Effect of Micro-Gas Inclusions on Abnormally Delayed Mechanical Behaviour of Intact Rocks After Excavation

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1. Introduction

- In-situ intact rocks can have the abnormally delayed behaviour that occurs after engineering excavation or tunnelling, such as rockburst.

Rockbursts occurred in intact rocks
Hoek and Martin (2014) pointed out that “The authors are not aware of any currently available numerical tools that offer any credible means of explaining or predicting the rockburst process”.

The mechanism of the abnormally delayed behaviour of intact rocks after excavation (e.g. rockburst, outburst) is still unclear.
Micro structure of intact rocks

- The intact rocks are not completely solids and can have various voids, and some voids can be isolated.

- The voids of intact rocks can be filled with gas, and form gas inclusions (e.g. H₂O, CH₄, CO, CO₂, SO₂).

(After He et al., 2010) (After Yue, 2012)
Gas induces residual stress

- Micro-fluid inclusions will induce the residual stress (locked-in stress), and they can be related to rockburst (Tan and Kang, 1991).

- Prof. Yue (2012) has proposed a micro-gas inclusion hypothesis to describe and quantify the residual stress in intact rocks.

\[ p_{\text{gas}} = \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) \]
2. Research Objectives

- Develop the laboratory setup to fabricate the rock-like solids with micro-gas inclusions.
- Carry out a systematic test programme to design, fabricate and test the rock-like solids so that they can have micro-gas inclusions with high pressures and show the abnormally delayed deformation and fractures.
- Use the micro-gas inclusion hypothesis to describe and explain the physical and mechanical properties and behaviours of the rock-like solids.
3. Experimental Setup and Method

- Overview of the experimental setup
  - Cylinder jacket, pistons, steel framework, load cell, hydraulic jack, and LVDT.
**Experimental procedures**

- Mix cement and water
- Cast and pressurize the cement paste
- Pump out of hardened specimens
## Specimens

### Intact specimens (w/c: 0.3)

<table>
<thead>
<tr>
<th>No.</th>
<th>Compression (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L001</td>
<td>-</td>
</tr>
<tr>
<td>L002</td>
<td>60</td>
</tr>
<tr>
<td>L003</td>
<td>50</td>
</tr>
<tr>
<td>L004</td>
<td>40</td>
</tr>
<tr>
<td>L005</td>
<td>30</td>
</tr>
<tr>
<td>L006</td>
<td>10</td>
</tr>
<tr>
<td>L007</td>
<td>0</td>
</tr>
</tbody>
</table>
Properties of specimens

- The density increases with increasing the compressive pressure.

Densities variation under different compressive pressure

(left: Φ80; right: Φ45)
Compressive strength

The compressive strength of the specimens is higher under higher compressive pressure.

Compressive strength of specimens under different compressive pressures
### Tensile strength

- The specimens have higher tensile strength under higher compressive pressure.

<table>
<thead>
<tr>
<th>No.</th>
<th>Size (mm)</th>
<th>Density (g/cm³)</th>
<th>Tensile Strength (MPa)</th>
<th>Average (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Φ50.20 × 24.58</td>
<td>2.12</td>
<td>3.53</td>
<td>3.94</td>
</tr>
<tr>
<td>A2</td>
<td>Φ50.20 × 24.86</td>
<td>2.10</td>
<td>4.34</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>Φ50.17 × 24.86</td>
<td>1.99</td>
<td>3.27</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>Φ50.10 × 23.54</td>
<td>1.99</td>
<td>3.57</td>
<td></td>
</tr>
</tbody>
</table>
Based on the test results, the experimental setup can provide enough and effective pressure on the unhardened rock-like solid samples.

What will happen if the rock-like solid specimen is made with gas?
Produce samples with gas inclusions

- Mix cement, water and $\text{H}_2\text{O}_2$
- Cast and pressurize the cement paste
- Pump out of hardened specimens
### 4. Results and Discussion

#### Fracture phenomenon of specimens

<table>
<thead>
<tr>
<th>No.</th>
<th>$\text{H}_2\text{O}_2$ (wt %)</th>
<th>Compression (MPa)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS001</td>
<td>9.5</td>
<td>31.69</td>
<td>1 fracture; 4 fissures</td>
</tr>
<tr>
<td>GS002</td>
<td>9.5</td>
<td>31.56</td>
<td>2 fractures; 2 fissures</td>
</tr>
<tr>
<td>GS003</td>
<td>9.5</td>
<td>32.32</td>
<td>1 fracture; 4 fissures</td>
</tr>
<tr>
<td>GS004</td>
<td>5.6</td>
<td>50.57</td>
<td>Intact</td>
</tr>
<tr>
<td>GS005</td>
<td>7.8</td>
<td>50.00</td>
<td>1 fracture; 1 fissure</td>
</tr>
<tr>
<td>GS006</td>
<td>8.7</td>
<td>50.00</td>
<td>3 fractures; 4 fissures</td>
</tr>
</tbody>
</table>
Monitoring of experiments

Before compression

Compressing

Hardened specimen

The fracture phenomenon should be related to the gas involved in the experiment.
Gas state during experiments

Assumptions:

- The cement paste is static fluid;
- The temperature change in the cement paste is not considered.

\[ \Delta P = P_a + \frac{2\gamma}{R} \]

(Young-Laplace Equation)
\[ P \geq \frac{\rho_c \gamma g + \tau_0 (P_a - \rho_c gh)}{\tau_0 + \frac{\rho_g \gamma g}{P_a}}; \quad R \leq \frac{2 \left( \frac{\tau_0 - \frac{\rho_g \gamma g}{P_a}}{\rho_c - \rho_g \left(1 - \frac{\rho_c gh}{P_a}\right)}\right)}{\cdot g} \]

Change in maximum radius and minimum pressure with yield stress of cement paste (\(\gamma=100 \text{ N/m}\))

The high-pressure micro-gas inclusions in the viscous fluid can be formed under compression.
Phenomenon of fractures

Hypothesis of initial fissures generation

Gas generation

Apply Compression

Compressed gas

Confinement Release

Gas escape

Schematic diagram of initial fissure generation in cement paste
5. Concluding Remarks

- The experimental setup designed can fabricate the rock-like solids with micro-gas inclusions under compression.
- The properties of the rock-like solids (e.g. density, uniaxial compressive strength, tensile strength) are related to the applied pressure during the hardening process.
- The compressed gas in the rock-like solids can induce fractures after disturbance.


Thank you!