Geological Storage and Fluid Flow Characteristics of Geothermal Reservoirs in Taiwan—A Case Study on the Datun Volcanic Group and Eastern Slate Belt

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Outline

- Introduction
- Methodology
- Results
- Conclusions
- Future work

- Taiwan is located on the Pacific Ring of Fire and is rich in geothermal resources.
- Geothermal power generation must meet three conditions:

1. Adequate heat source：Heating fluid (water)
2. Water：Capable of absorbing heat from geothermal sources
3. Channels for fluids to flow through a rock mass：
   To transport fluid to the subsurface for heating and to transport the heated fluid to the surface for electricity generation.

Joint plane　　Foliation plane

Study Area

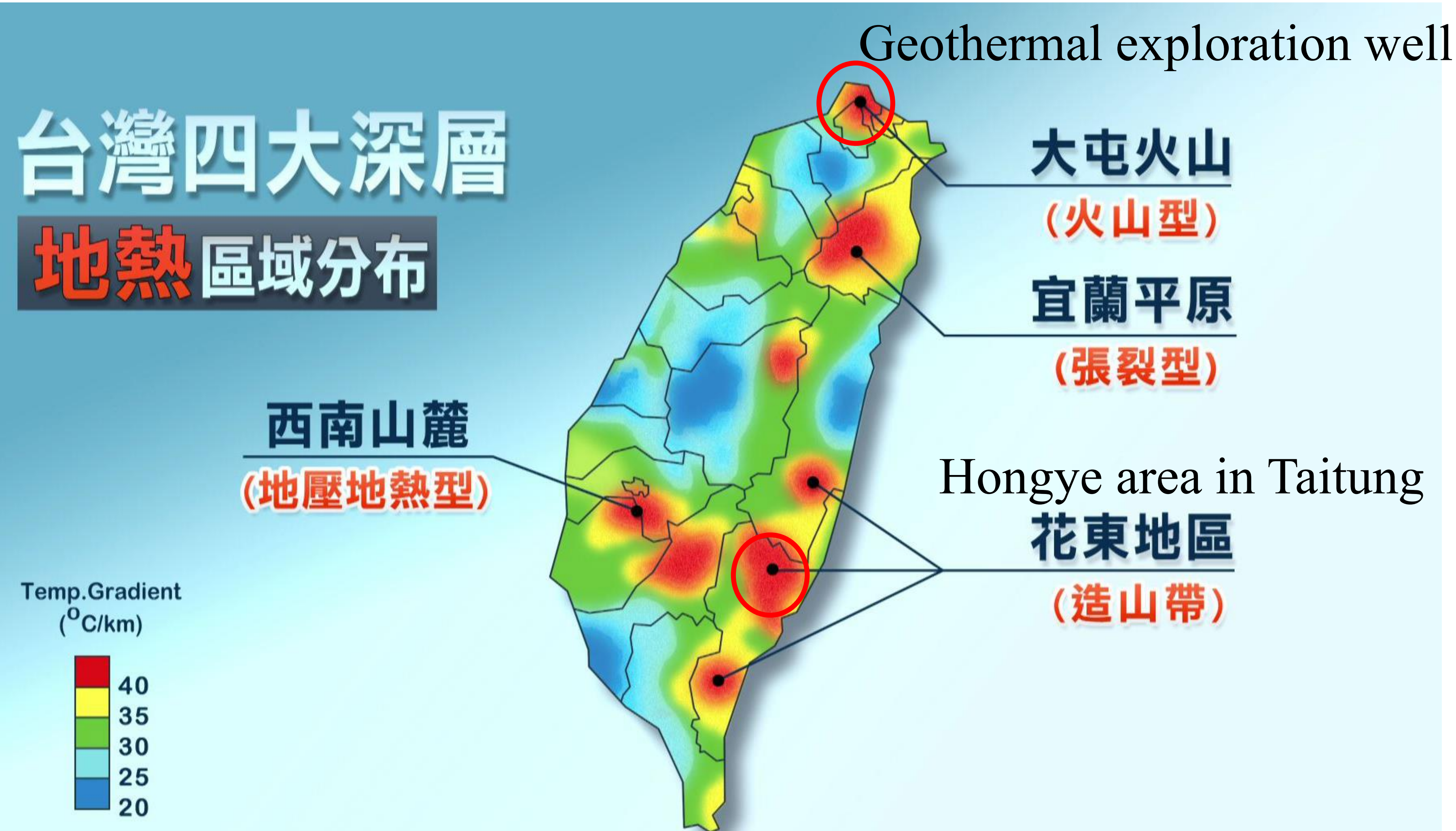


Fig.1 The four major deep geothermal distribution areas in Taiwan Source：GSMMA

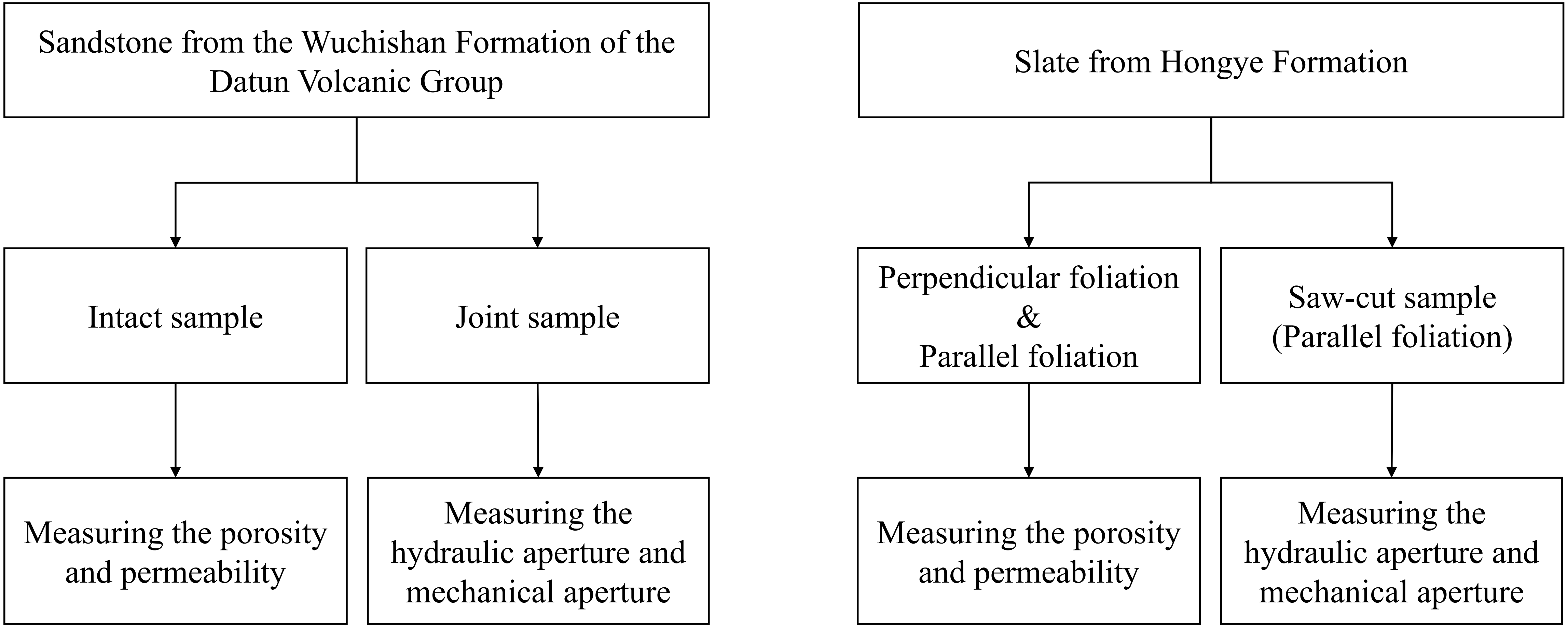


Fig.2 Experiment flow diagram

Sandstone

(1) Porosity measurement of intact sandstone

Boyle's Law

$$P_{i1} \cdot V_s + P_{i2} \cdot (V_l + V_p) = P_f \cdot (V_s + V_l + V_p)$$

$$\emptyset = \frac{V_p}{V} \times 100\%$$

P_{i1} ： The pressure when the gas flows into V_s (MPa)
P_{i2} ：One atmospheric pressure (MPa)
P_f ： Balance air pressure (MPa)
V_l ： The volume of the thin tube (mm^3)
V_s ： The volume of confined space (mm^3)
V_p ：The pore volume of rock sample (mm^3)
V ： The volume of sample (mm^3)
$\emptyset$ ：The porosity of sample (%)

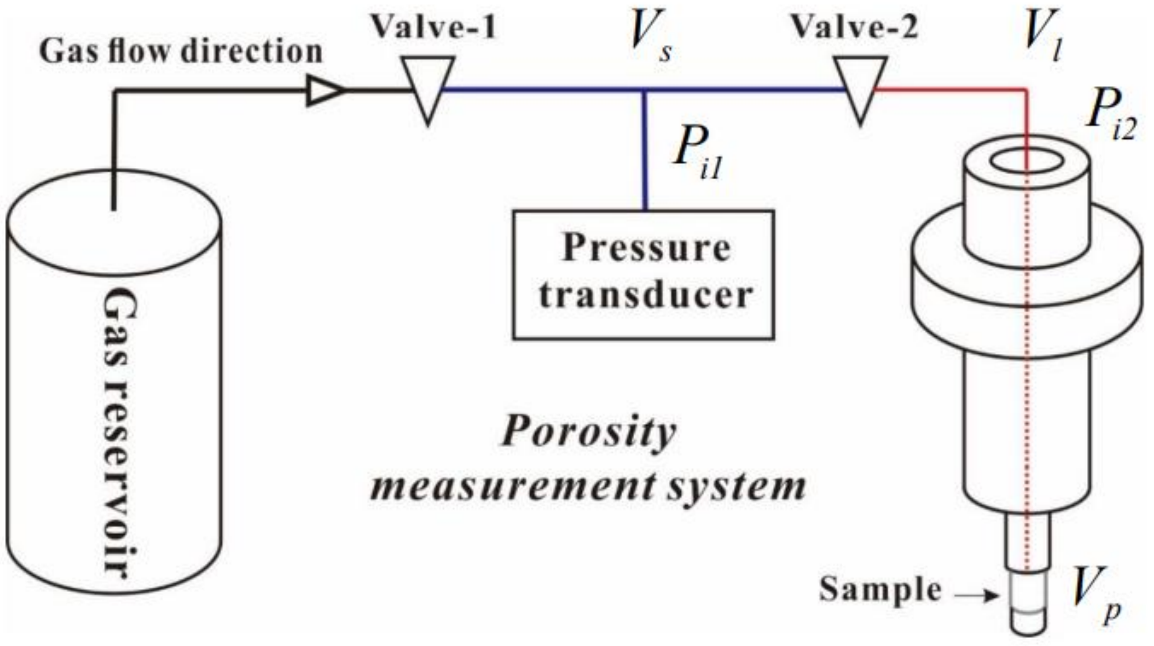


Fig.3 Schematic diagram of porosity measurement system (楊盛博，2015)

Sandstone

(2) Mechanical aperture measurement of sandstone joints

Boyle's Law

$$P_{i1} \cdot V_s + P_{i2} \cdot (V_l + V_j) = P_f \cdot (V_s + V_l + V_j)$$

$$E = \frac{V_j}{A_j}$$

P_{i1} : The pressure when the gas flows into V_s (MPa)
P_{i2} : One atmospheric pressure (MPa)
P_f : Balance air pressure (MPa)
V_l : The volume of the thin tube (mm^3)
V_s : The volume of confined space (mm^3)
V_j : The volume of joint (mm^3)
E : The mechanical aperture of sample (mm)
A_j : The area of joint (mm^2)

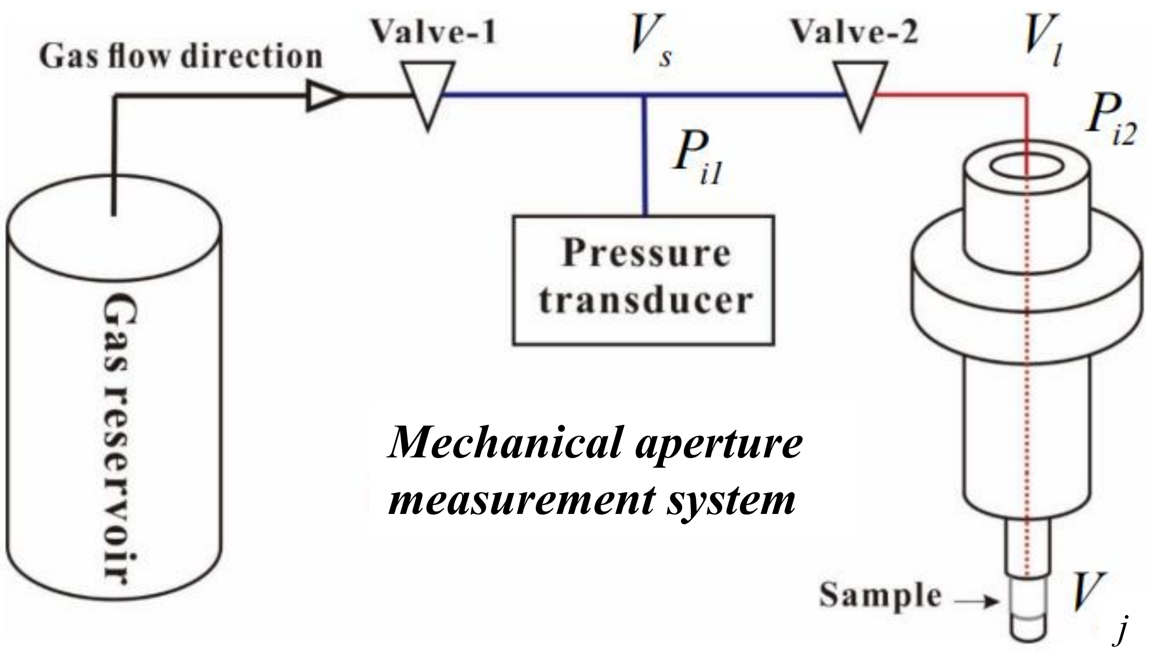


Fig.4 Schematic diagram of mechanical aperture measurement system (楊盛博，2015)

Sandstone

(3) Permeability measurement of intact sandstone

Steady state

$$k_{gas} = \frac{2Q\mu_g L}{A} \times \frac{P_d}{P_u^2 - P_d^2}$$

k_{gas}： The gas permeability of sample (m^2)
Q： Flow rate of gas (m^3/s)
μ_g： Viscosity coefficient of gas (MPa*s)
L： The length of the sample (m)
A： Cross-sectional area of sample (m^2)
P_u： The pore pressure above the sample (MPa)
P_d： The pore pressure under the sample (MPa)

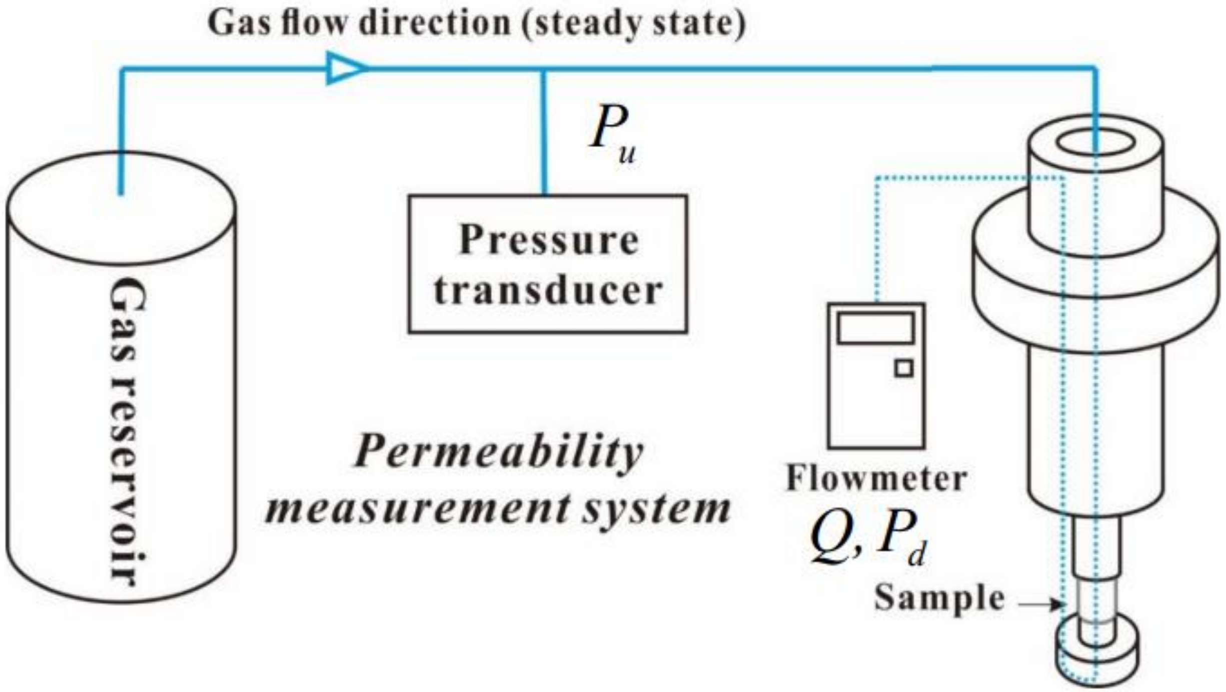


Fig.5 Schematic diagram of permeability measurement system (楊盛博，2015)

Sandstone

(4) Hydraulic aperture measurement of sandstone joints

Steady state

$$e = \sqrt[3]{\frac{Q}{\Delta P/L} \times \frac{12\mu_g}{w}}$$

e : The hydraulic aperture of sample (μm)
Q : Flow rate of gas (m^3/s)
w : The width of the joint
μ_g : Viscosity coefficient of gas (MPa*s)
L : The length of the sample (m)
ΔP : $(P_u^2 - P_d^2)/2P_d$ (MPa)
P_d : The pore pressure above the sample (MPa)
P_u : The pore pressure under the sample (MPa)

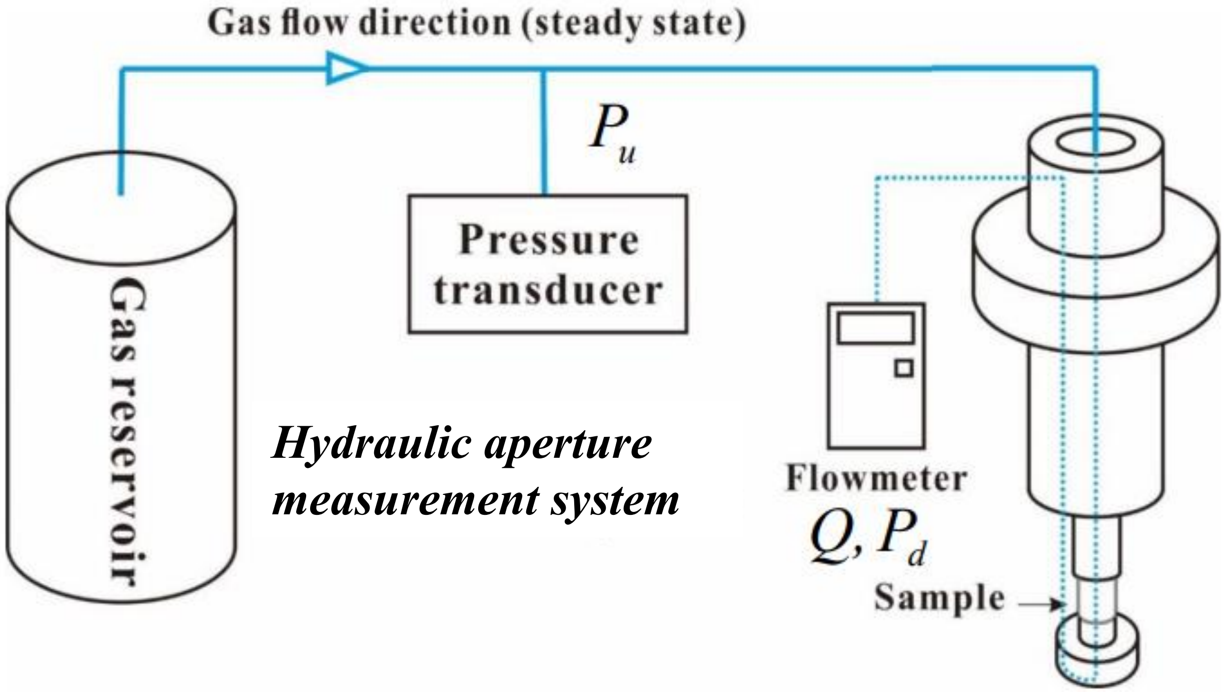


Fig.6 Schematic diagram of hydraulic aperture measurement system (楊盛博，2015)

Slate

(1) Porosity measurement of intact slate

Boyle's Law

$$P_{i1} \cdot V_s + P_{i2} \cdot (V_l + V_p + V_m) = P_f \cdot (V_s + V_l + V_p + V_m)$$

$$\emptyset = \frac{V_p}{V} \times 100\%$$

P_{i1} : The pressure when the gas flows into V_s (MPa)
P_{i2} : One atmospheric pressure (MPa)
P_f : Balance air pressure (MPa)
V_l : The volume of the thin tube (mm^3)
V_s : The volume of confined space (mm^3)
V_p : The pore volume of rock sample (mm^3)
V_m : The pore volume of perforated metal gaskets(mm^3)
V : The volume of sample (mm^3)
$\emptyset$: The porosity of sample (%)

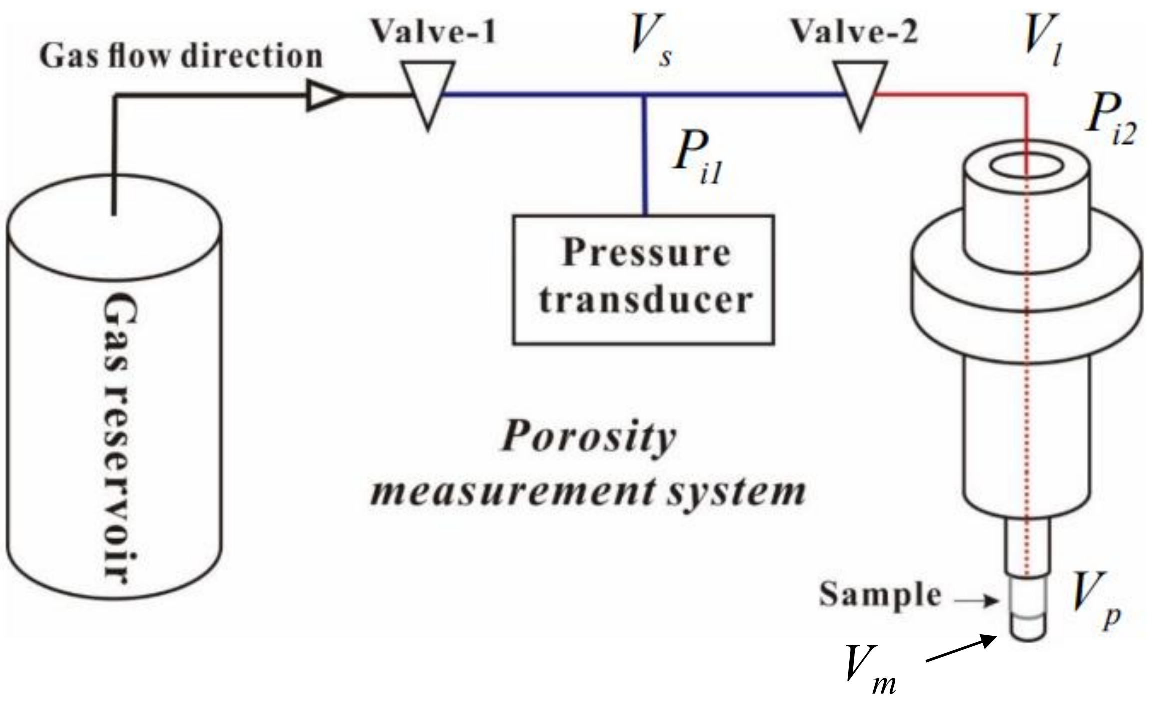


Fig.7 Schematic diagram of porosity measurement system (楊盛博，2015)

Slate

(2) Mechanical aperture measurement of saw-cut slate

Boyle's Law

$$P_{i1} \cdot V_s + P_{i2} \cdot (V_l + V_j + V_m) = P_f \cdot (V_s + V_l + V_j + V_m)$$

$$E = \frac{V_j}{A_{SC}}$$

P_{i1} ： The pressure when the gas flows into V_s (MPa)
P_{i2} ：One atmospheric pressure (MPa)
P_f ： Balance air pressure (MPa)
V_l ： The volume of the thin tube (mm^3)
V_s ： The volume of confined space (mm^3)
V_j ： The volume of joint (mm^3)
V_m ：The pore volume of perforated metal gaskets(mm^3)
E ： The mechanical aperture of sample (mm)
A_{SC} ： The area of saw-cut (mm^2)

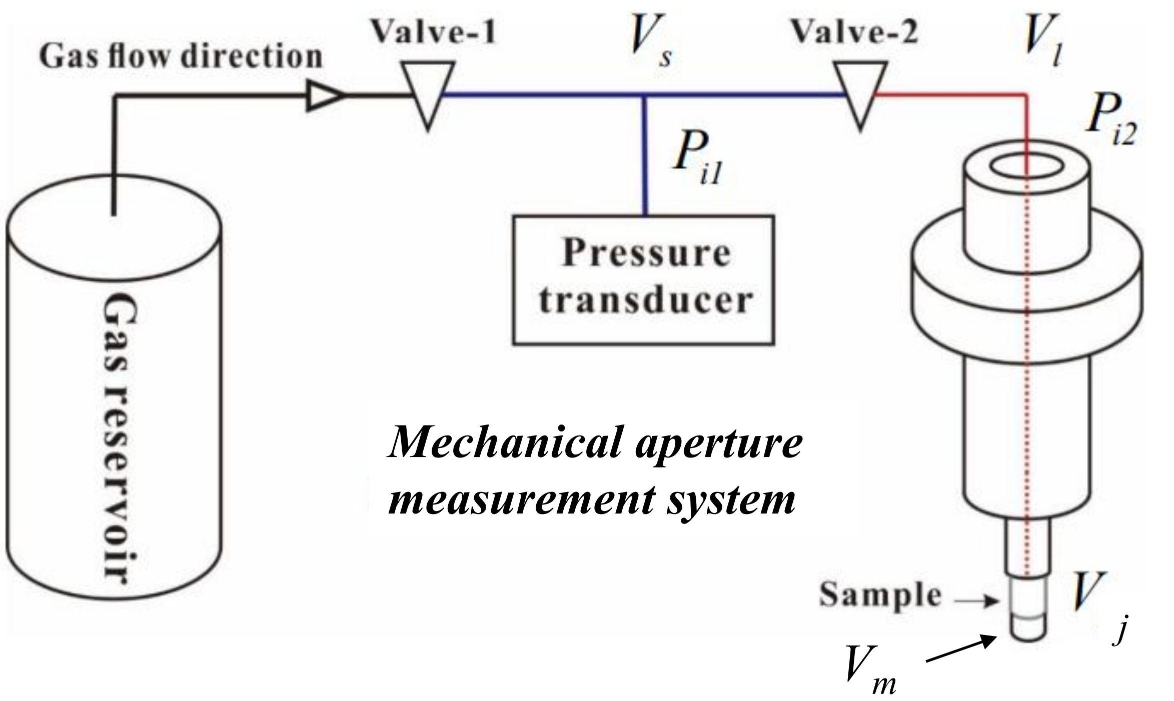


Fig.8 Schematic diagram of mechanical aperture measurement system (楊盛博，2015)

Slate

(3) Permeability and hydraulic aperture measurement of intact and saw-cut slate

Pulse decay

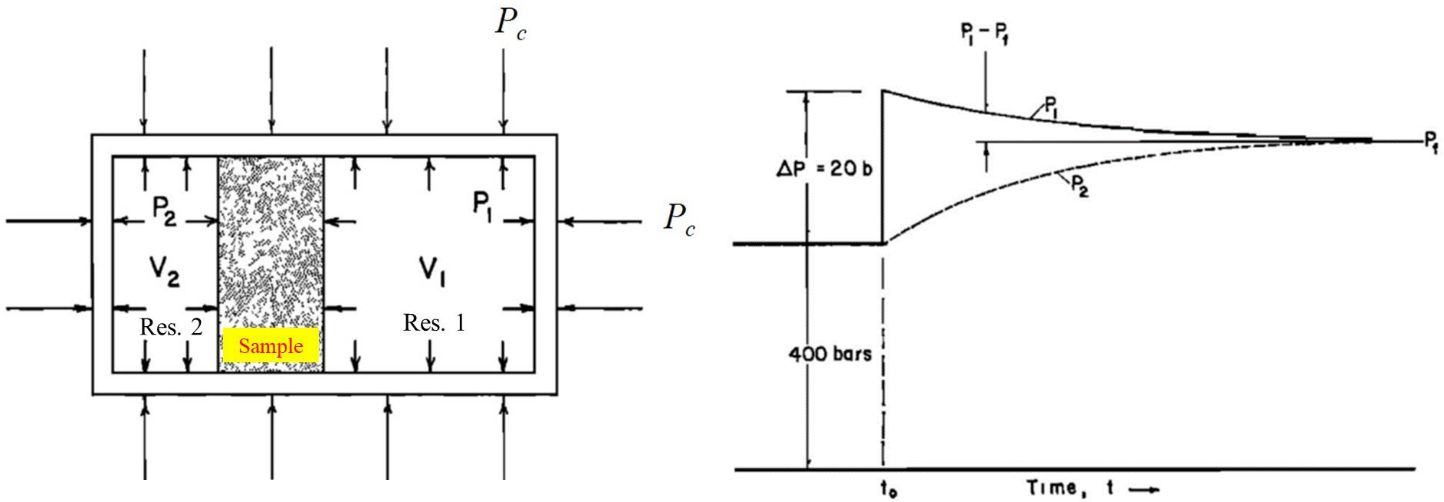


Fig.9 Experiment concept diagram of pulse decay method (Brace et al., 1968)

V_1 : Volume of Reservoir 1 (mm^3)
V_2 : Volume of Reservoir 2 (mm^3)
P_1 : Initial Pressure of Reservoir 1 (MPa)
P_2 : Initial Pressure of Reservoir 2 (MPa)
$P_1'(0)$: The air pressure at the moment the experiment started (MPa)

P_c : Confining Pressure (MPa)
Res. 1 : Reservoir 1
Res. 2 : Reservoir 2

Before experiment , confirm $P_1 = P_2$

↓

Driving pressure pulse into Res. 1

↓ $P_1 > P_2$ Gas flow from Res. 1 to Res. 2

Recording the decay curve of P_1 over time.

↓

The pressure balance , $P_1 = P_2$

↓

Deducing permeability and hydraulic aperture

Sandstone

(1) Porosity of intact sandstone

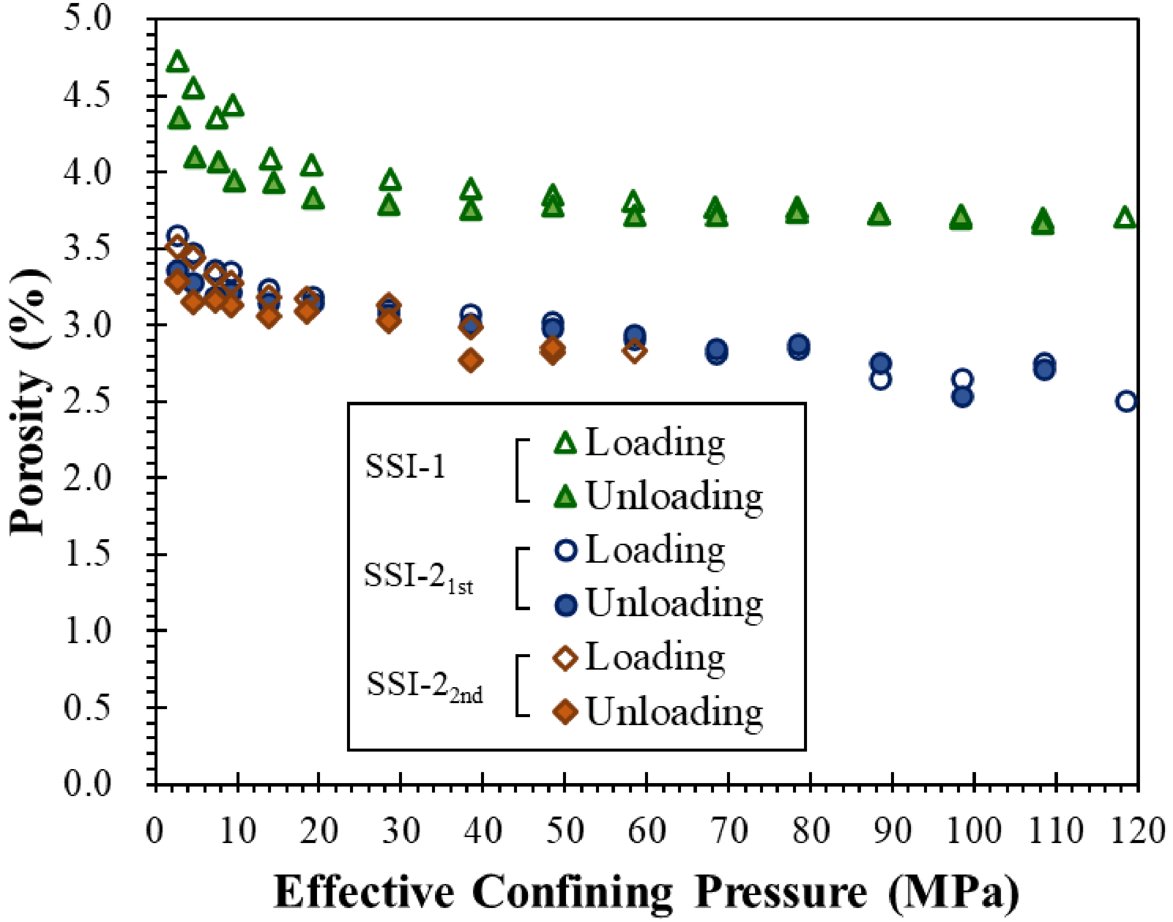


Fig.10 The porosity of SSI-1 and SSI-2

SSI-1

Φ = 25.5 mm
L = 7.8 mm

SSI-2

Φ = 25.7 mm
L = 39.3 mm

Φ ：Diameter of sample、L ：length of sample

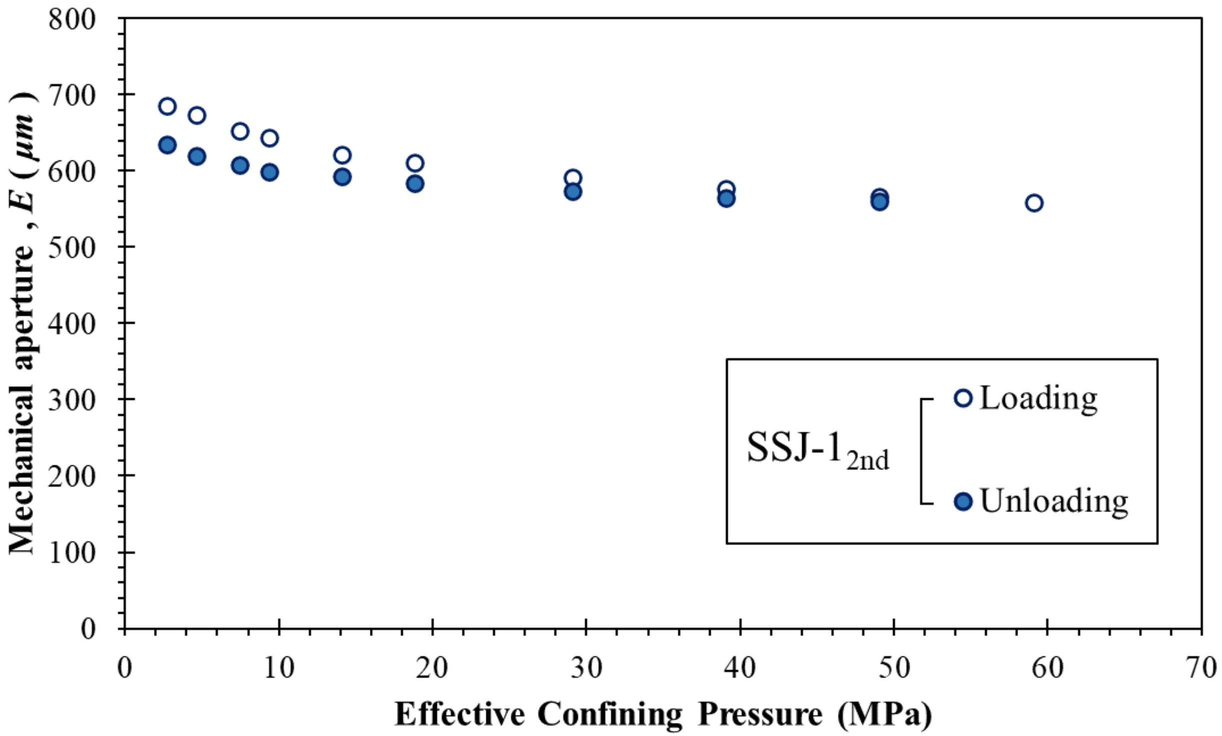
Sandstone

(2) Mechanical aperture of the sandstone joint

SSJ-1

Φ = 25.5 mm
L = 34.9 mm
A_j= 812.4 mm

Φ : Diameter of sample
L : Length of sample
A_j : The area of joint



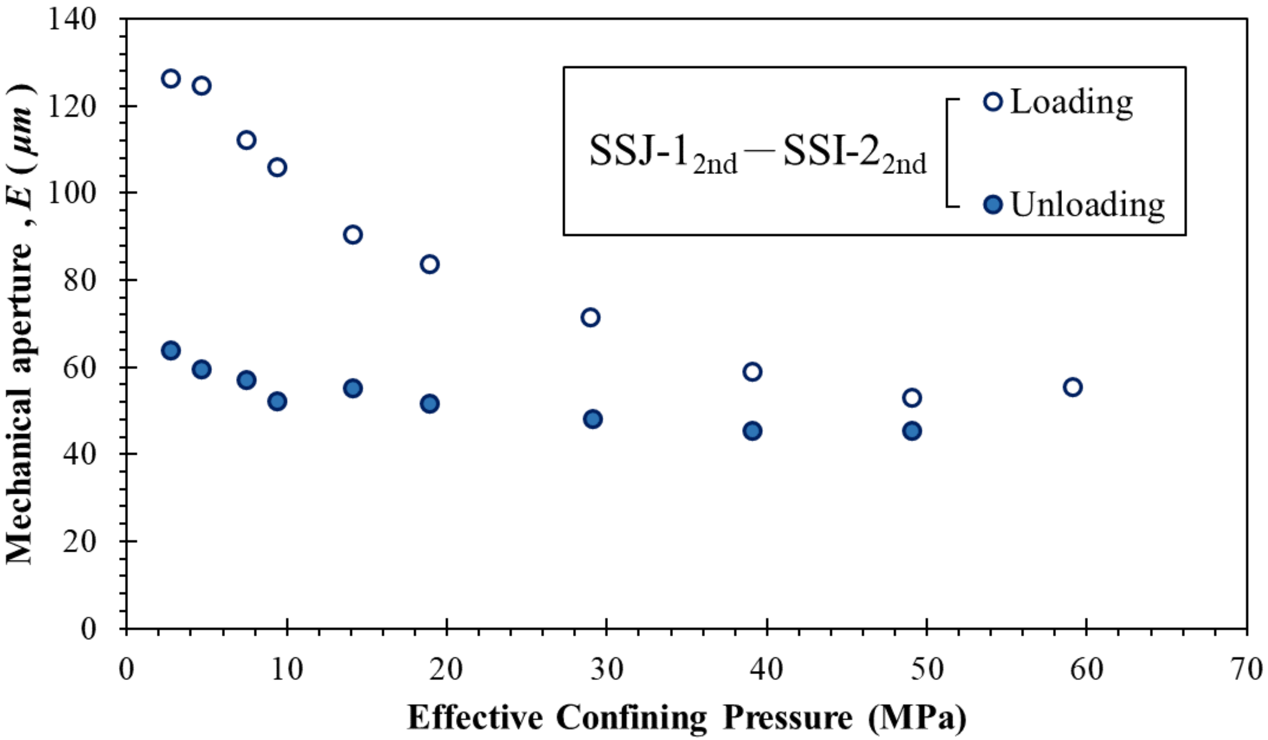


Fig.11 The mechanical aperture of SSJ-1. Uncorrected (left) and corrected (right)

Sandstone

(3) Permeability of intact sandstone

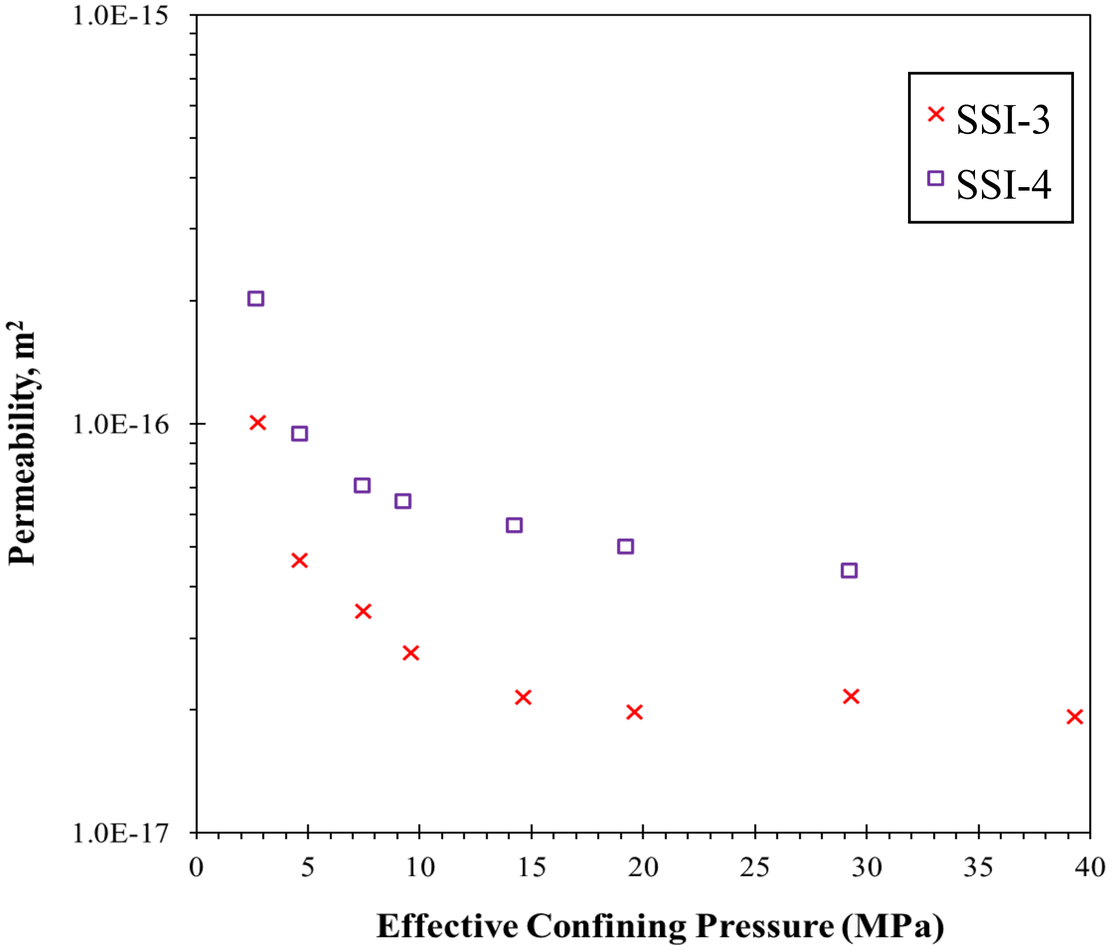


Fig.12 The permeability of SSI-3 and SSI-4

SSI-3

Φ = 25.5 mm
L = 11.7 mm

SSI-4

Φ = 25.5 mm
L = 11.7 mm

Φ ：Diameter of sample、L ：length of sample

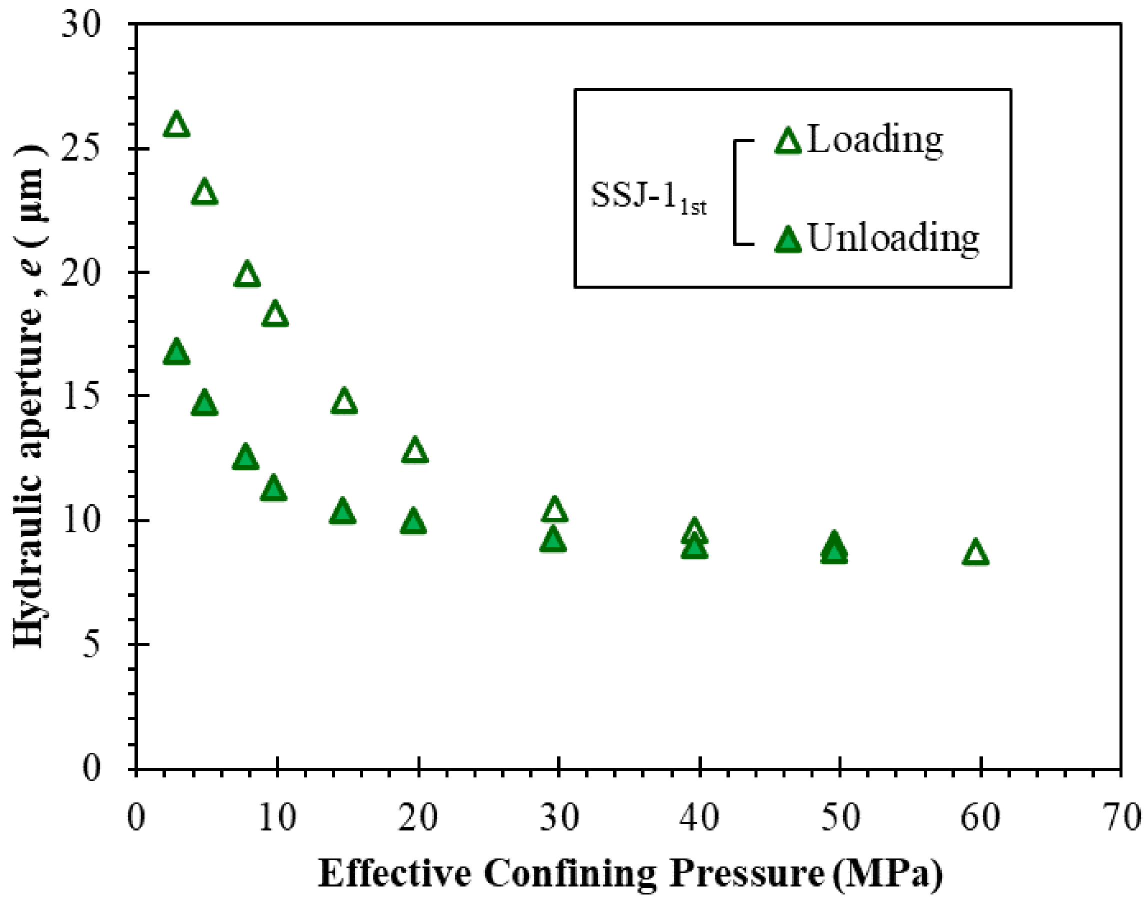
Sandstone

(4) Hydraulic aperture of the sandstone joint

SSJ-1

Φ = 25.5 mm
L = 34.9 mm
A_j= 812.4 mm

Φ ：Diameter of sample
L ：Length of sample
A_j ：The area of joint



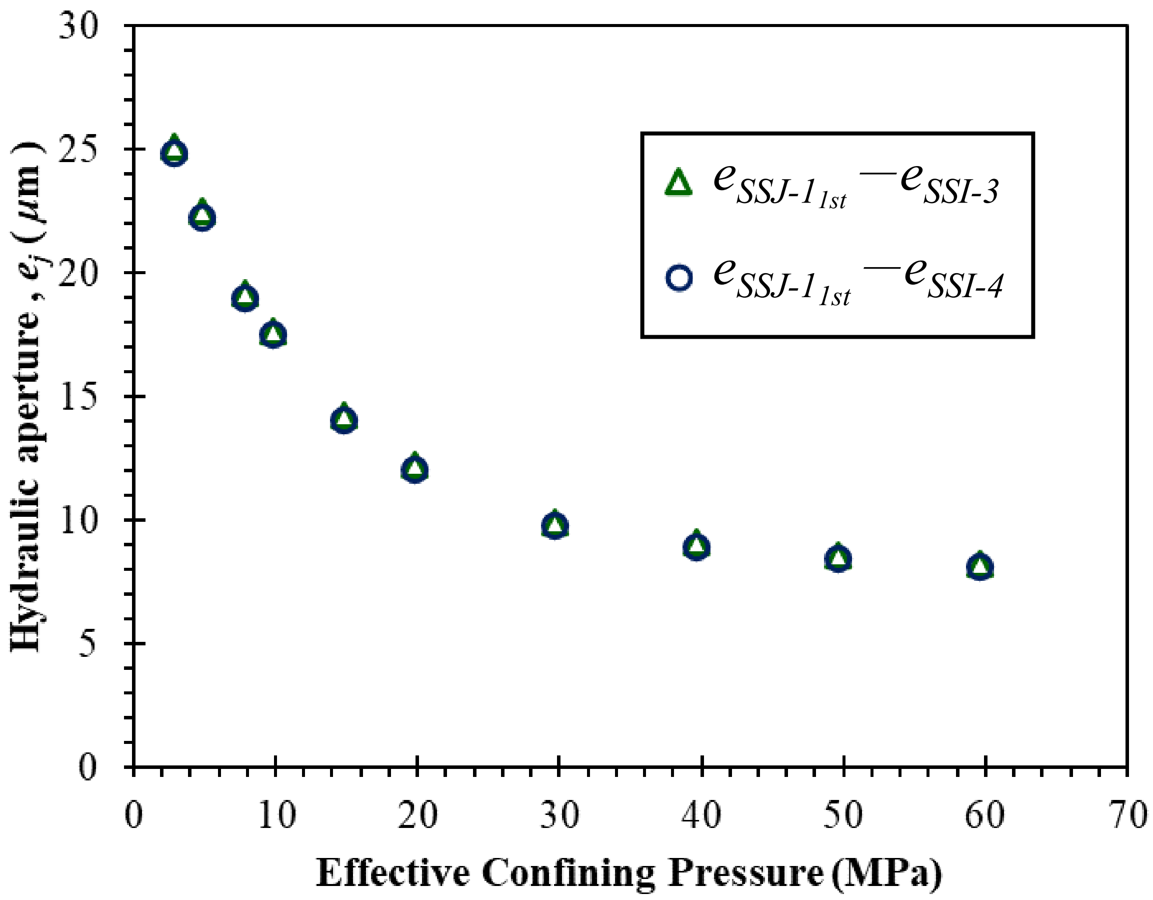
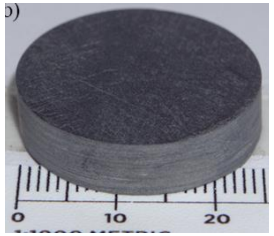


Fig.13 The hydraulic aperture of SSJ-1. Uncorrected (left) and corrected (right)

Slate

(1) Porosity of intact slate

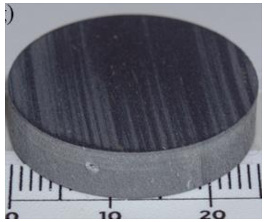


Perpendicular foliation

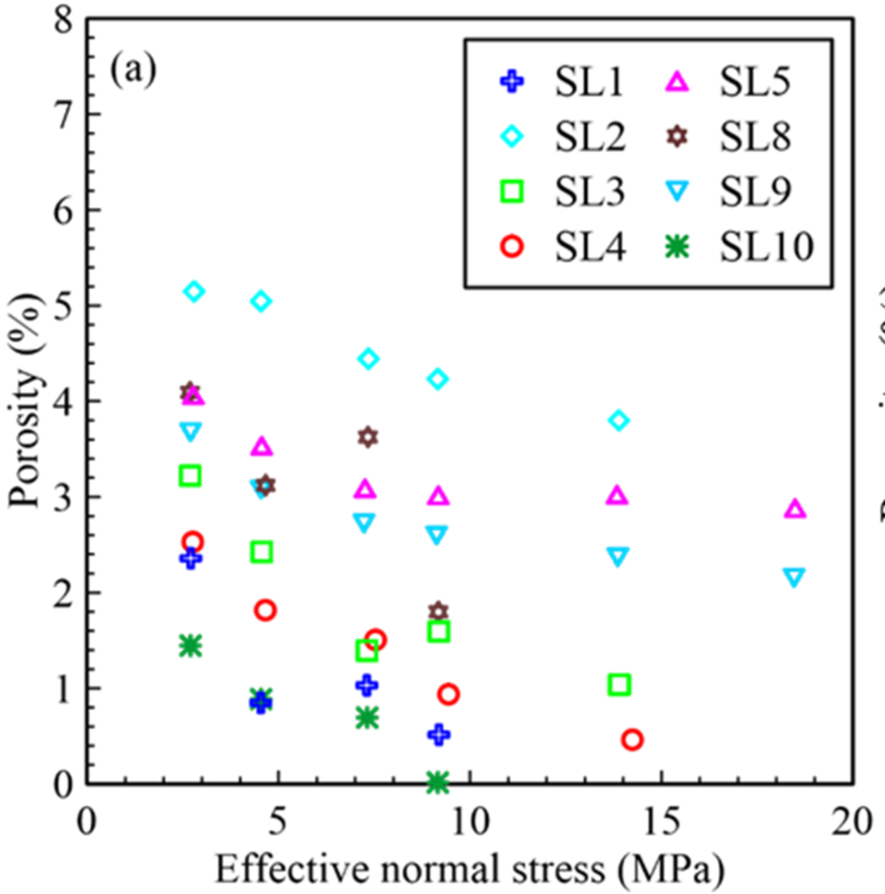
$SL_{\perp}1\sim8$: $\Phi = 25.5mm$、$L = 5\sim12mm$

$SL_{//}1\sim4$: $\Phi = 25.5mm$、$L = 5\sim12mm$

Φ : Diameter of sample、L : Length of sample



Parallel foliation



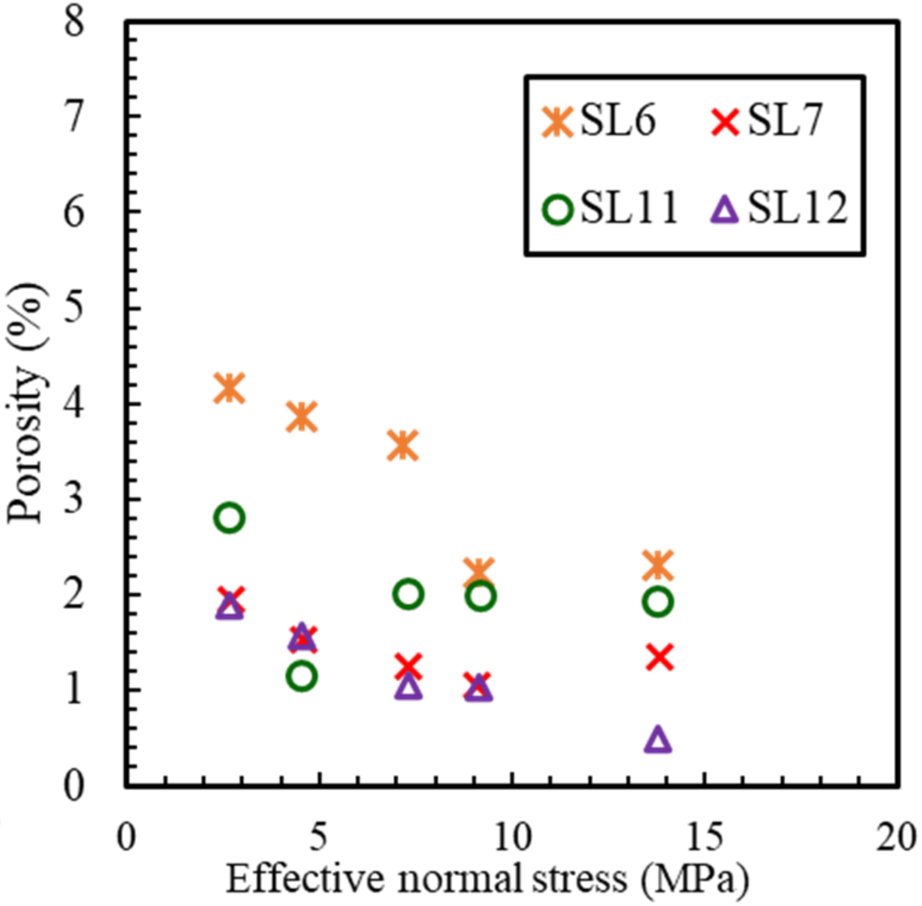


Fig.14 The porosity of perpendicular foliation (left) and parallel foliation (right)

Slate

(2) Mechanical aperture of saw-cut slate

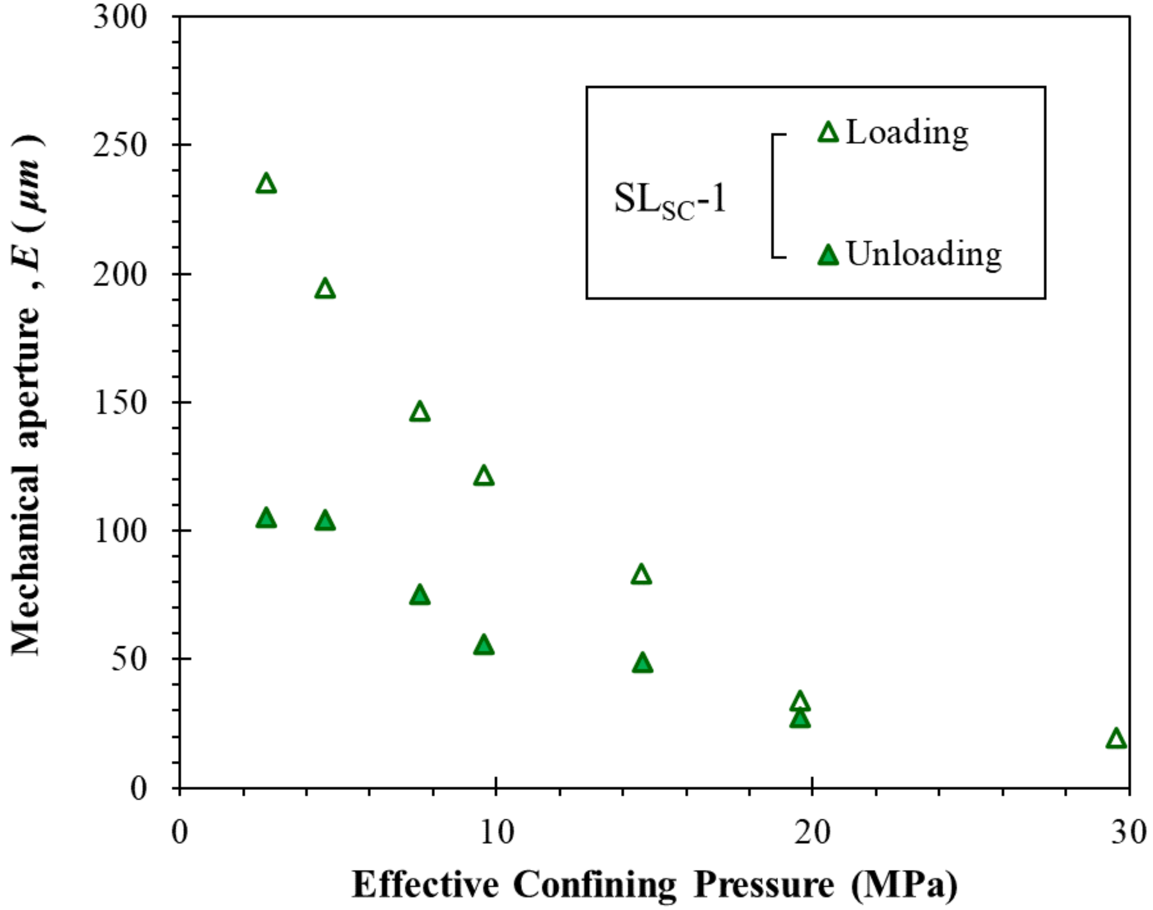
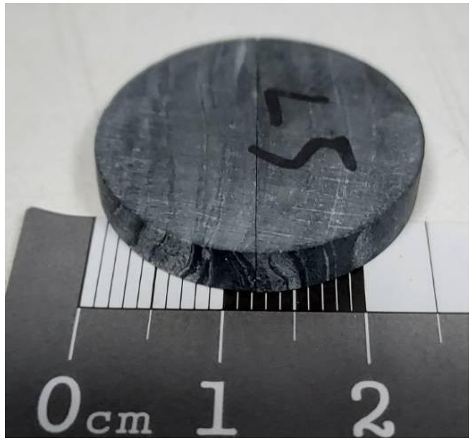


Fig.15 The mechanical aperture of SL_{SC}-1



SL_{SC}-1

Φ = 25.7 mm
L = 5 mm
A_{SC} = 106.1 mm

Φ ：Diameter of sample
L ：Length of sample
A_{SC} ：The area of saw-cut

Slate

(2) Mechanical aperture of saw-cut slate

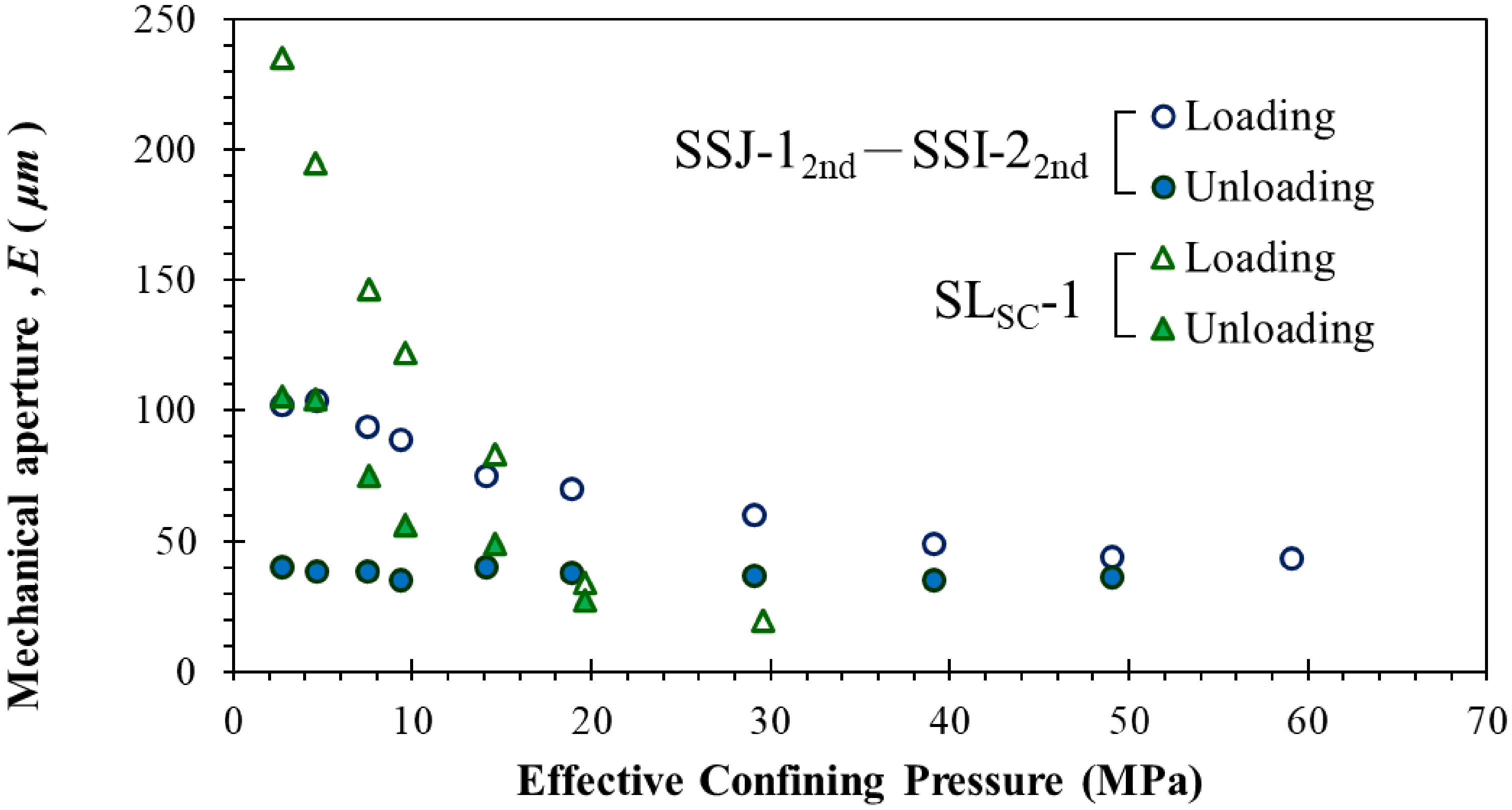
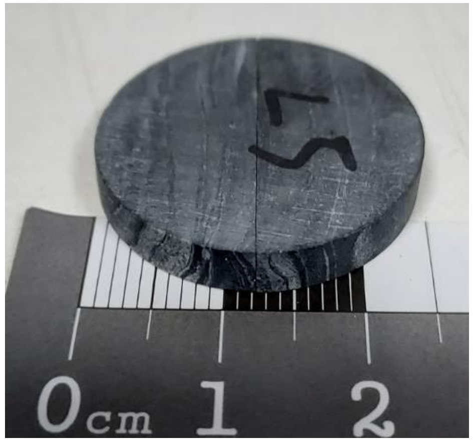


Fig.16 The mechanical aperture of SL_{SC}-1 and SSJ-1



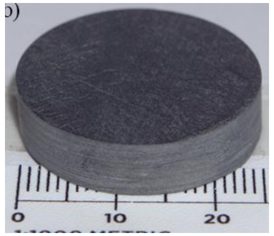
SL_{SC}-1

Φ = 25.7 mm
L = 5 mm
A_{SC} = 106.1 mm

Φ : Diameter of sample
L : Length of sample
A_{SC} : The area of saw-cut

Slate

(3) Permeability of intact slate

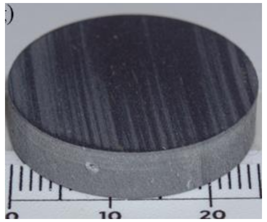


Perpendicular foliation

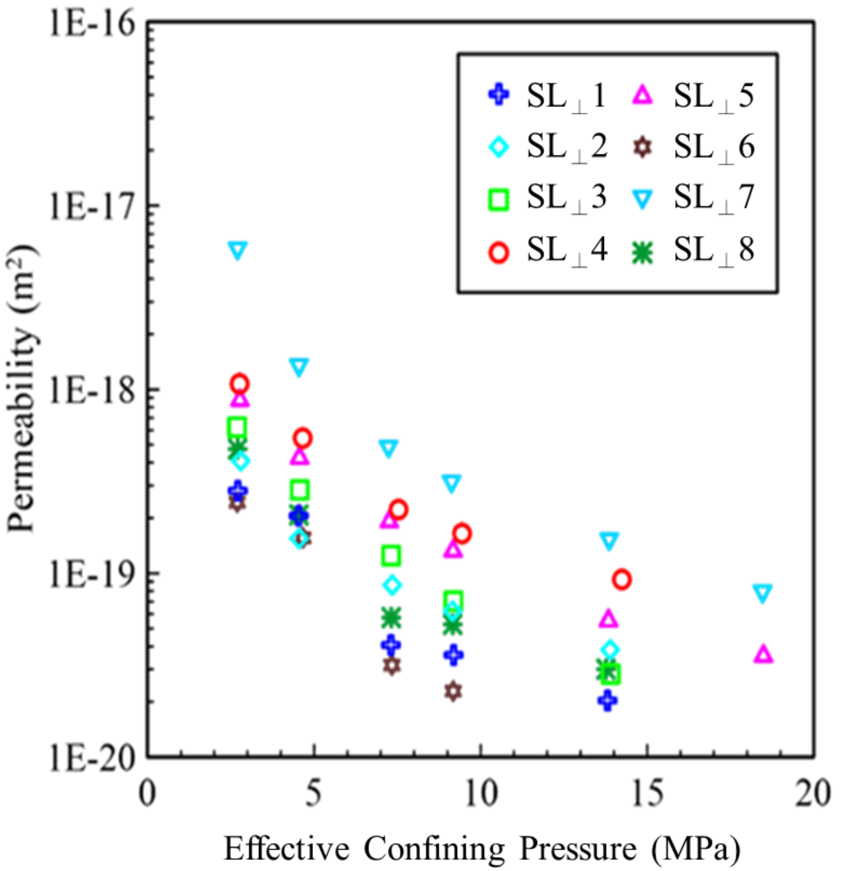
$SL_{\perp}1\sim8$: $\Phi = 25.5mm$ 、 $L = 5\sim12mm$

$SL_{//}1\sim4$: $\Phi = 25.5mm$ 、 $L = 5\sim12mm$

Φ : Diameter of sample、L : Length of sample



Parallel foliation



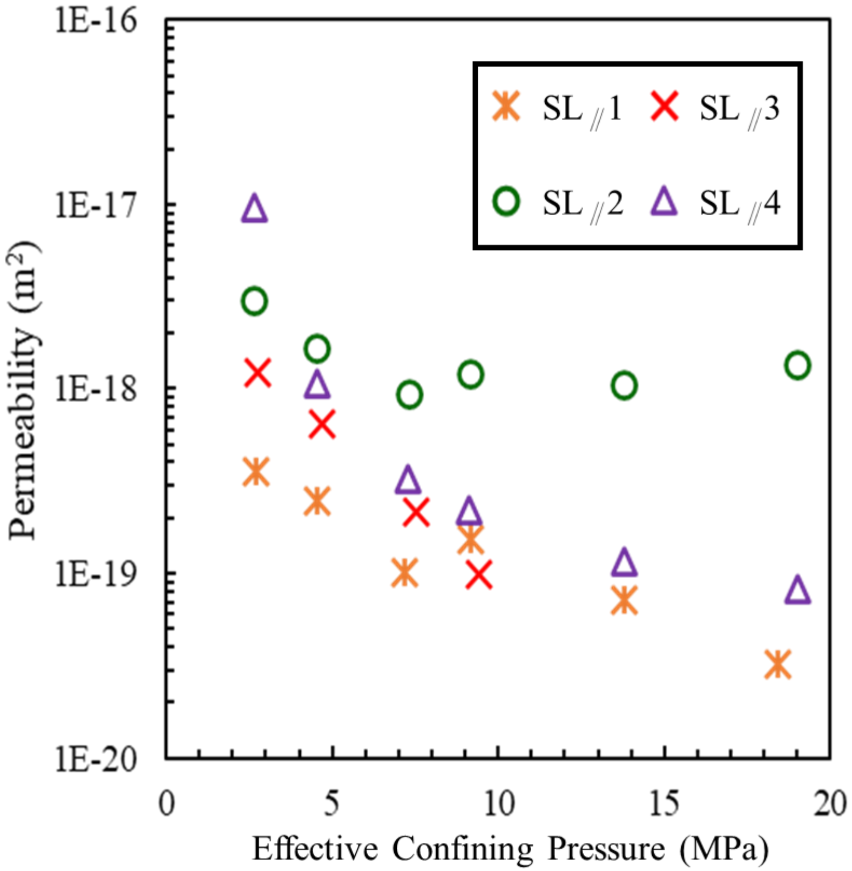


Fig.17 The permeability of perpendicular foliation (left) and parallel foliation (right)

Slate

(4) Hydraulic aperture of saw-cut slate

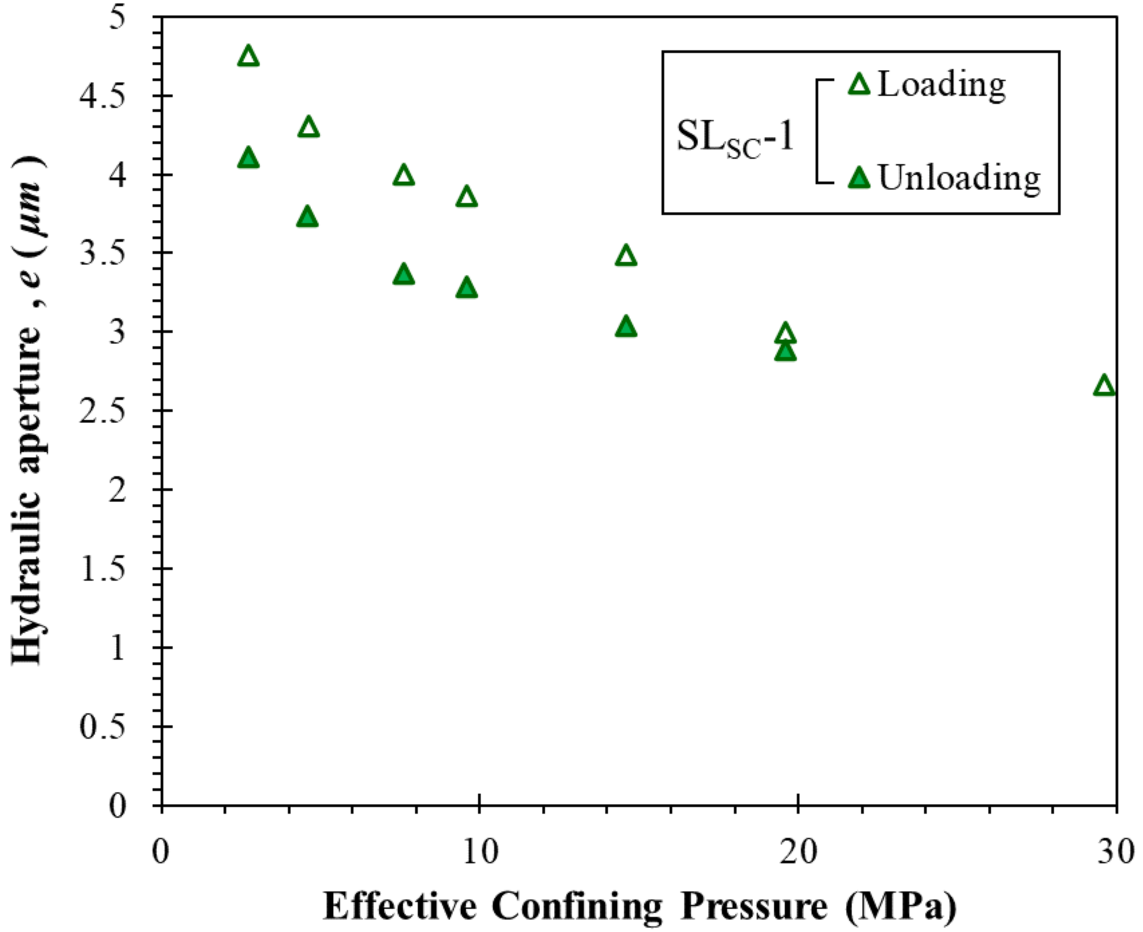
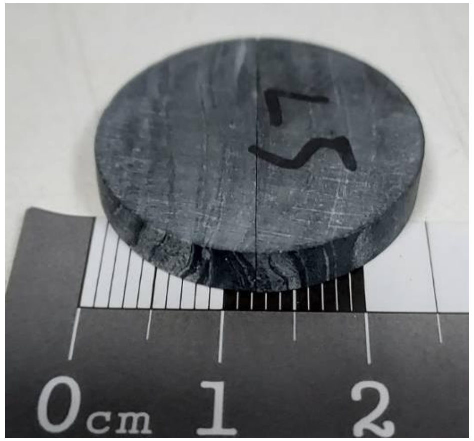


Fig.18 The hydraulic aperture of SL_{SC}-1



SL_{SC}-1

Φ = 25.7 mm

L = 5 mm

A_{SC} = 106.1 mm

Φ：Diameter of sample

L：Length of sample

A_{SC} ：The area of saw-cut

Slate

(4) Hydraulic aperture of saw-cut slate

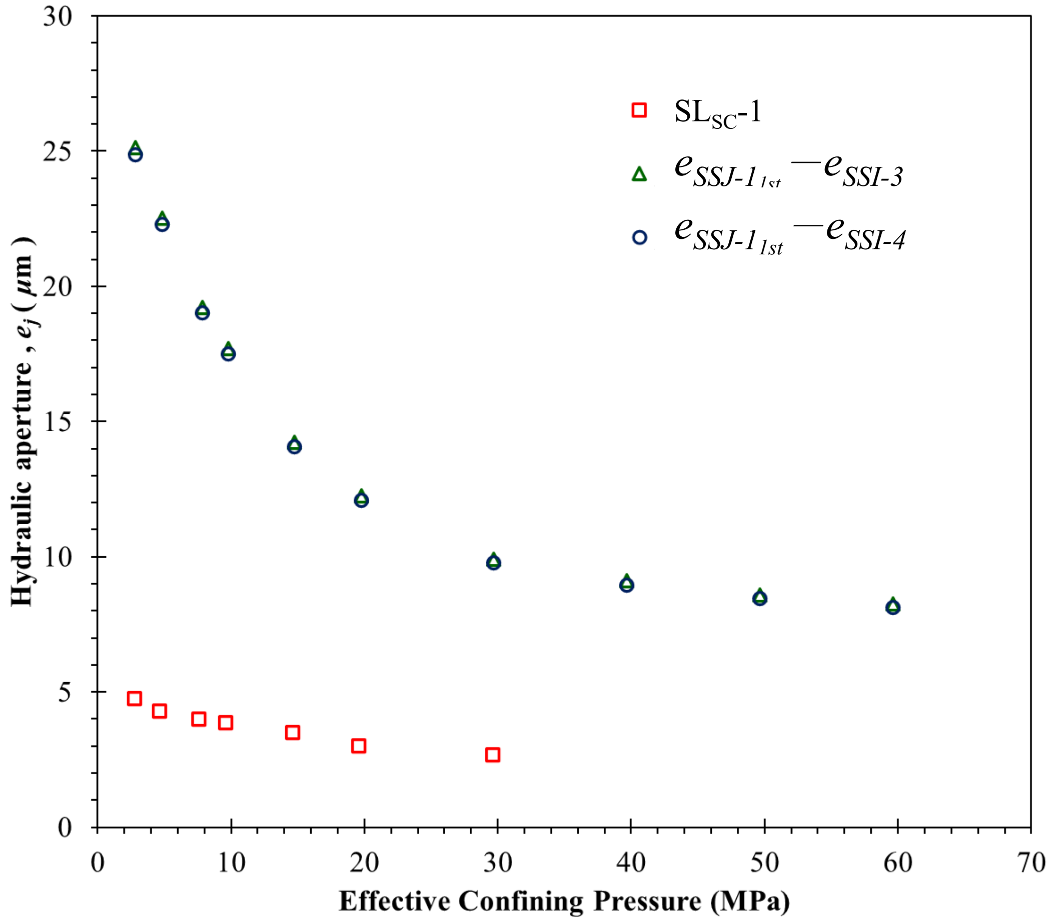
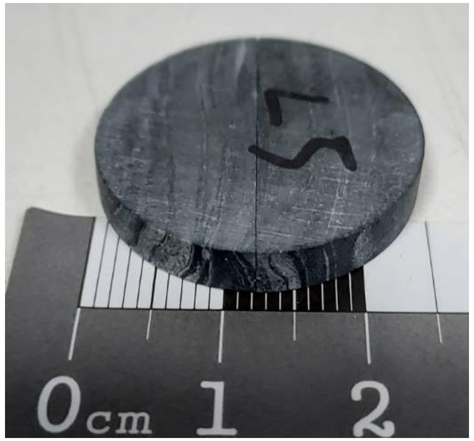


Fig.19 The hydraulic aperture of SL_{SC}-1 and SSJ-1



SL_{SC}-1

Φ = 25.7 mm

L = 5 mm

A_{SC} = 106.1 mm

Φ ：Diameter of sample

L ：Length of sample

A_{SC} ：The area of saw-cut

1. In general, the porosity and permeability of intact sandstone are greater than of intact slate, especially the permeability of intact sandstone, which is higher by 1 to 3 orders of magnitude compared to intact slate.
2. Generally, the permeability of slate in the parallel foliation is greater than that in the perpendicular foliation.
3. Although the mechanical aperture of saw-cut slate is greater than that of sandstone joints at effective pressure below 15 MPa , the hydraulic aperture of saw-cut slate is less than that of sandstone joints. Therefore, the efficiency of geothermal power generation using saw-cut slate would be smaller.
4. To sum up, considering only lithology, if we want to use geothermal power to generate electricity, the power generation efficiency of Datun Volcanic Group will be greater than that of Hongye area.

1. Using scanning electron microscopy (SEM) to observe the foliation density of slate and different materials can help explain the differences in porosity and permeability among different types of slate.

2. The mechanical aperture and hydraulic aperture of tensile fracture slate were measured and compared with saw-cut slate.

3. Using steady state method to measure the hydraulic aperture of saw-cut slate and compare with pulse decay method.

Thank you for your attention

(1) Determine total volume Vtt
(2) Determine intact volume Vm
(3) Determine rock joint volume Vj = Vtt - Vm

Sandstone

(2) Mechanical aperture measurement of sandstone joints

Boyle's law

$$P_{i1} \cdot V_s + P_{i2} \cdot (V_l + V_j) = P_f \cdot (V_s + V_l + V_j)$$

$$E = \frac{V_j}{A_j}$$

P_{i1} : The pressure when the gas flows into V_s (MPa)
P_{i2} : One atmospheric pressure (MPa)
P_f : Balance air pressure (MPa)
V_l : The volume of the thin tube (mm^3)
V_s : The volume of confined space (mm^3)
V_j : The volume of joint (mm^3)
E : The mechanical aperture of sample (mm)
A_j : The area of joint (mm^2)

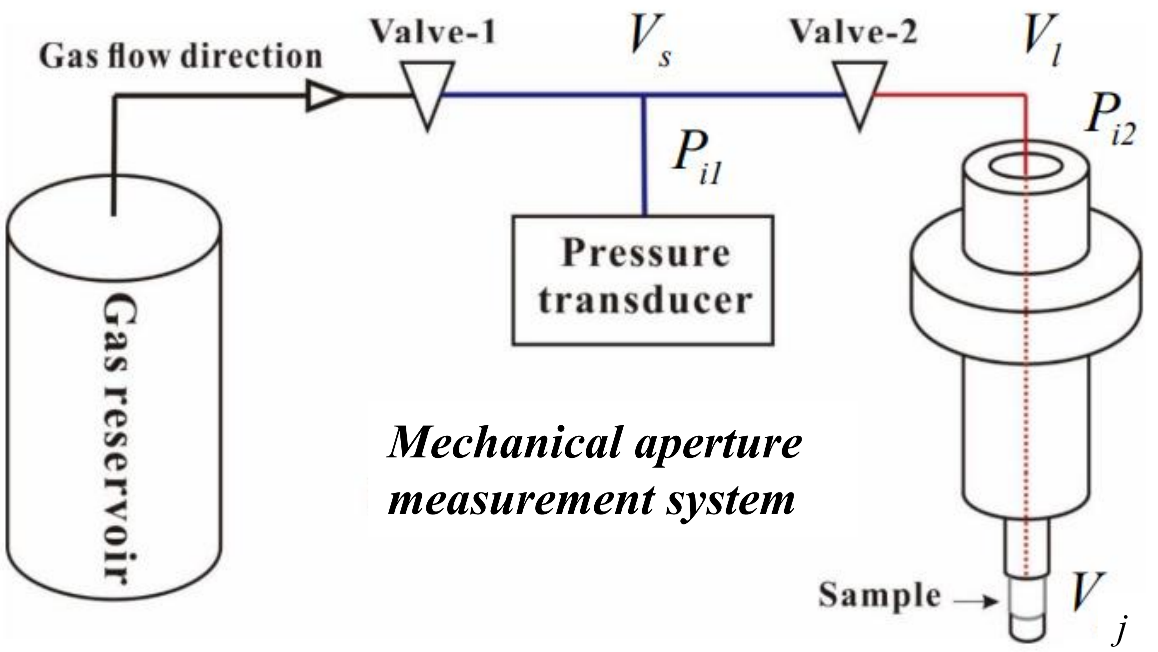


Fig. Schematic diagram of mechanical aperture measurement system (楊盛博，2015)

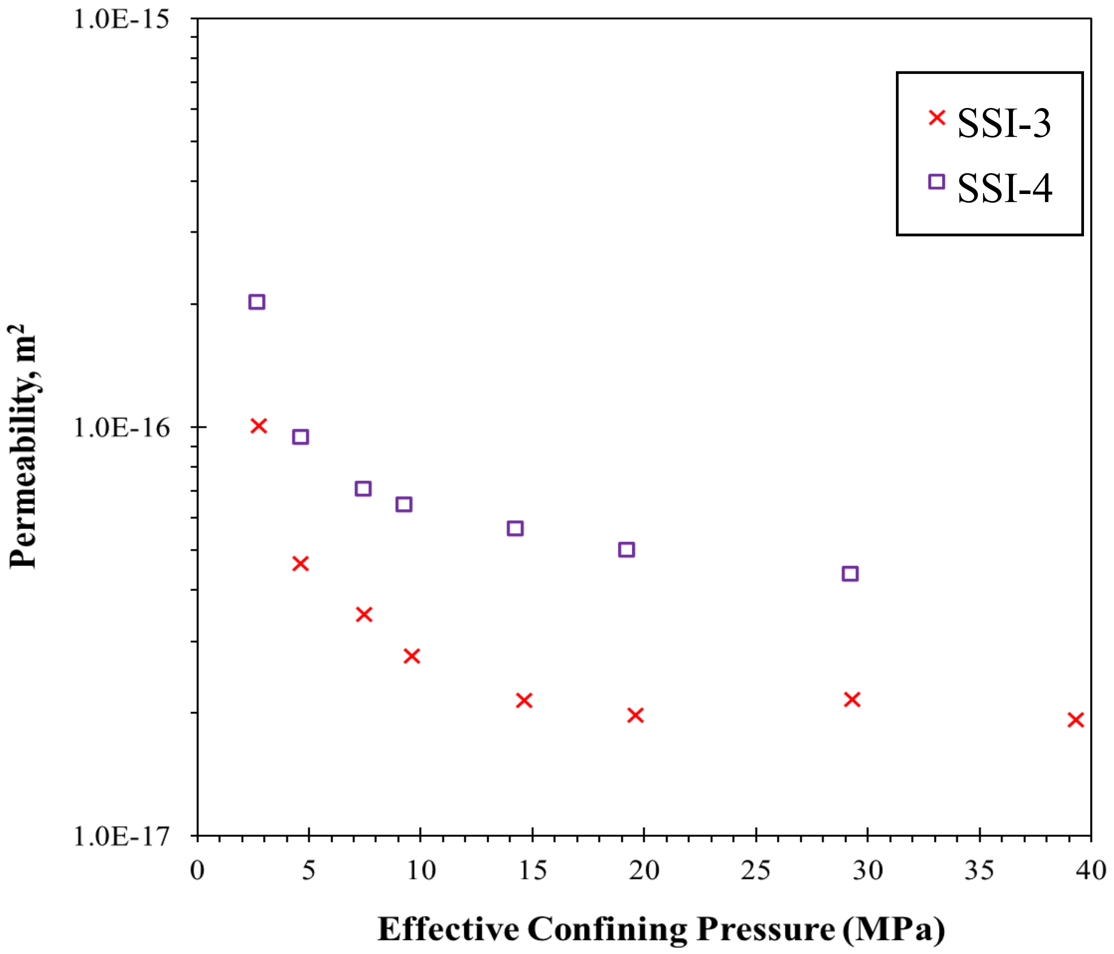


Fig. The permeability of sandstones for SSI-3 and SSI-4

$$k = \frac{e^2}{12}$$

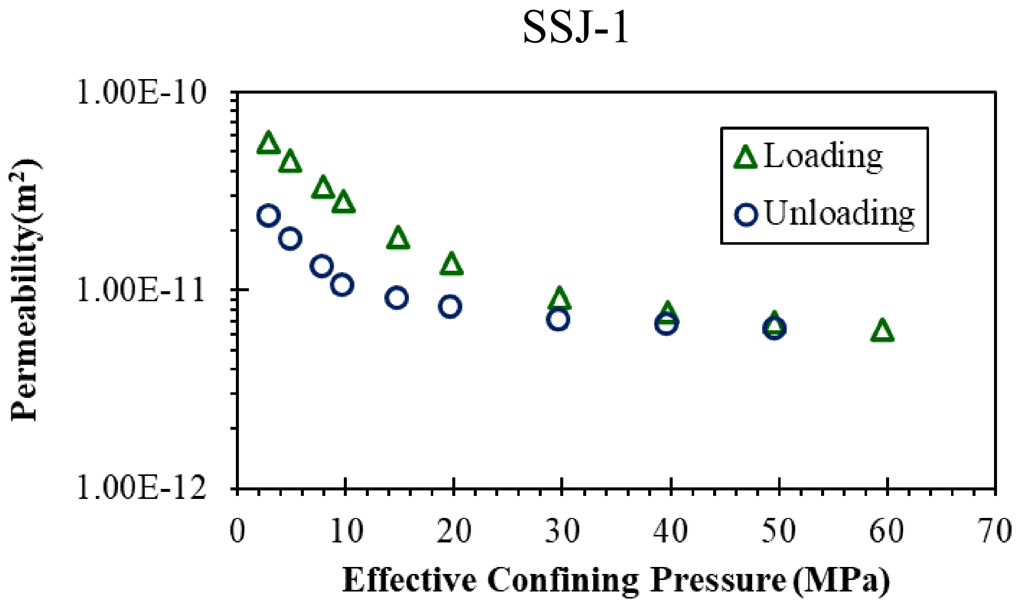


Fig. The permeability of sandstones for SSJ-1

Equivalent hydraulic aperture of intact sandstones

$$e_{eqi} = \sqrt[3]{\frac{12kA_{cs}}{w}}$$

e_{eqi} ：Equivalent hydraulic aperture (mm)
k：Permeability of intact sample (m^2)
A_{cs}： Cross-sectional area of intact sample (mm^2)
w： Diameter of intact sample (mm)

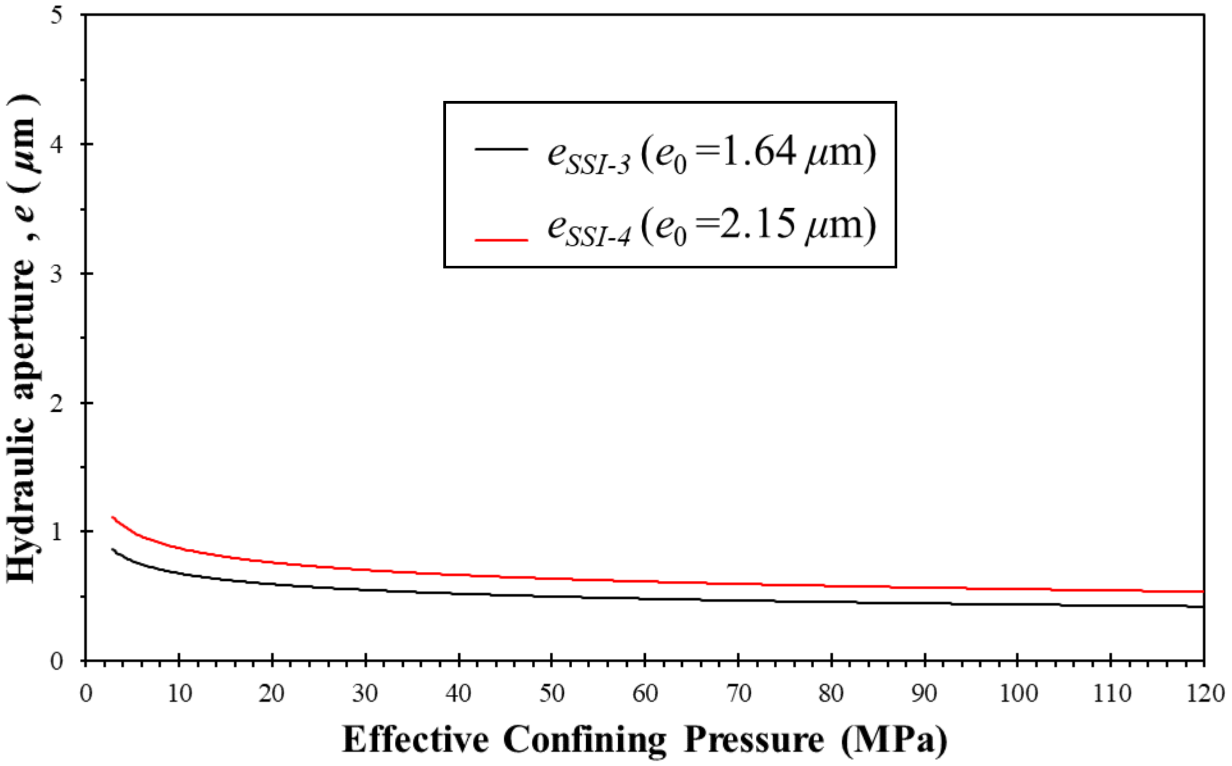


Fig. Curve fitting of the equivalent hydraulic aperture of intact sandstone for SSI-3 and SSI-4

$$e = e_0 \left(\frac{P_e}{P_0}\right)^{-p}$$

e : Hydraulic aperture
e_0 : The hydraulic aperture under atmospheric pressure
P_e : Effective confining pressure
P_0 : Atmospheric pressure
p : Material constant

Sample number	Hydraulic aperture		
	Power law $e = e_0 \left(\frac{P_e}{P_0}\right)^{-p}$		
	$e_0 (\mu m)$	p	R^2
SSJ-1	105.06	0.394	0.9791
SSI-3	1.64	0.191	0.8495
SSI-4	2.15	0.196	0.8835

e : Hydraulic aperture
e_0 : The hydraulic aperture under atmospheric pressure
P_e : Effective confining pressure
P_0 : Atmospheric pressure
p : Material constant

Fig. Curve fitting of the hydraulic aperture of jointed sandstone for SSJ-1 and the equivalent hydraulic aperture of intact sandstone for SSI-3 and SSI-4

Contribution of intact rock to hydraulic aperture

P_e ：Effective confining pressure
e_{SSJ-1} ： Hydraulic aperture of SSJ-1
e_{SSI-3} ：The equivalent hydraulic aperture of SSI-3
e_{SSI-4} ：The equivalent hydraulic aperture of SSI-4

Table. Hydraulic apertures of each sandstone sample under different effective pressures

Pe	e_{SSJ-1}(μm)	e_{SSI-3}(μm)	e_{SSI-4}(μm)	e_{SSI-3}/e_{SSJ-1}	e_{SSI-4}/e_{SSJ-1}
2.85	25.98	0.86	1.12	3.32%	4.30%
4.86	23.30	0.78	1.01	3.34%	4.32%
7.84	19.94	0.71	0.92	3.57%	4.60%
9.83	18.38	0.68	0.88	3.70%	4.77%
14.78	14.86	0.63	0.81	4.24%	5.44%
19.76	12.85	0.60	0.76	4.64%	5.95%
29.71	10.47	0.55	0.71	5.26%	6.74%
39.67	9.63	0.52	0.67	5.42%	6.92%
49.62	9.10	0.50	0.64	5.49%	7.01%
59.60	8.74	0.48	0.62	5.52%	7.04%

$$k_{gas} = \frac{2Q\mu_g L}{A} \times \frac{P_d}{P_u^2 - P_d^2} \Rightarrow Q = \frac{k_{gas}A}{\mu_g} \times \frac{\Delta P}{L}$$

$$\frac{\Delta P}{L} = \frac{P_u^2 - P_d^2}{2LP_d}$$

$$Q = \frac{e^3 w}{12\mu_g} \times \frac{\Delta P}{L}$$

$$\frac{k_{gas}A}{\mu_g} \times \frac{\Delta P}{L} = \frac{e^3 w}{12\mu_g} \times \frac{\Delta P}{L}$$

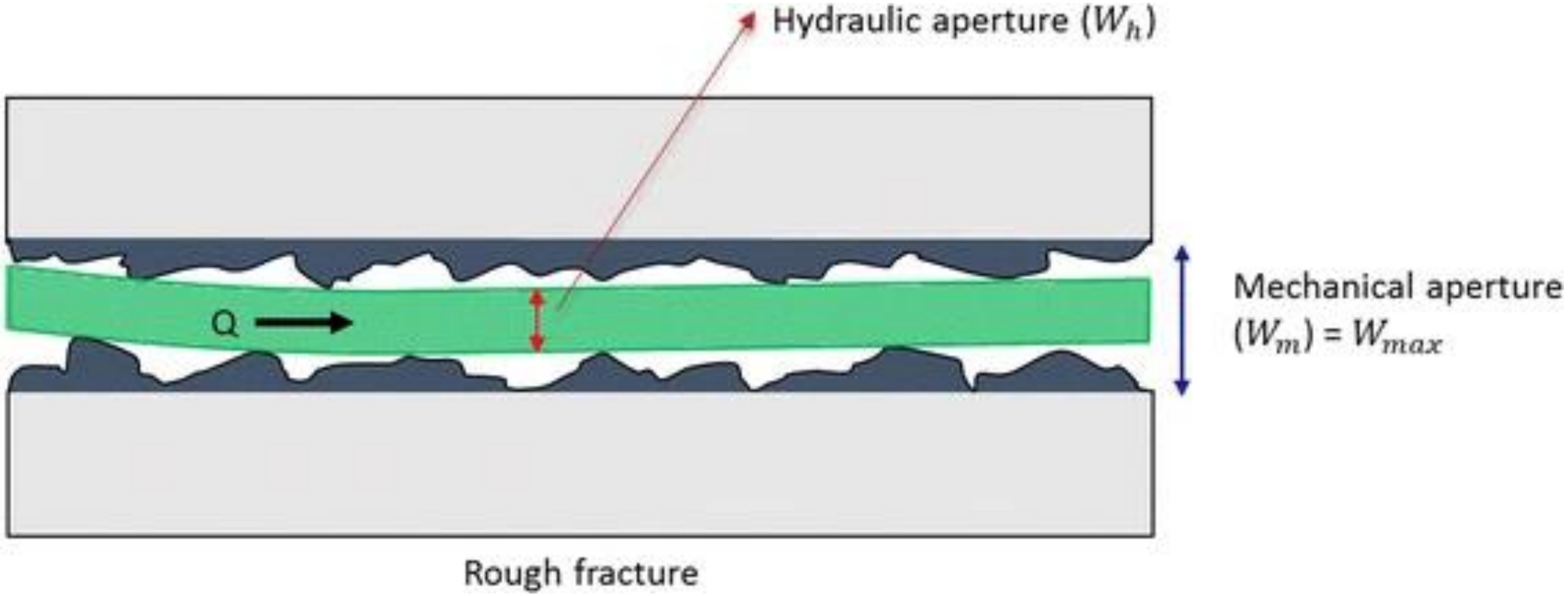


Fig. A schematic illustration of fracture hydraulic and mechanical apertures with flow (Q) passing through them