Geological Storage and Fluid Flow Characteristics of Geothermal Reservoirs in Taiwan: A Case Study of the Datun Volcanic Group and Eastern Slates Areas

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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.
- In recent years, the government has begun to conduct investigations to supplement basic information and increase industry investment.
- Geothermal power generation must meet three conditions:

1. Adequate heat source
2. Water
3. Channels for fluids to flow through a rock mass { Joint plane / Foliation plane }

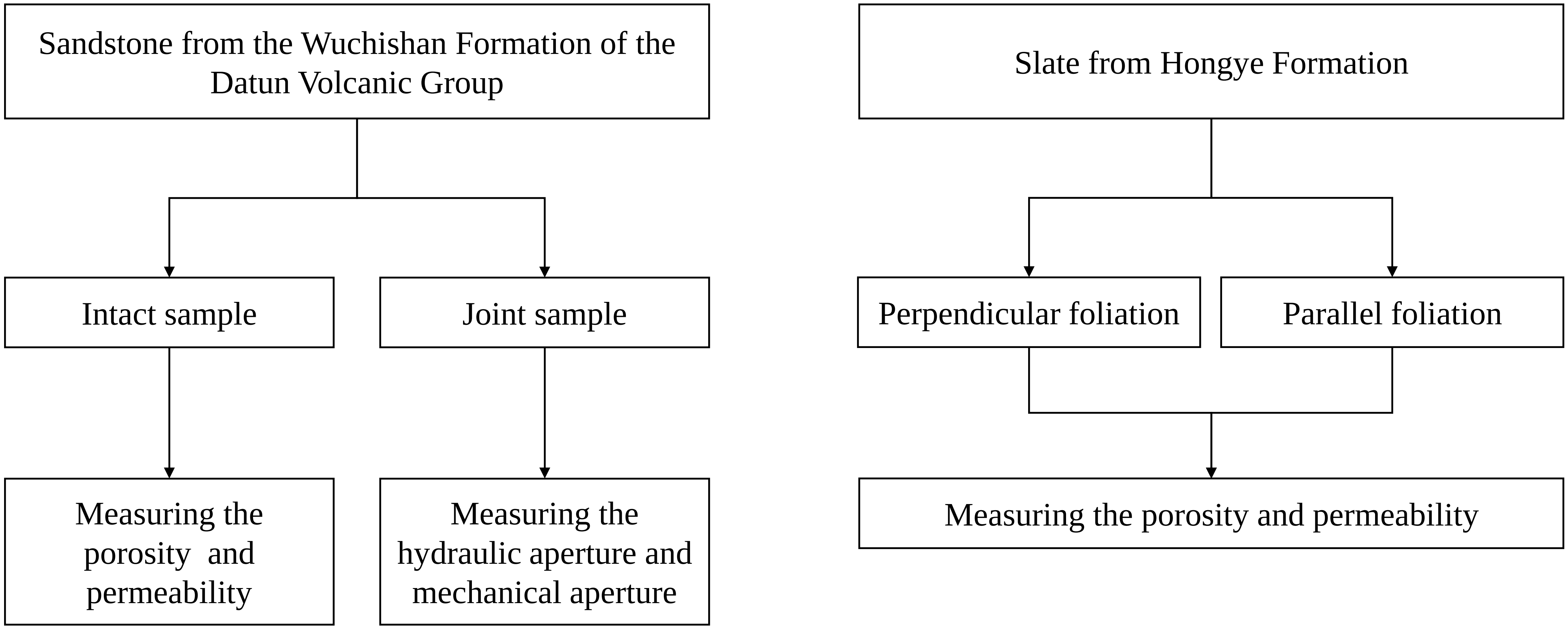


Fig.1 Experiment flow diagram

Table.1 Introduction of slate samples

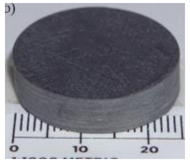
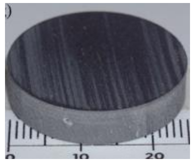
Formation	Sample	Sample number	Sample size	Drilling orientation	Depth	Sample figure
Hongye	Slate	SL1~5 SL8~10	Φ = 25.5mm L = 5~12mm	foliation-perpendicular (⊥)	200~780m	
		SL6、7 SL11、12		foliation-parallel (∥)		

Table.2 Introduction of sandstones sample

Formation	Sample	Sample number	Sample size	Sample type	Depth	Measure	Sample figure
Wuchishan	Sandstone	S2	Φ = 25.5mm L = 7.8mm	Intact	About 1000m	Porosity	
		S4、S5	Φ = 25.5mm L = 11.7mm			Permeability	
		F1	Φ = 25.5mm L = 34.9mm	Jointed		Hydraulic & Machenical aperture	

YOKO2 system

Fig.2 High confining pressure porosity/permeability measuring instrument

Measure →

- Porosity
- Permeability
- Hydraulic aperture
- Machenical aperture

Measuring the porosity of sandstones

Boyle's law

$$P_{i1} \cdot V_s + P_{i2} \cdot (V_l + V_p) = P_f \cdot (V_s + V_l + V_p) \quad \ldots(1)$$

$$\Rightarrow V_p = \left(\frac{P_{i1} - P_f}{P_f - P_{i2}}\right) \cdot V_s - V_l \quad \ldots(2)$$

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

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 (%)

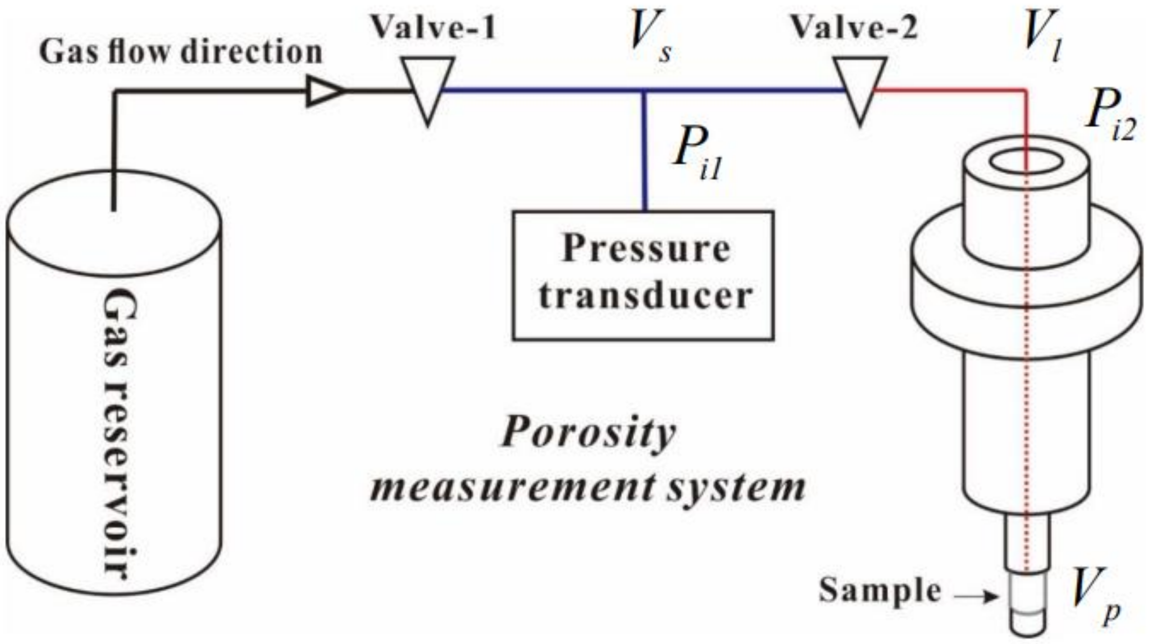


Fig.3 Schematic diagram of porosity measurement system (楊盛博，2015)

Measuring the permeability of sandstones

Steady state method

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

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)

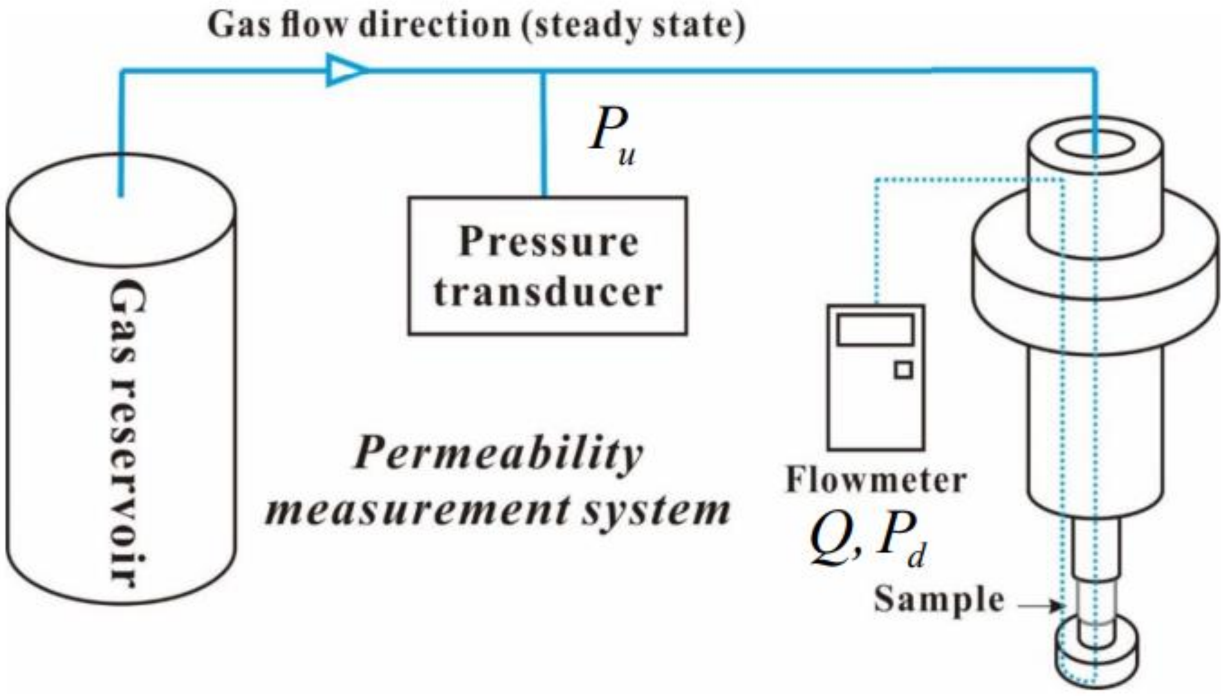


Fig.4 Schematic diagram of permeability measurement system (楊盛博，2015)

Measuring the porosity and permeability of slates

Pulse decay method

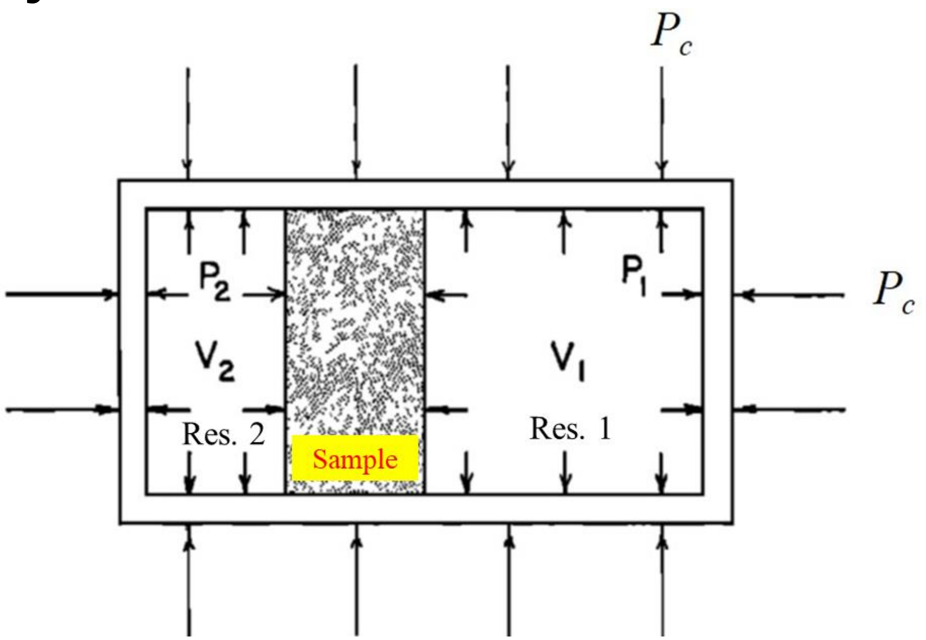
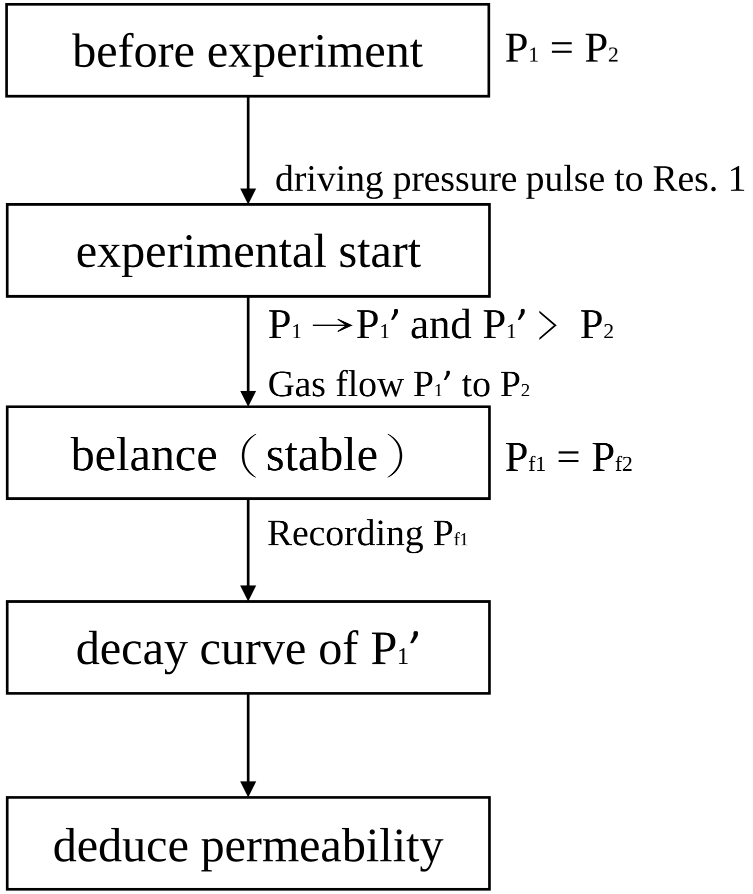


Fig.5 Experiment concept diagram of pulse decay method

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)

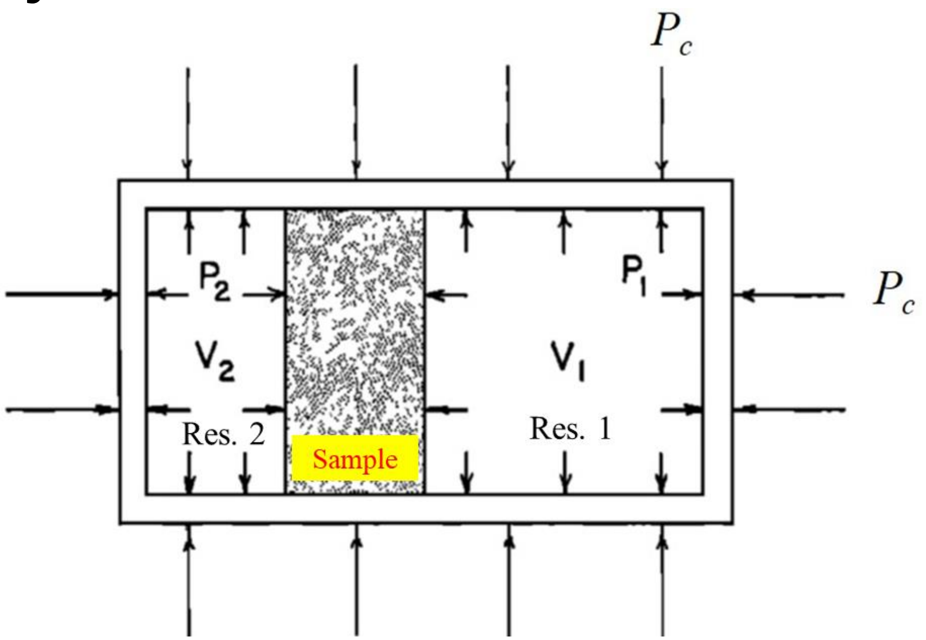
P_c : Confining Pressure (MPa)
Res. 1 : Reservoir 1
Res. 2 : Reservoir 2



P_{f1} : Final Pressure of Reservoir 1
P_{f2} : Final Pressure of Reservoir 2

Measuring the porosity and permeability of slates

Pulse decay method



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V_1 : Volume of Reservoir 1 (mm^3)
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$P_1'(0)$: The air pressure at the moment the experiment started (MPa)
P_c : Confining Pressure (MPa)
Res. 1 : Reservoir 1
Res. 2 : Reservoir 2

porosity

$$P_1'(0) \cdot V_1 + P_2 \cdot (V_2 + V_p) = P_f \cdot (V_1 + V_2 + V_p) \quad \ldots(3)$$

$$\Rightarrow V_p = \left(\frac{P_1'(0) - P_f}{P_f - P_2}\right) \cdot V_1 - V_2 \quad \ldots(4)$$

P_f : Balance air pressure

permeability

$$P_1 - P_f = \Delta P \left(\frac{V_2}{V_1} + V_2\right) e^{-\alpha t} \quad \ldots(5)$$

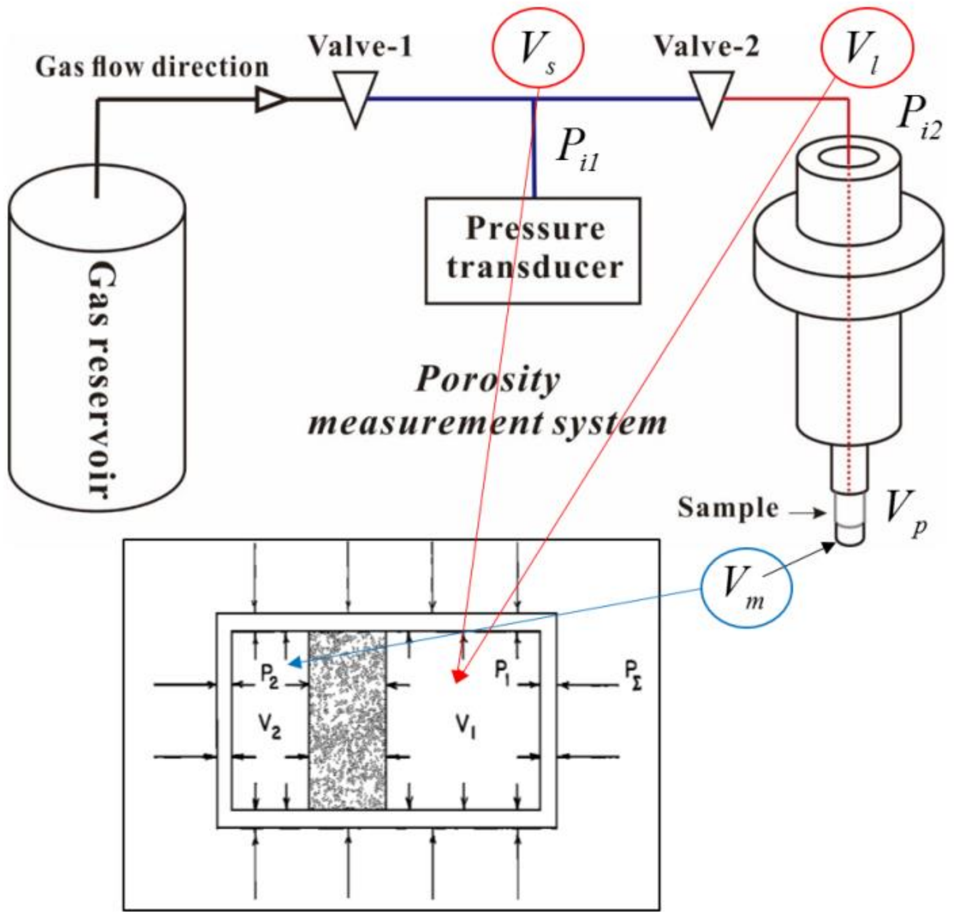
ΔP : $P_1'(0) - P_2$ $\quad t$: Time (s)

$$\alpha = \frac{k_{gas} A}{\mu_g \beta L}\left(\frac{1}{V_1} + \frac{1}{V_2}\right) \quad \ldots(6)$$

k_{gas} : The gas permeability of sample (m^2)
μ_g : Viscosity coefficient of gas (MPa*s)
L : The length of the sample (m)
A : Cross-sectional area of sample (m^2)
α : Attenuation coefficient
β : Volume compressibility coefficient of gas (MPa^{-1})

Measuring the porosity and permeability of slates

Pulse decay method applied in YOKO2 system



porosity

$$V_p = \left(\frac{P_{i1} - P_f}{P_f - P_{i2}}\right) \cdot V_s - (V_l + V_m) \quad \dots(7)$$

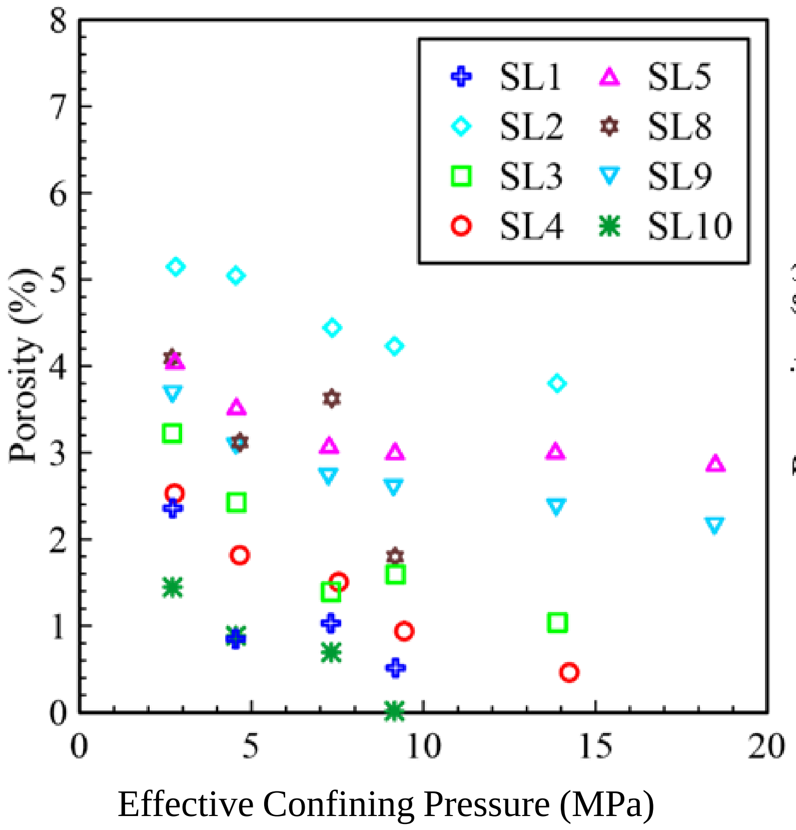
permeability

$$P_{i2} - P_f = \Delta P \left(\frac{V_m}{V_s + V_l} + V_m\right) e^{-\alpha t} \quad \dots(8)$$

$$\alpha = \frac{k_{gas} A}{\mu_g \beta L}\left(\frac{1}{V_s + V_l} + \frac{1}{V_m}\right) \quad \dots(9)$$

Fig.6 Concept diagram of YOKO2 porosity/permeability simultaneous measurement system (戴秉倫，2016)

Porosity of slates



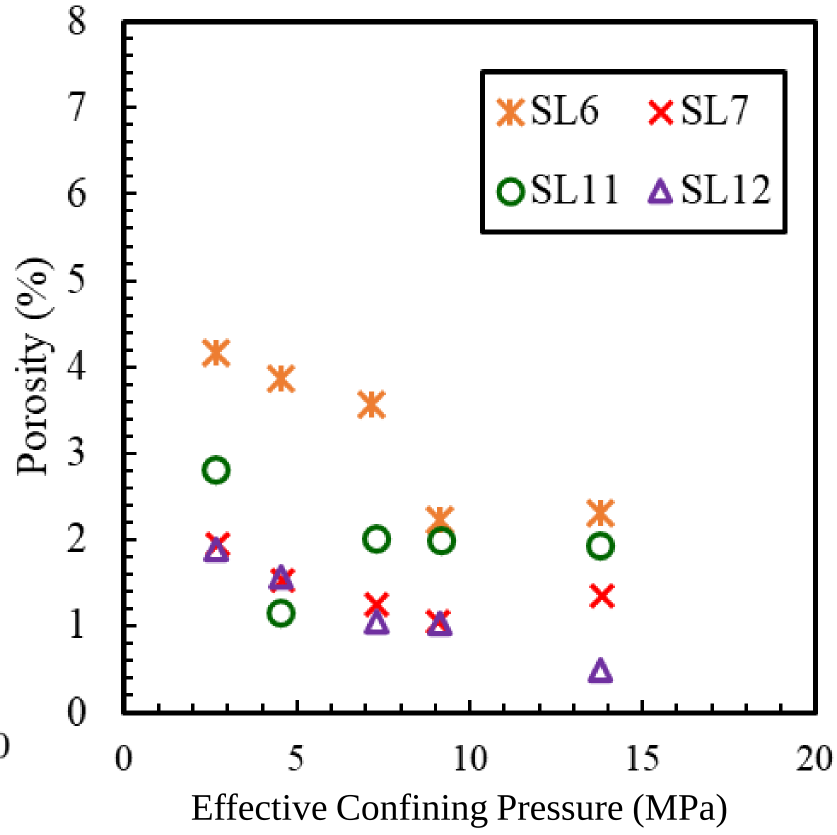


Fig.7 The porosity of foliation-perpendicular (left) and foliation-parallel (right)

Permeability of slates

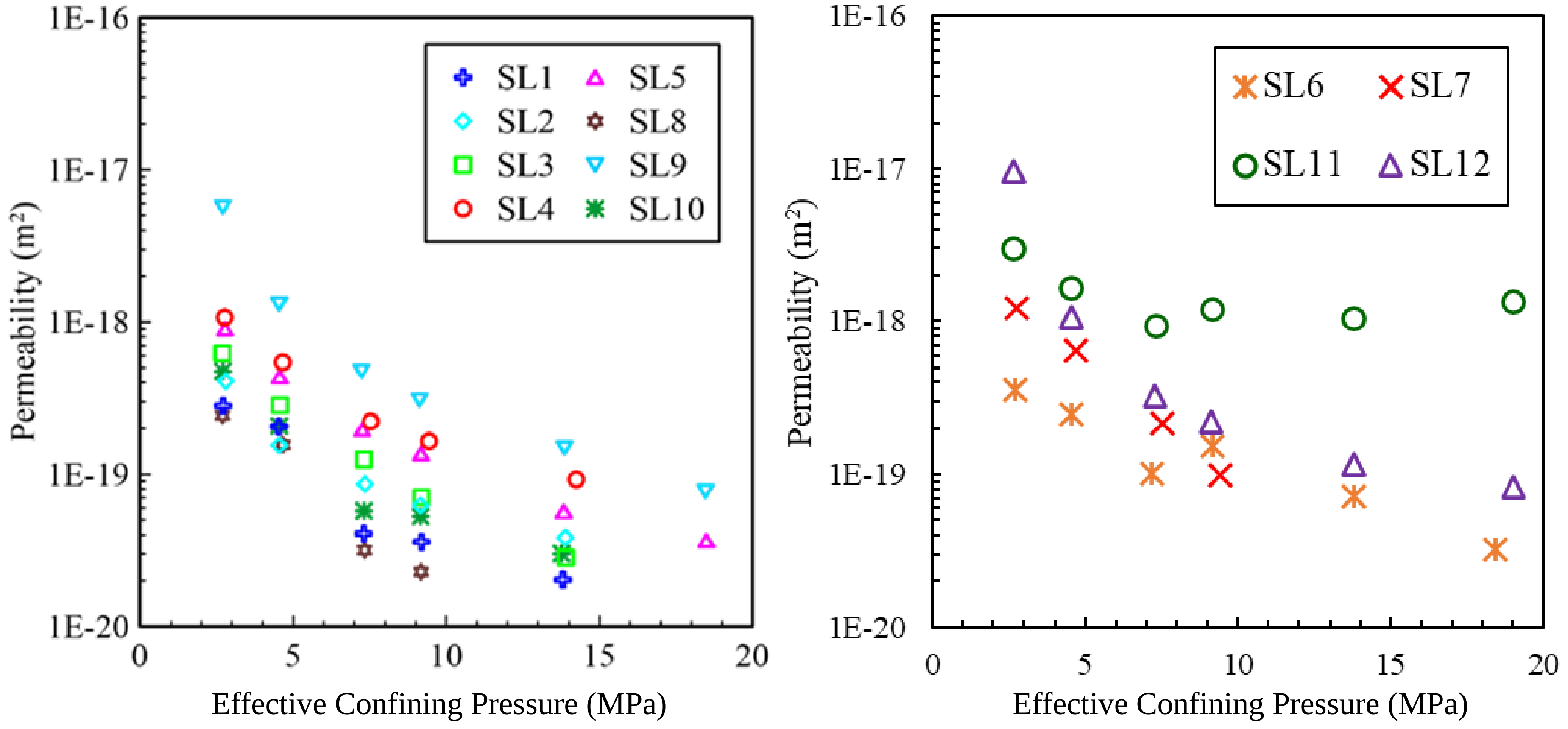


Fig.8 The permeability of foliation-perpendicular (left) and foliation-parallel (right)

Porosity and Permeability of intact sandstones

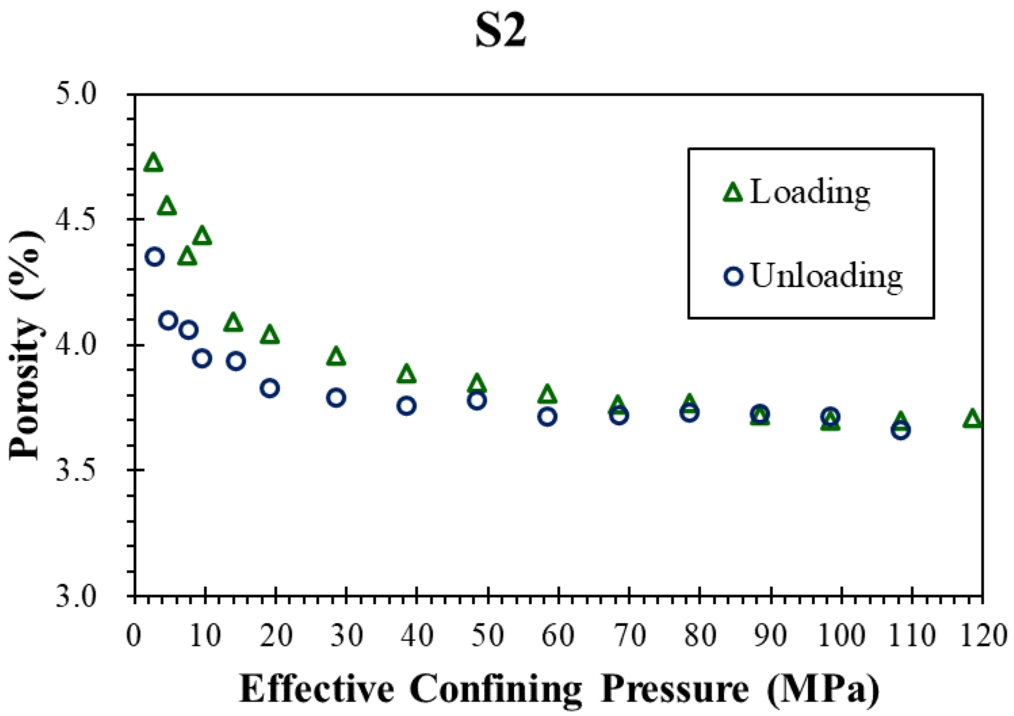


Fig.9 The porosity of sandstones for S2

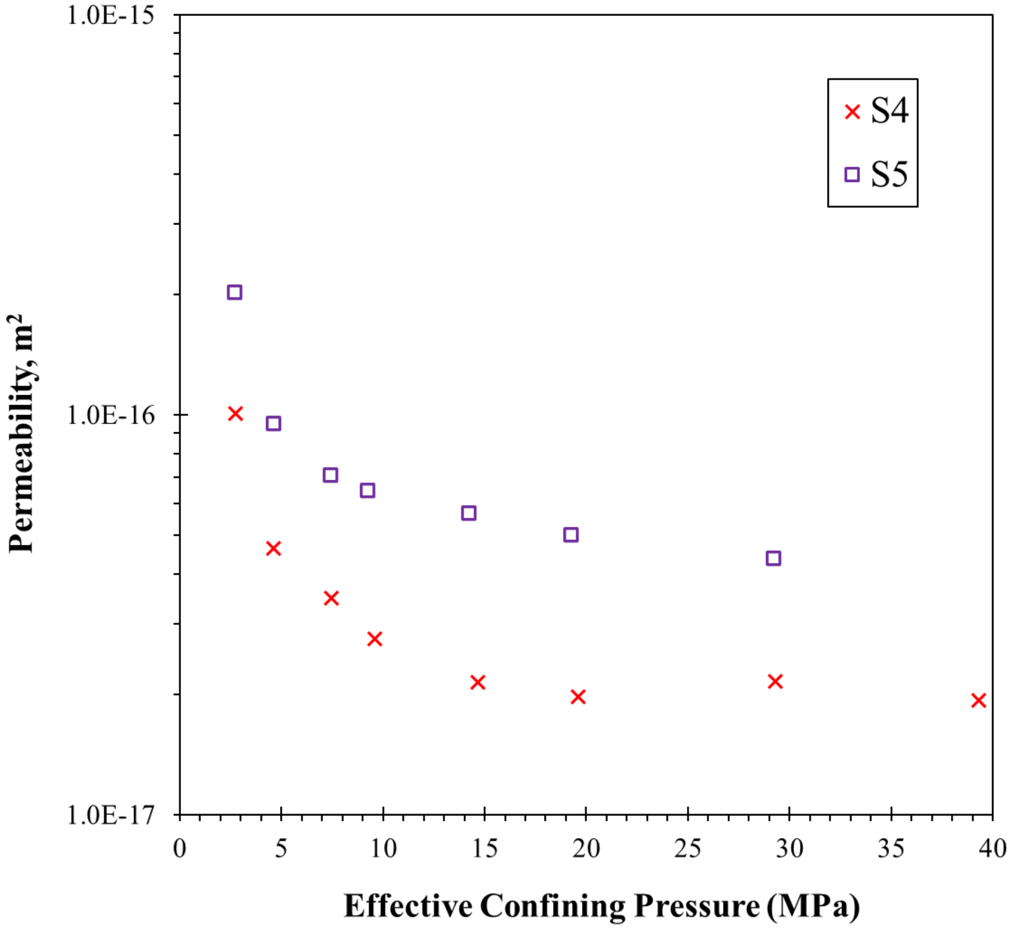


Fig.10 The permeability of sandstones for S4 and S5

Hydraulic and Machenical aperture of jointed sandstone

Steady state method

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

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)
$\triangle P$ ： $(P_u^2 - P_d^2)/2P_d$ (MPa)
P_d ： The pore pressure above the sample (MPa)
P_u ： The pore pressure under the sample (MPa)

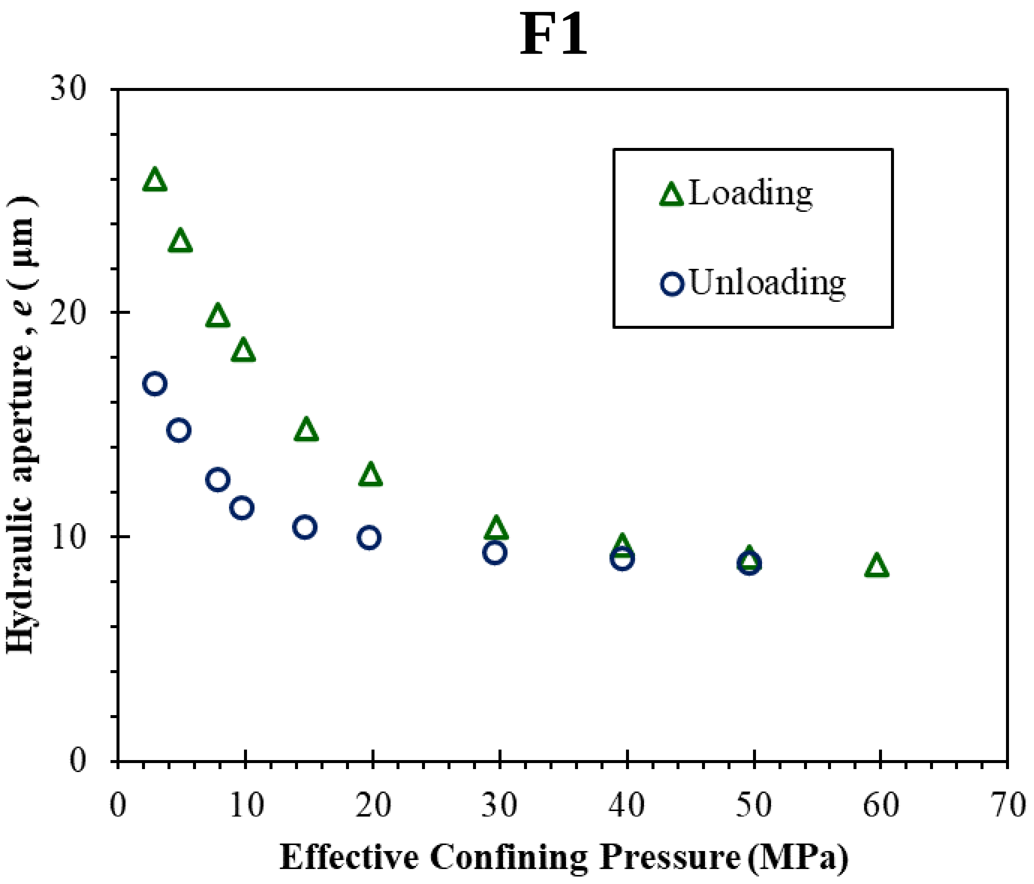


Fig.11 The hydraulic aperture of sandstones for F1

Hydraulic and Machenical aperture of jointed sandstone

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

$$\Rightarrow V_j = \left(\frac{P_{i1} - P_f}{P_f - P_{i2}}\right) \cdot V_s - V_l$$

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

E : The machenical aperture of sample (mm)
V_j : The volume of joint (mm^3)
A_j : The area of joint (mm^2)

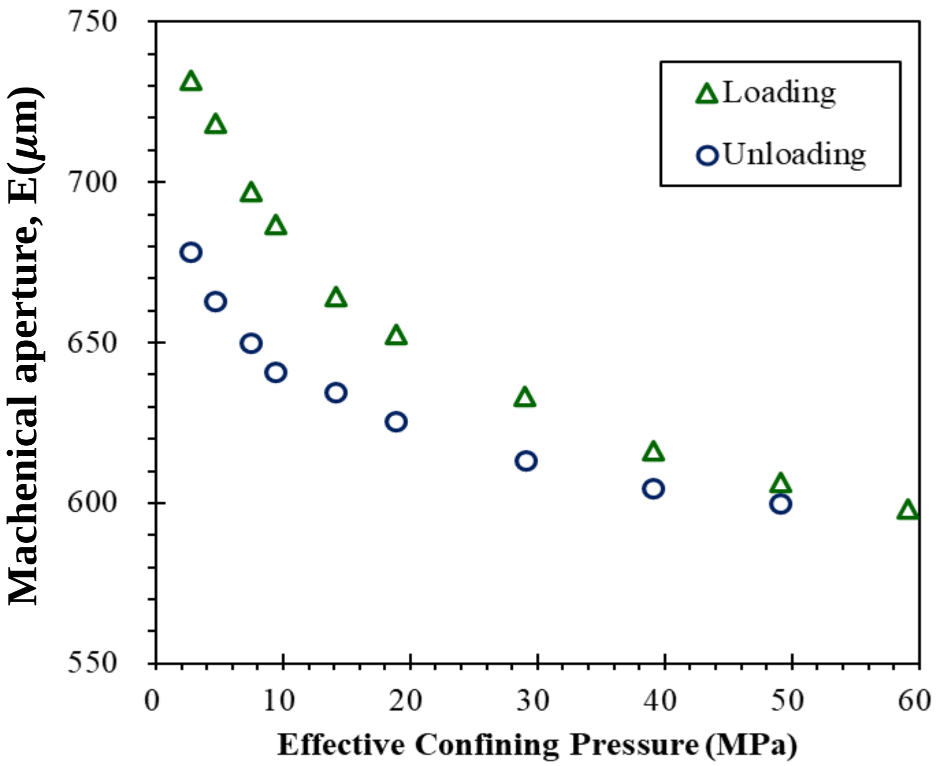


Fig.12 The machenical aperture of sandstones for F1

Equivalent hydraulic aperture of intact sandstones

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

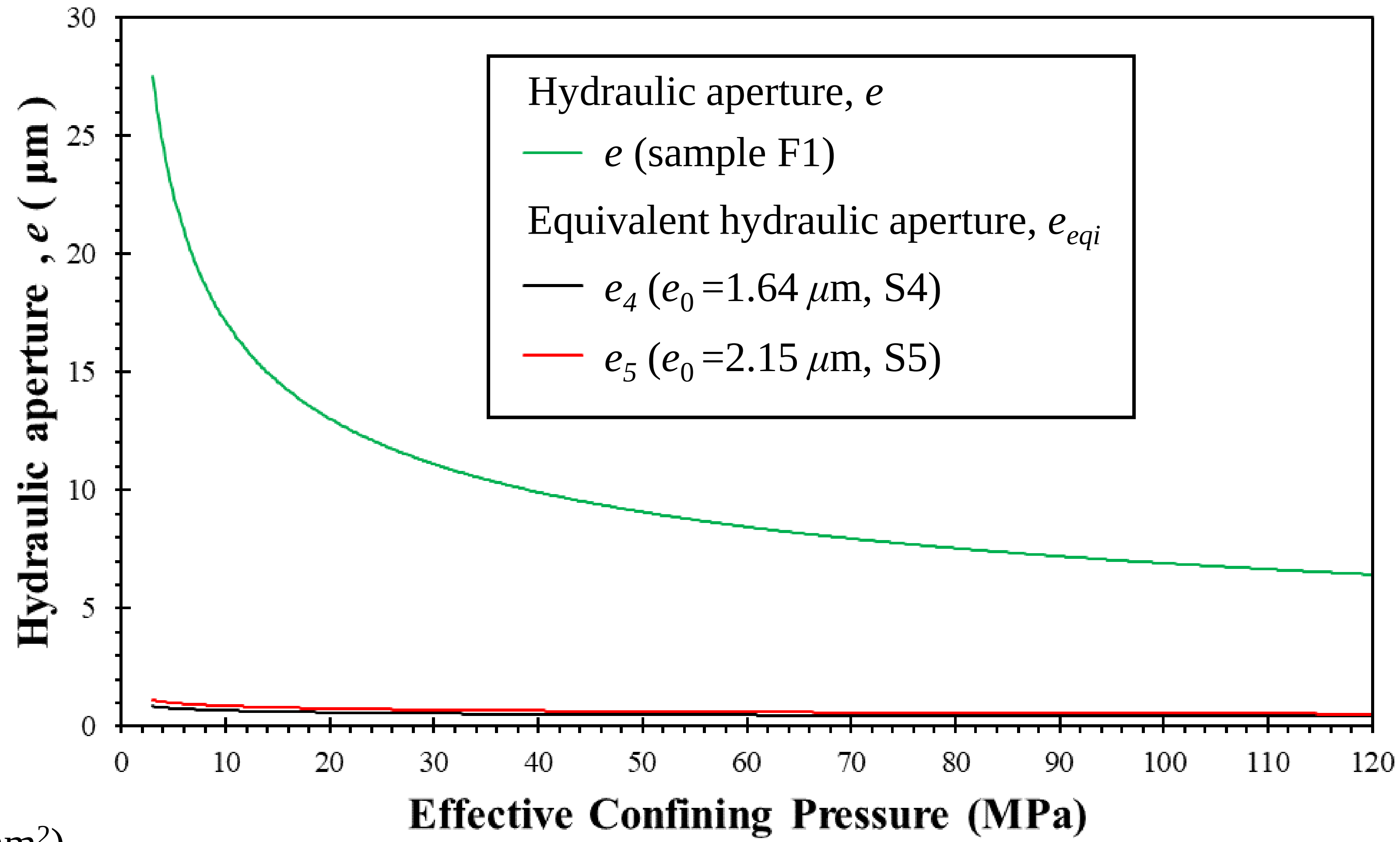


Fig.13 Curve fitting of the hydraulic aperture of jointed sandstone for F1 and the equivalent hydraulic aperture of intact sandstone for S4 and S5

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)

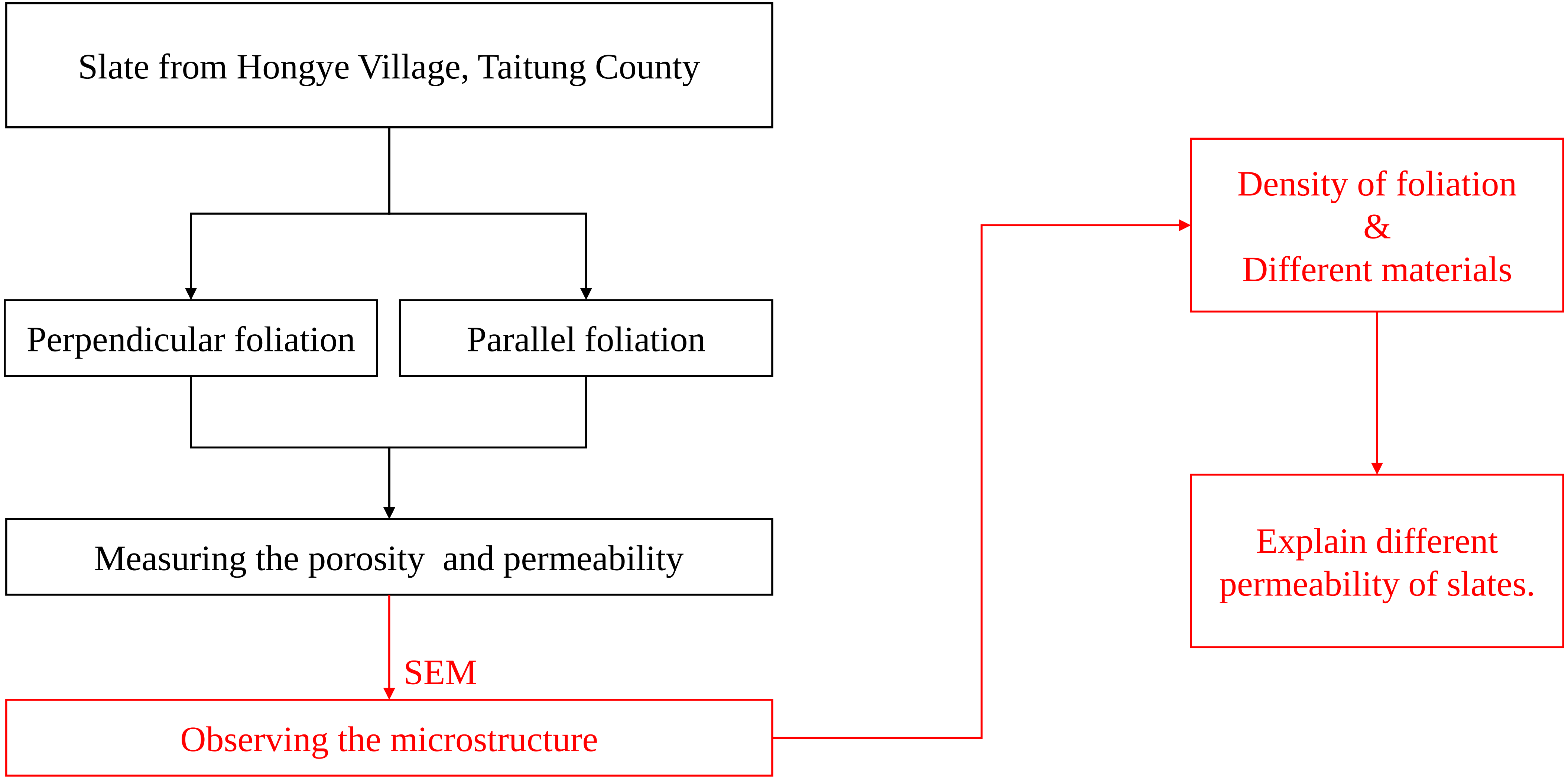
Contribution of intact rock to hydraulic aperture

P_e : Effective confining pressure
e : Hydraulic aperture of F1
e_4 : The equivalent hydraulic aperture of S4
e_5 : The equivalent hydraulic aperture of S5

Table.3 Hydraulic apertures of each sandstone sample under different effective pressures

Pe	e(μm)	e_4(μm)	e_5(μm)	e_4/e	e_5/e
3	27.51	0.85	1.11	3.10%	4.02%
5	22.49	0.77	1.00	3.44%	4.45%
8	18.69	0.71	0.91	3.79%	4.88%
10	17.12	0.68	0.87	3.96%	5.10%
15	14.59	0.63	0.81	4.30%	5.53%
20	13.03	0.59	0.76	4.56%	5.85%
30	11.10	0.55	0.70	4.95%	6.34%
40	9.91	0.52	0.67	5.25%	6.71%
50	9.08	0.50	0.64	5.50%	7.02%
60	8.45	0.48	0.61	5.70%	7.27%

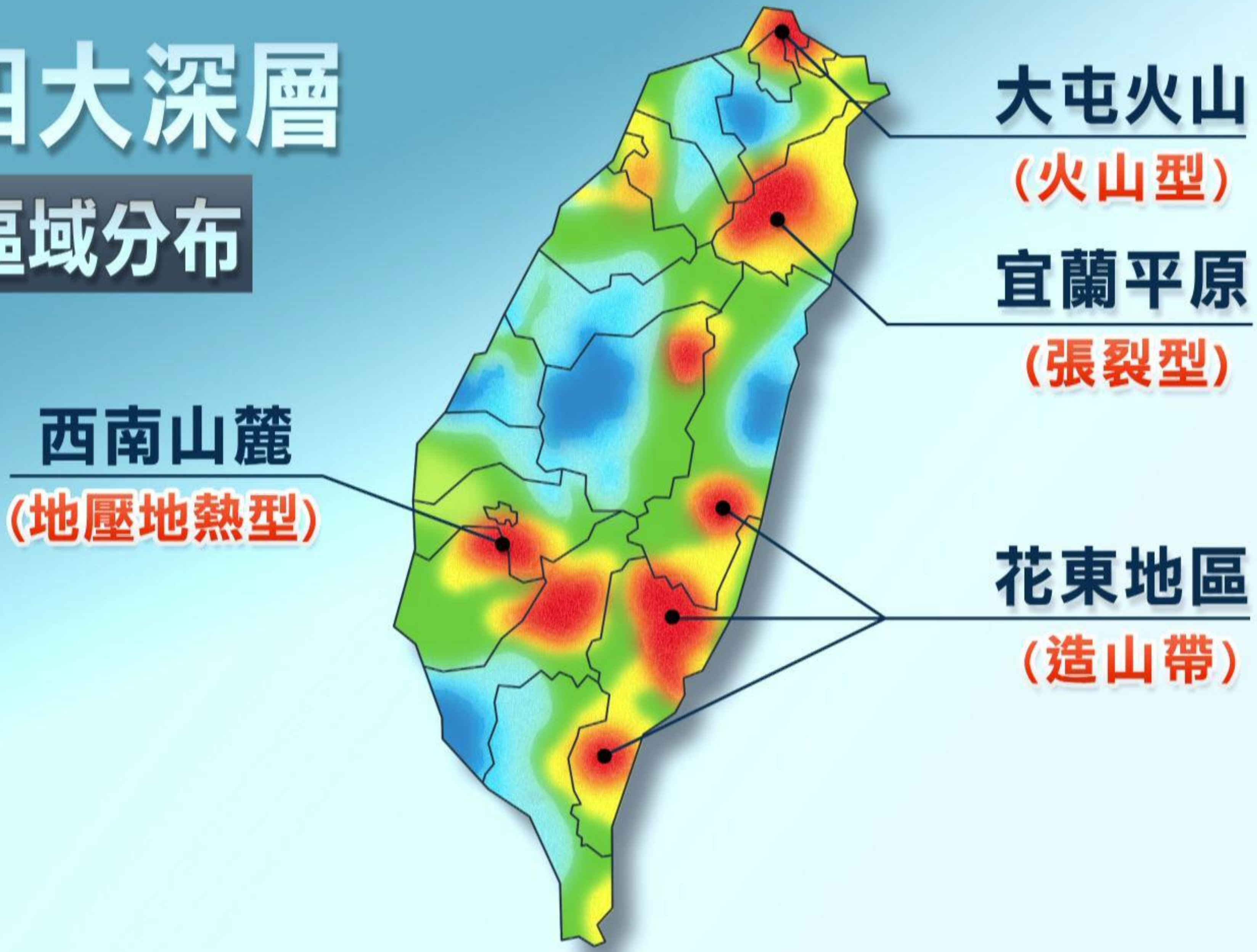
- For slate samples, there is not much difference in the porosity of between the parallel foliation orientation and the perpendicular foliation orientation.With generally higher permeability in the parallel foliation orientation.
- For sandstone samples, the porosity was 3.7% to 4.7%, and permeability ranged from 10^{-16} to 10^{-17} m^2.
- For sandstone sample with joints, hydraulic apertures varied from 9 to 26 μm, and mechanical apertures ranged from 600 to 730 μm.
- The jointed sandstone exhibited significantly greater contributions to fluid flow than intact rock.

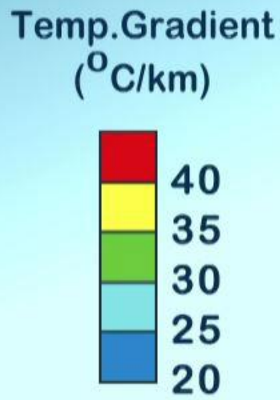

Slate from Hongye Village, Taitung County
Perpendicular foliation
Parallel foliation
Measuring the porosity and permeability
SEM
Observing the microstructure
Density of foliation
&
Different materials
Explain different permeability of slates.

Thank you for your attention

台灣四大深層

地熱區域分布





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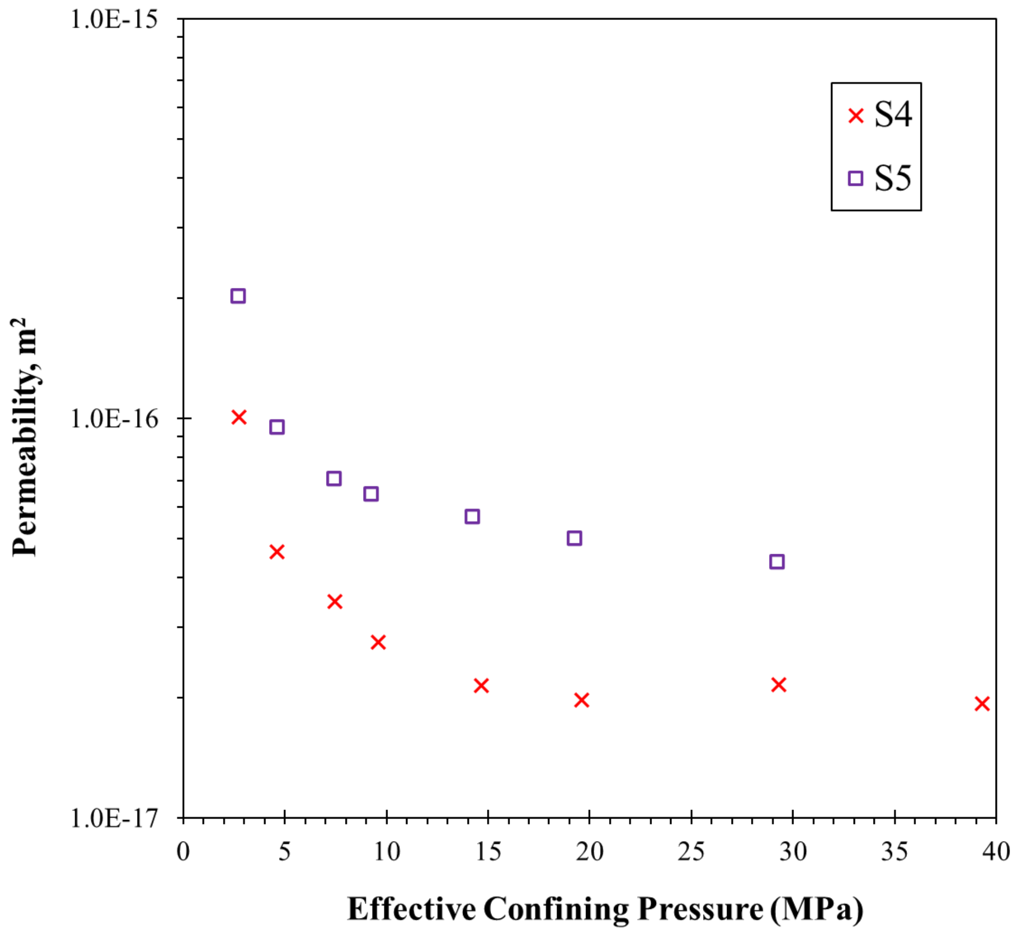


Fig. The permeability of sandstones for S4 and S5

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

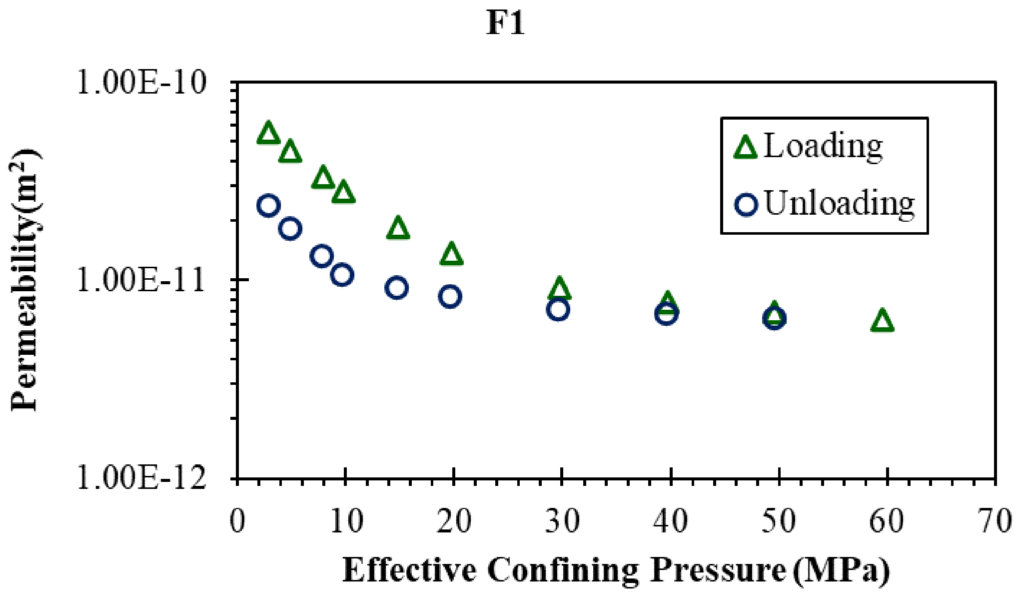


Fig. The permeability of sandstones for F1

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

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
F1	105.06	0.394	0.9791
S4	1.64	0.191	0.8495
S5	2.15	0.196	0.8835

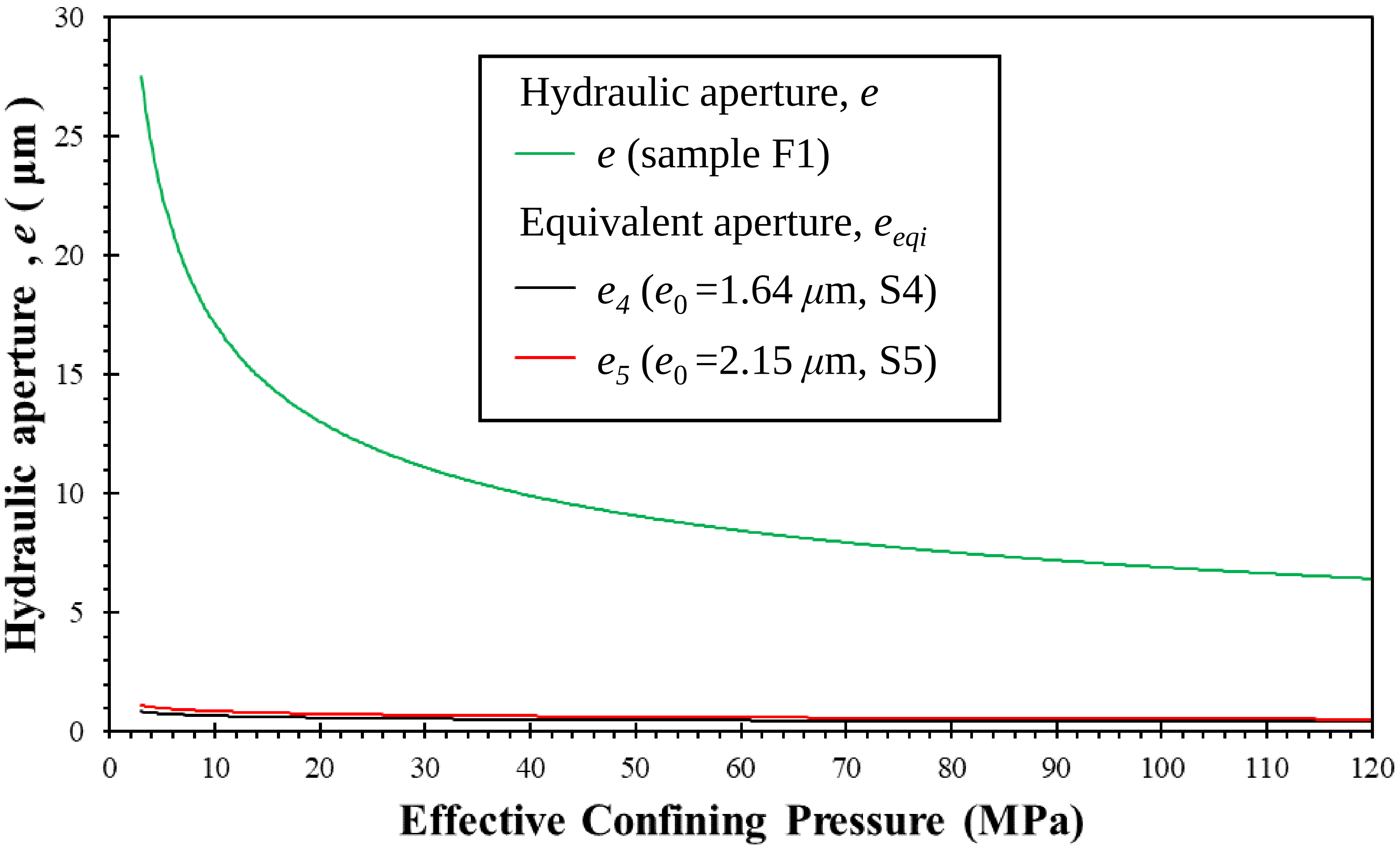
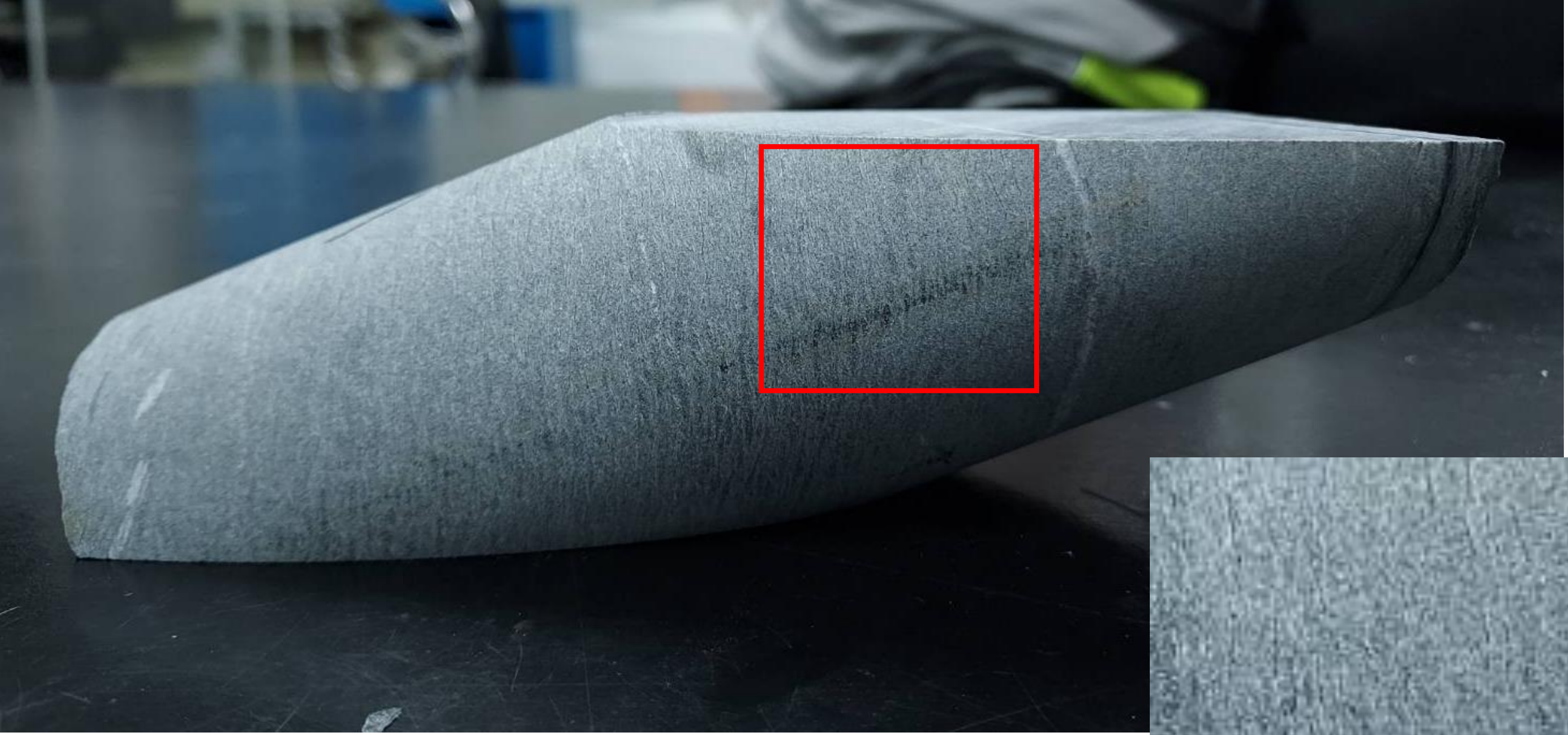


Fig.Curve fitting of the hydraulic aperture of jointed sandstone for F1 and the equivalent hydraulic aperture of intact sandstone for S4 and S5




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

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

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

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