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

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Contents

1. Introduction

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

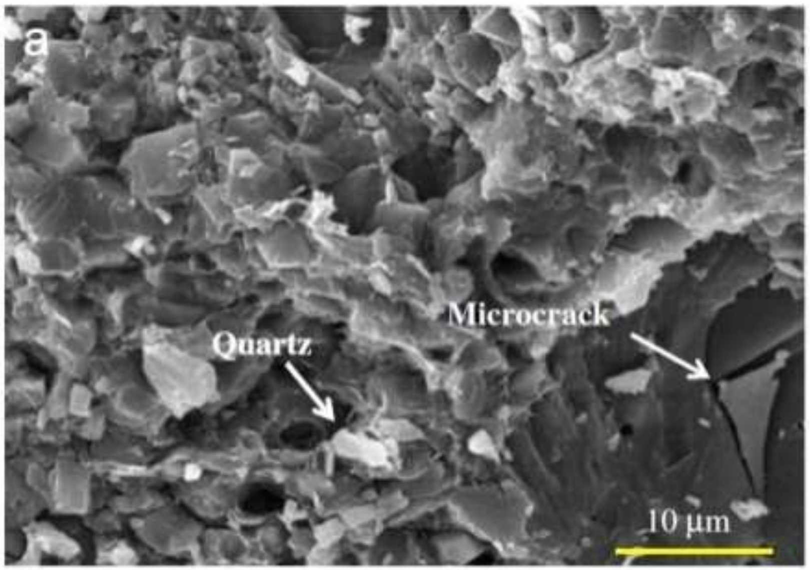
Rockbursts occurred in intact rocks

- 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*".

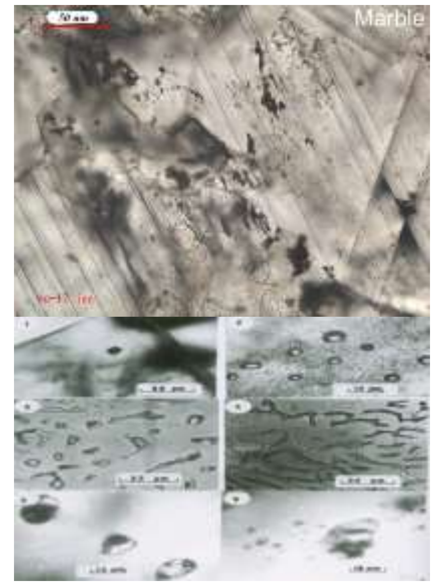
The mechanism of the abnormally delayed behaviour of intact rocks after excavation (e.g. rockburst, outburst) is still unclear.

◻ Micro structure of intact rocks

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



(After He *et al.*, 2010)



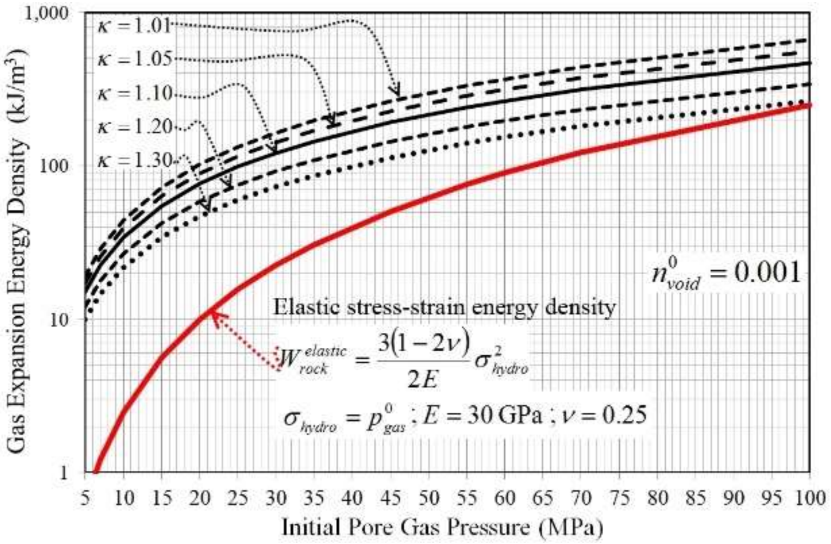
(After Yue, 2012)

- ➢ The voids of intact rocks can be **filled with gas**, and **form gas inclusions** (e.g. H_2O, CH_4, CO, CO_2, SO_2).

◻ 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.

$$p_{\text{gas}} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$$



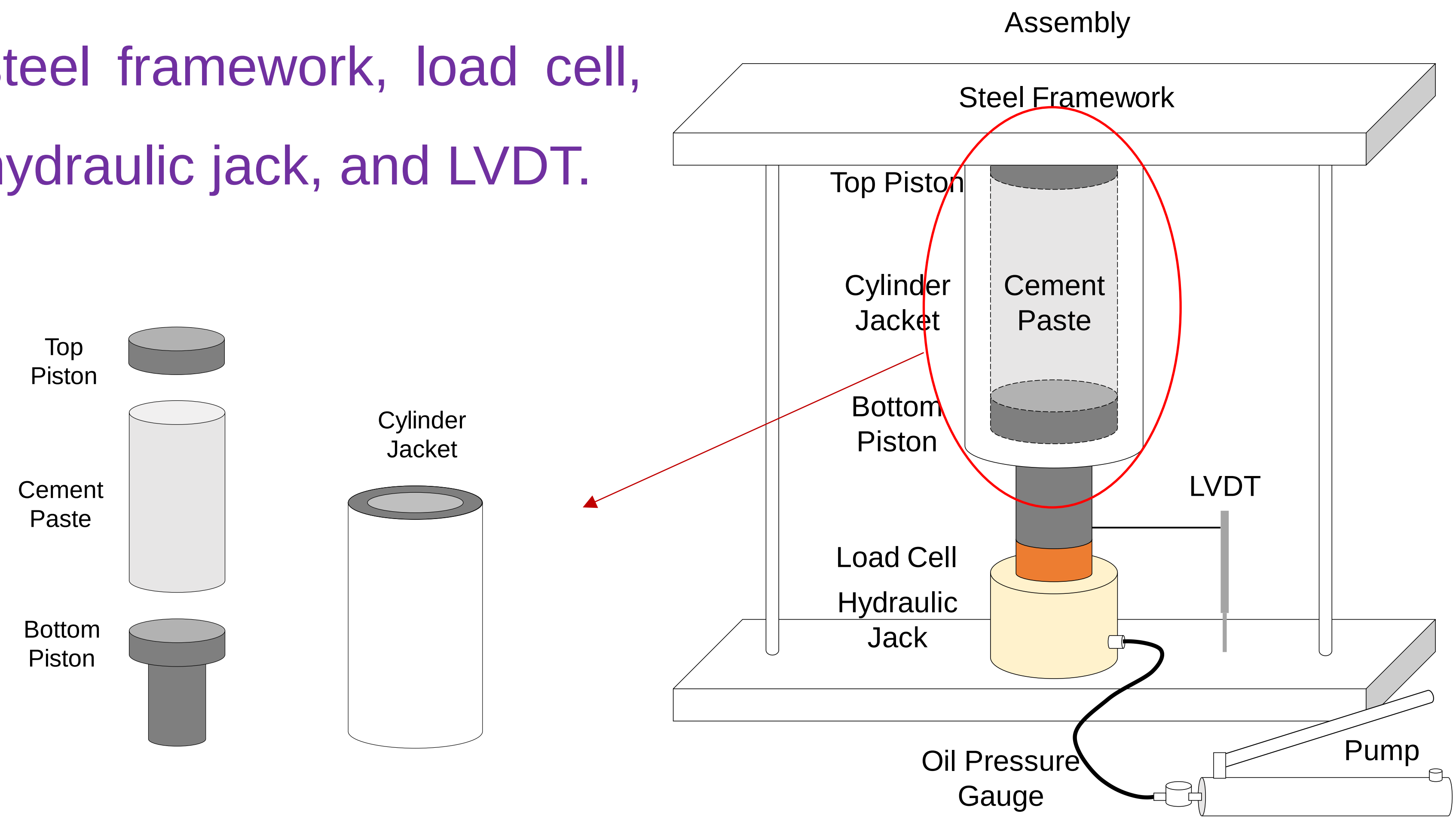
2. Research Objectives

- 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

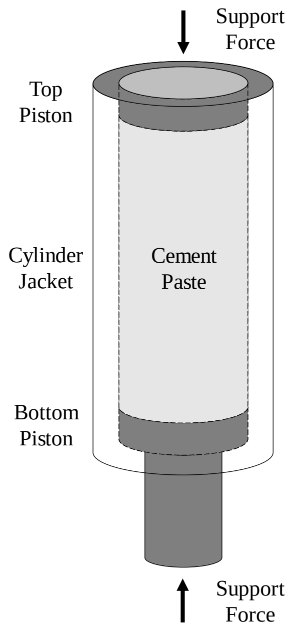
☐ Overview of the experimental setup

- Cylinder jacket, pistons, steel framework, load cell, hydraulic jack, and LVDT.

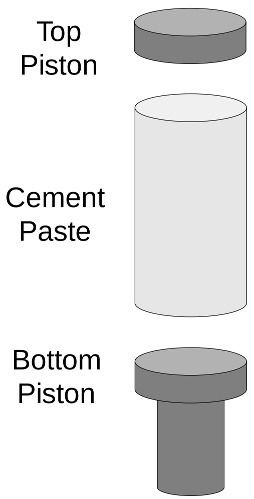


Experimental procedures

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



Compress fresh cement paste



Pump out of the cement paste

Specimens

- Intact specimens (w/c: 0.3)

No.	Compression (MPa)
L001	-
L002	60
L003	50
L004	40
L005	30
L006	10
L007	0

Φ80.00 ×119.85

Φ80.00 ×120.00

Φ80.00 ×124.90

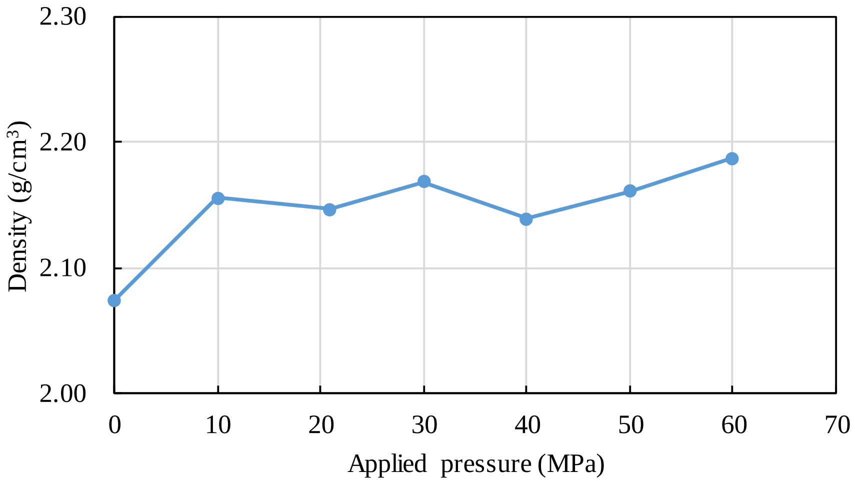
Φ80.00 ×118.55

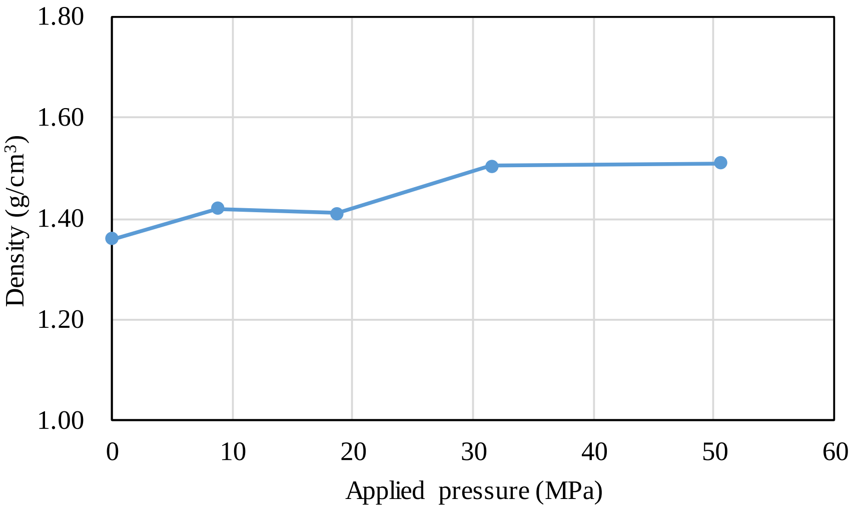
Φ80.00 ×124.60

Φ80.00 ×126.35

Properties of specimens

➢ The density increases with increasing the compressive pressure.



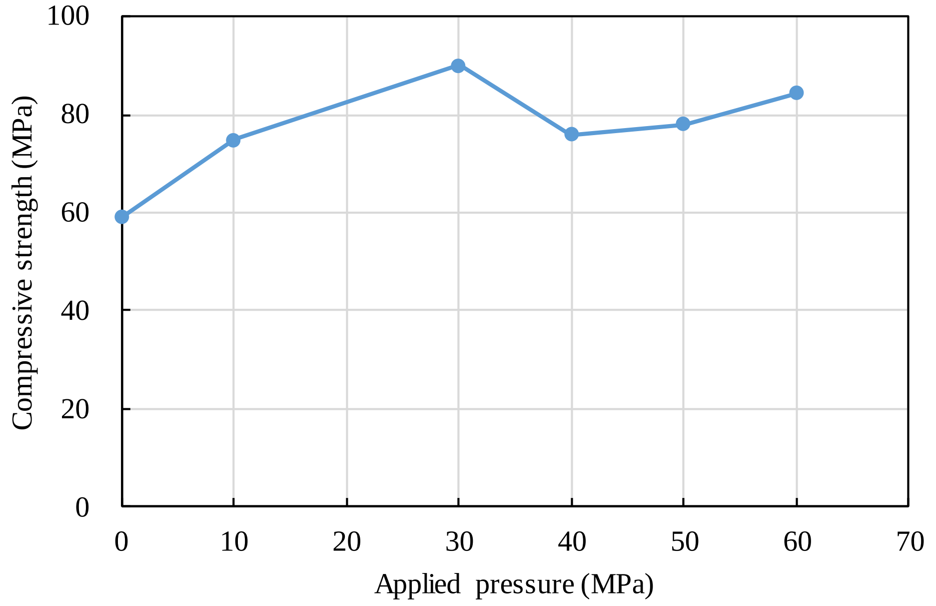


Densities variation under different compressive pressure

(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.

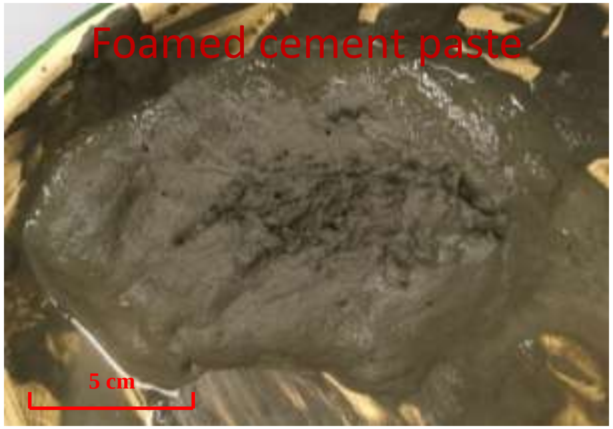
No.	Size (mm)	Density (g/cm³)	Tensile Strength (MPa)	Average (MPa)
A1	Φ50.20×24.58	2.12	3.53	3.94
A2	Φ50.20×24.86	2.10	4.34	
B1	Φ50.17×24.86	1.99	3.27	3.42
B2	Φ50.10×23.54	1.99	3.57	

Based on the test results, the experimental setup can provide enough and effective pressure on the unhardened rock-like solid samples.

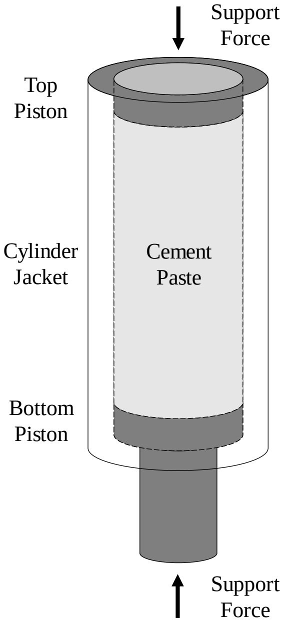
What will happen if the rock-like solid specimen is made with gas?

Produce samples with gas inclusions

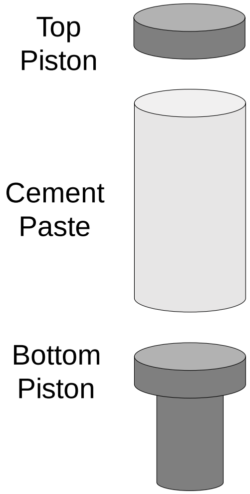
- Mix cement, water and $\boxed{H_2O_2}$
- Cast and pressurize the cement paste
- Pump out of hardened specimens



Mixture of cement, water and H_2O_2



Compress fresh cement paste



Pump out of the cement paste

4. Results and Discussion

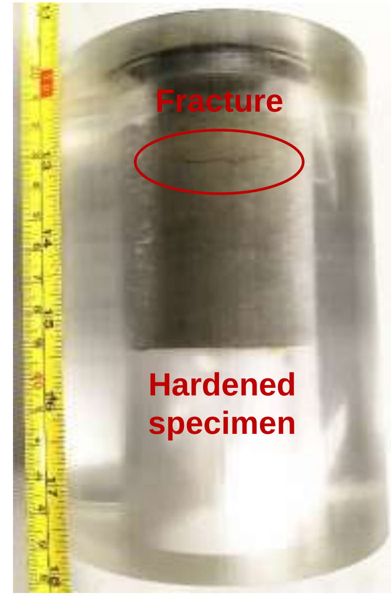
□ Fracture phenomenon of specimens

No.	H_2O_2 (wt %)	Compression (MPa)	Description
GS001	9.5	31.69	1 fracture; 4 fissures
GS002	9.5	31.56	2 fractures; 2 fissures
GS003	9.5	32.32	1 fracture; 4 fissures
GS004	5.6	50.57	Intact
GS005	7.8	50.00	1 fracture; 1 fissure
GS006	8.7	50.00	3 fractures; 4 fissures

◻ Monitoring of experiments

Before compression

Compression



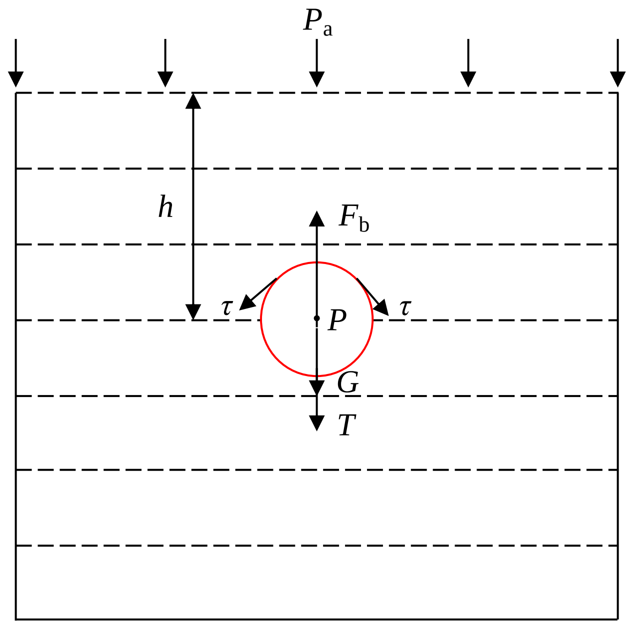
Hardened

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.

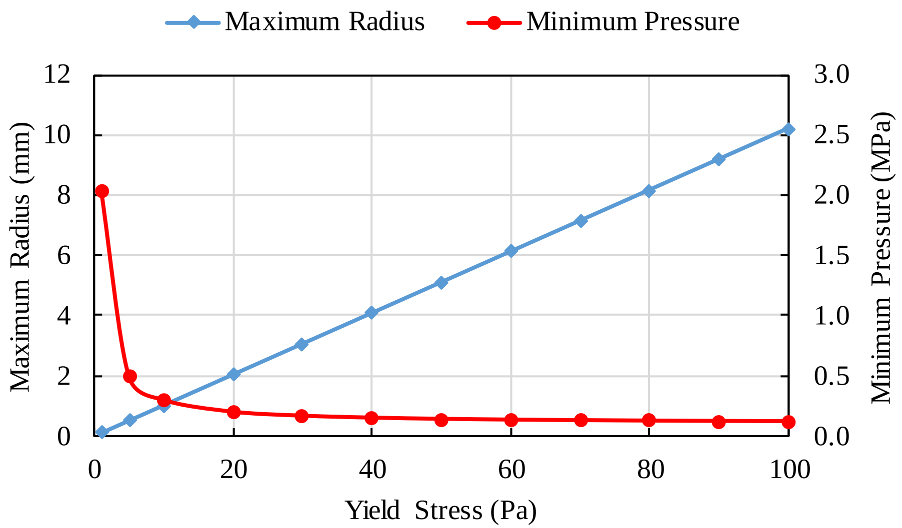


Model of the gas state in fresh cement paste

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

(Young-Laplace Equation)

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

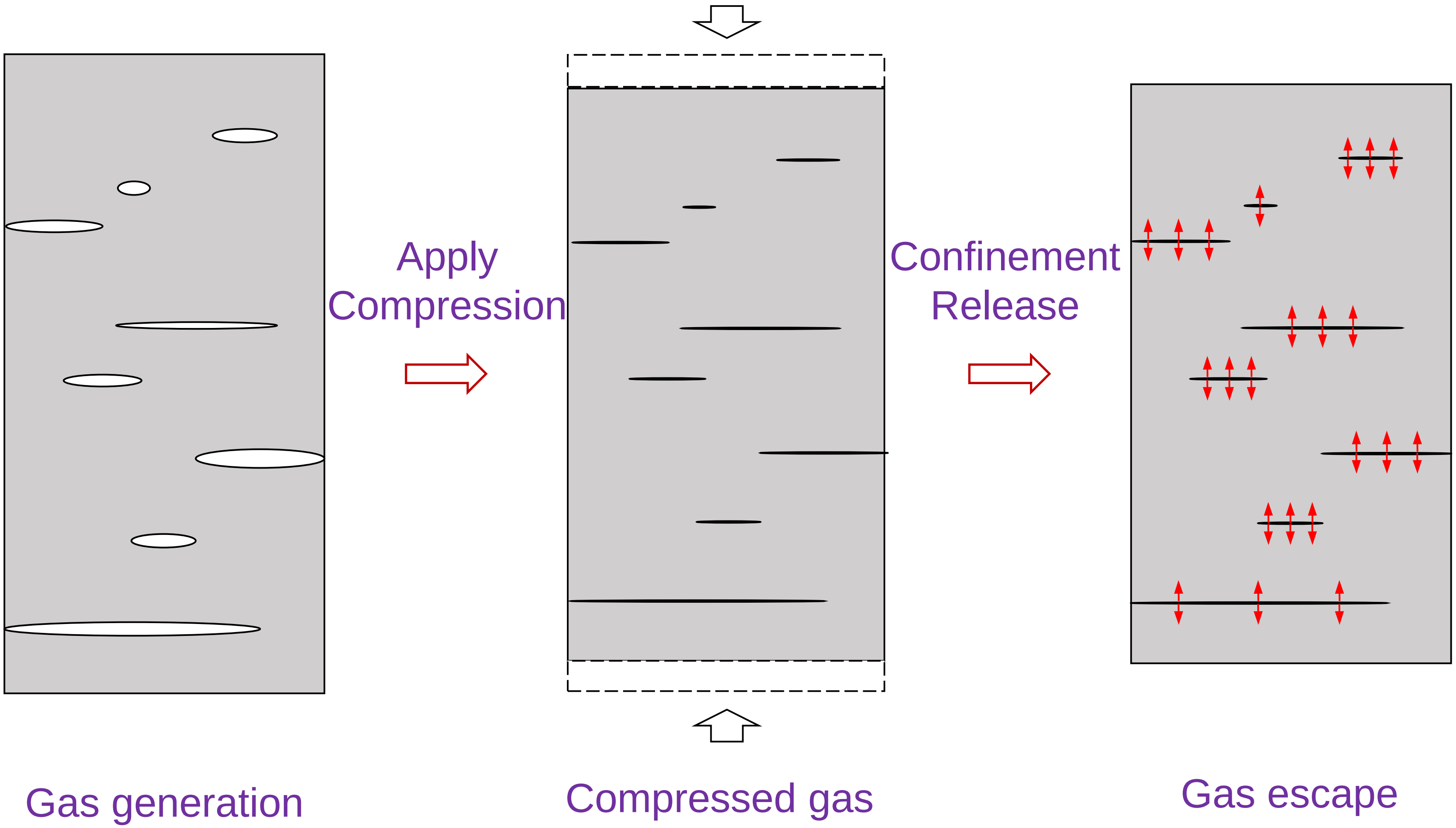


Change in maximum radius and minimum pressure with yield stress of cement paste (γ=100 N/m)

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

Phenomenon of fractures

- Hypothesis of initial fissures generation



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.

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Thank you!