxial compression tests on specimen having experienced high temperature

\[ \varepsilon_v = (\varepsilon_1 + 2\varepsilon_3) \]
Uniaxial strength and elastic modulus changes

Uniaxial compression strength [MPa]

Temperature (°C)

Elasticity Modulus [GPa]

Temperature (°C)

- Thermally treated specimens
- Ga1 (650), Mechanically damaged specimen
- Mechanically damaged specimen

Introduction
Rocks characterization
AE monitoring
T+M damages investigation
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Sonic wave velocity changes (Vs and Vp)
Acoustic emission monitoring

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Photos of specimen – macroscopic failure
Microscopic investigations of thermally treated specimens

Oxidation appearance at 500°C

Oxidation development in pyroxenes at 800°C

Micro-crack initiation due to different thermal expansion coefficient between pyroxene and a surrounded crystal

Blow up liquid and gas inclusion at 300°C effects
Microscopic investigations of Mechanically damaged specimens

Evidences of ultra high triaxial mechanical damage in plagioclase
Tomography investigations

Intact rock

800°C loaded

600°C loaded

1000°C loaded

Rocks characterization

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AE monitoring

Conclusions
Conclusions
Conclusions (1/2)

Damage investigations on intact rocks:

- AE monitoring is more efficient way than rock deformation data to determine damage thresholds during uniaxial compression tests,

- We found also that AE energy parameter delineates the different steps of rock failure procedures more accurately than conventional AE hit number,
Conclusions (2/2)

Thermally treated rocks:

- Physical properties ($E$, $\sigma_{\text{max}}$, $V_p$, $V_s$ and AE energy and AE hit parameters) decrease with the temperature increase,

- Above 600°C mechanical properties of thermally treated gabbro drastically decrease,

- Oxidation in high temperature and different expansion coefficients between crystals are the main causes of damage in thermally treated specimens.

Mechanically damaged rock:

- In spite of ultra high pressure, the mechanical and physical parameters of rock decrease only up to 25%. We conclude that this is due to smaller porosity of gabbro. However, AE monitoring demonstrates mechanical damage better than uniaxial test and sonic wave velocity measurements,

- In thin section studies, the development of micro-cracks through the crystalline structure is typical of mechanical damage.
Thank you