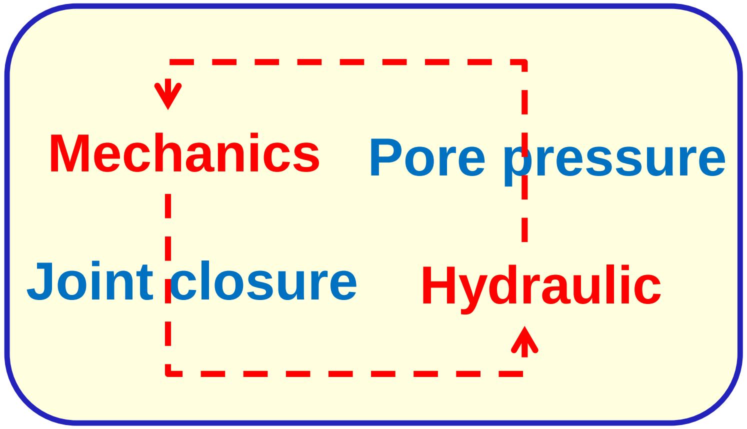
應用地質研究所
Graduate Institute of Applied Geology, NCU, Taiwan

The Influence of JRC and Surface Geometry on the Mechanical/Hydraulic Aperture of 3D Printed Joints

Presenter: Tan-Minh Le
Advisor: Prof Jia-Jyun Dong
Date: 2022/04/15

Seminar Presentation

Factors influent Hydromechanical Coupling of jointed rock masses:

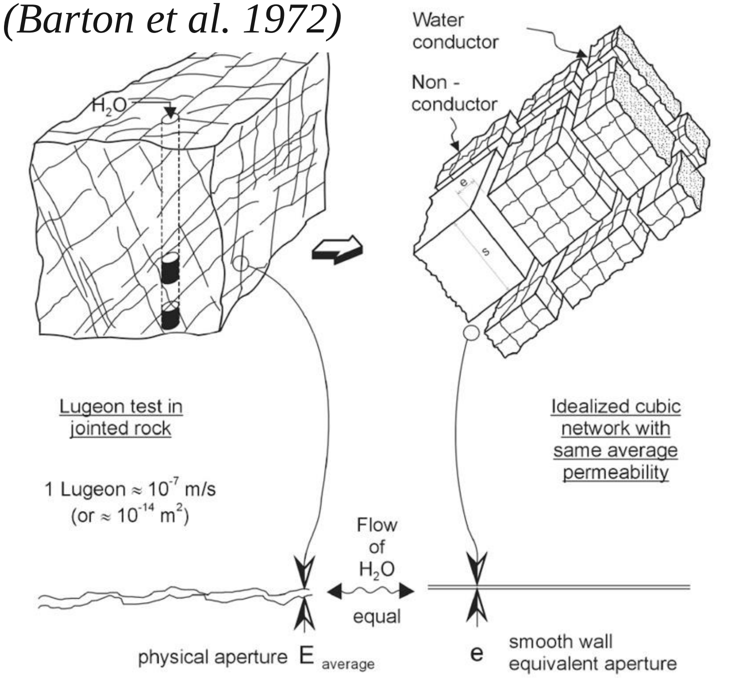


- **Characterization of** the **hydraulic and mechanical aperture** (including the laboratory and in-situ test) still **critical** and **challenging** issues
- **Hydraulic aperture** is one of the **key source of uncertainty**

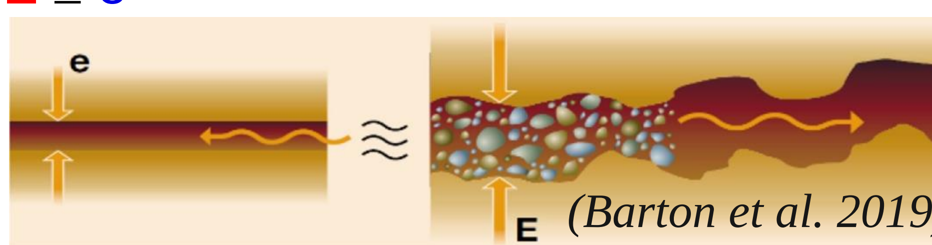
e: aperture accommodating a particular flux **assuming a parallel plate model**.

E: Mean physical distance between two fracture surfaces

(Barton et al. 1972)



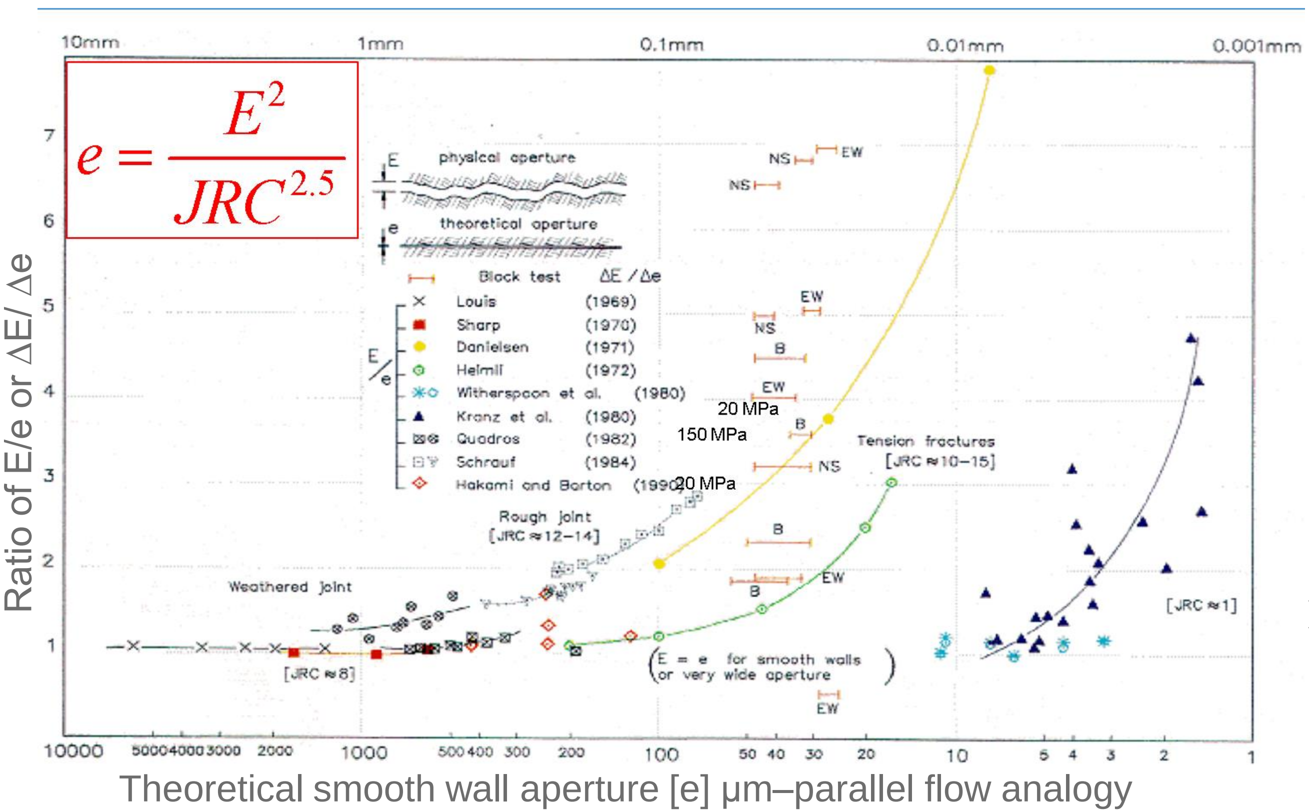
$E \geq e$



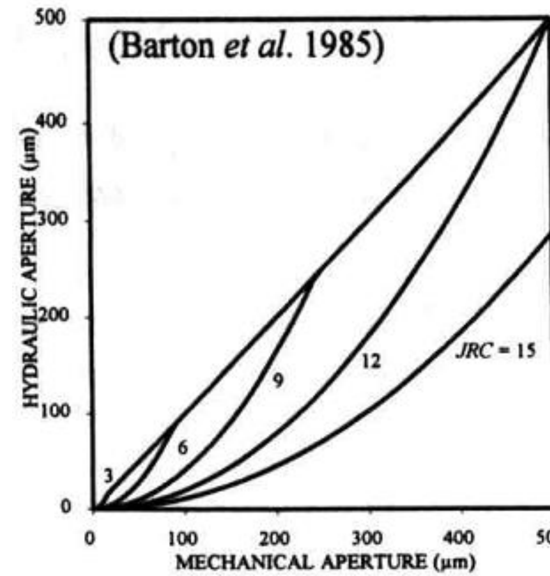
(Barton et al. 2019)

If two joints with the **same JRC**, will they have the **same** Hydraulic Aperture and Mechanical Apertures?

Synthetic joints created via **3D printer!!**



Constitutive model relating hydraulic aperture with mechanical aperture and joint roughness *(Barton et al. 1985)*



In which:.

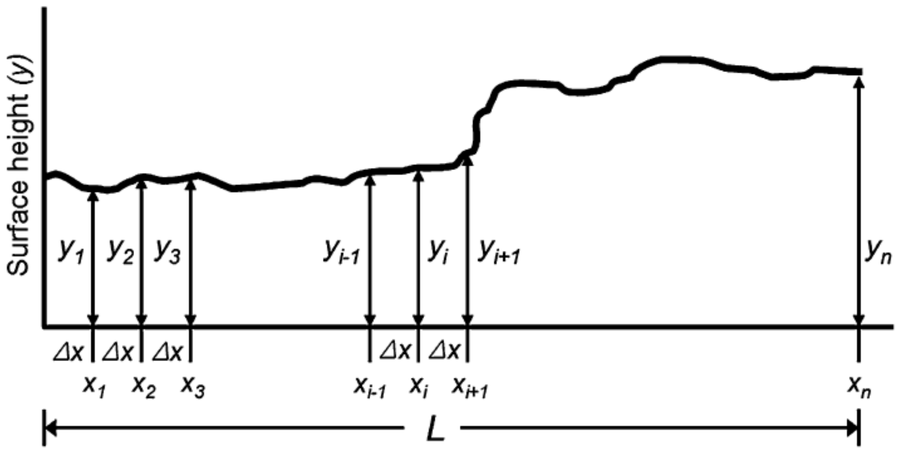
- *JRC:* jointed roughness coefficient
- E : Mechanical aperture *(μm)*
- *e:* Hydraulic aperture *(μm)*

Workflow

1. **Generate fracture 2D profiles**
2. **Import STL files into *Connex3 Objet260 Printer***
3. **3D printed samples**
4. **Morphology quantification**
5. **YOKO 2 measurement system**
6. **Data analysis and interpretation**

Conclusion

1. **Generate fracture 2D profiles**



$JRC = 61.79 * Z_2 - 3.47$

(Yu and Vayssade, 1991)

$$Z_2 = \left[\frac{1}{L}\int_{x=0}^{x=L}\left(\frac{dy}{dx}\right)^2 dx\right]^{1/2} = \left[\frac{1}{L}\sum_{i=1}^{n-1}\frac{(y_{i+1}-y_i)^2}{x_{i+1}-x_i}\right]^{1/2}$$

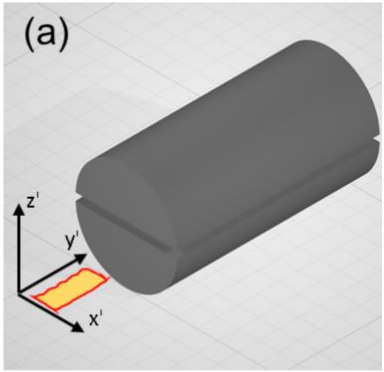
$$-0.25 \leq a \leq 0.25 \quad for \;\; 2 \leq JRC \leq 4$$

a: Asperity amplitude (mm)

Z_2: root mean square first derivative of profile

Δx: sample interval (mm)

2. **Import STL files into *Connex3 Objet260 Printer***



Printing directions

Material: Vero Pure White resin

Accuracy: 0.2mm

3. **3D printed sample**

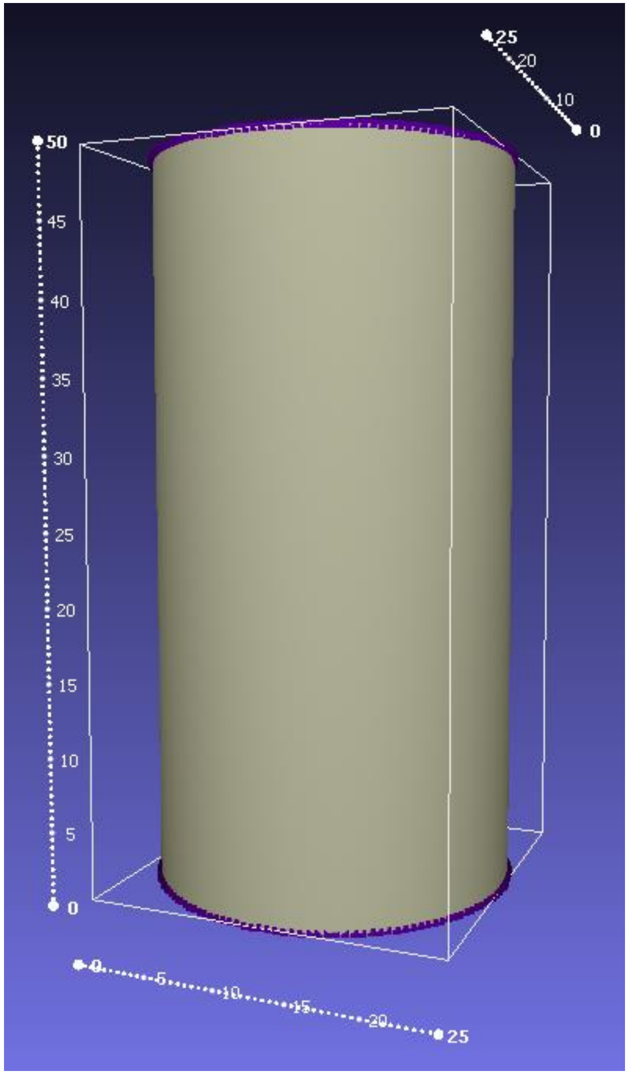


Table 1. Geo-mechanical properties of Vero Pure White material compare with Granite

	Vero Pure White	Granite
Density	1.17 - 1.18 g/cm^3	2.63 g/cm^3
Tensile strength	50 - 65 MPa	18 MPa
Flexural strength	75 - 110 MPa	17 MPa
Young's modulus	2 - 3 GPa	20 - 75 GPa
Water Absorption	1.1 -1.5%	0.36%

Intact sample

4. Morphology quantification

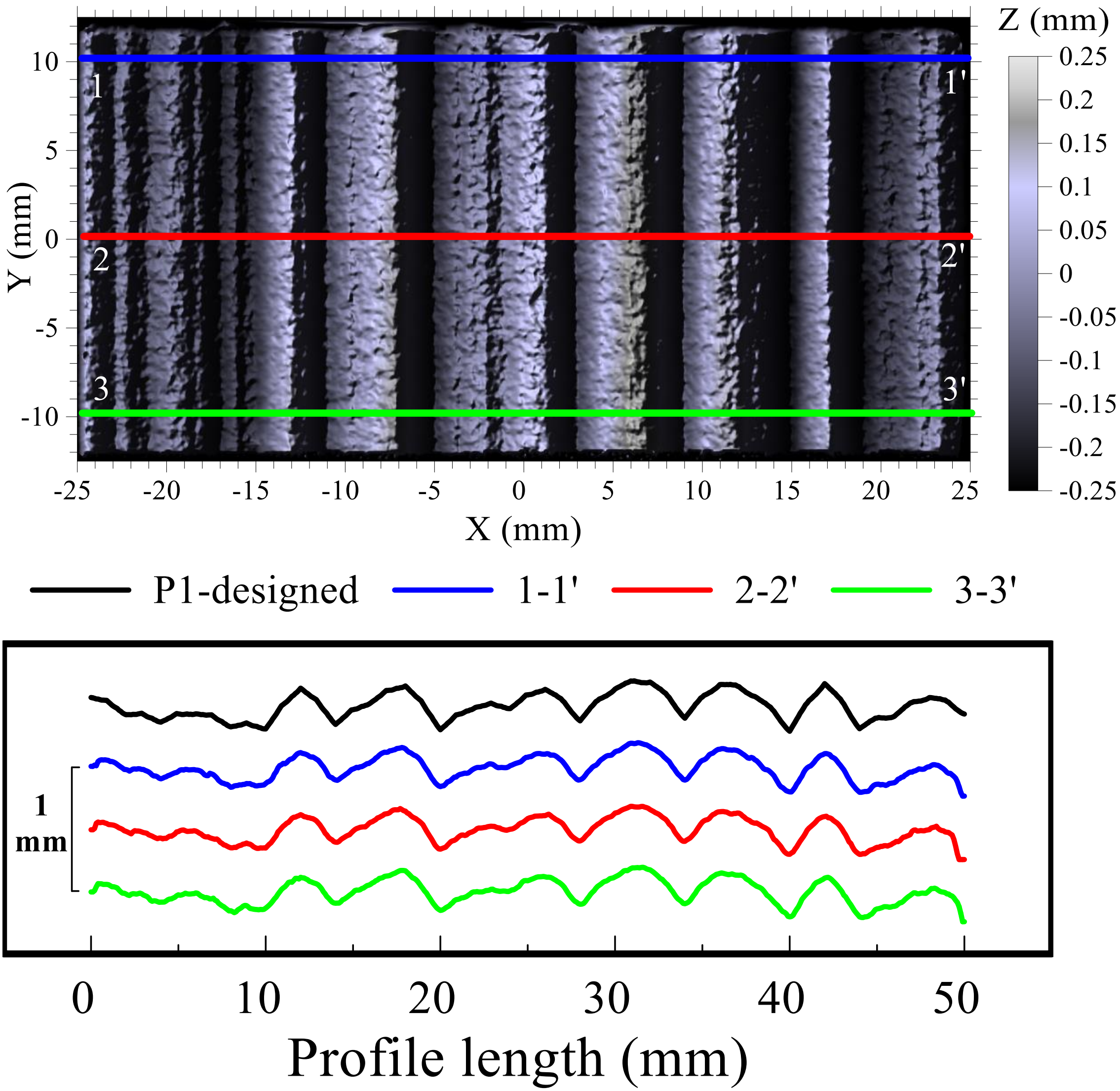


Figure . Scanned results of 3D-printed fracture surfaces (from P1_Mat_E1)

HDI 120 ADVANCED 3D SCANNER	
Resolution (mm)	0.110-0.180
VDI/VDE Accuracy (mm)	0.06

Figure . HDI 120 advanced 3D scanner in Soil and Rock Mechanics Research Group at NCU, Taiwan

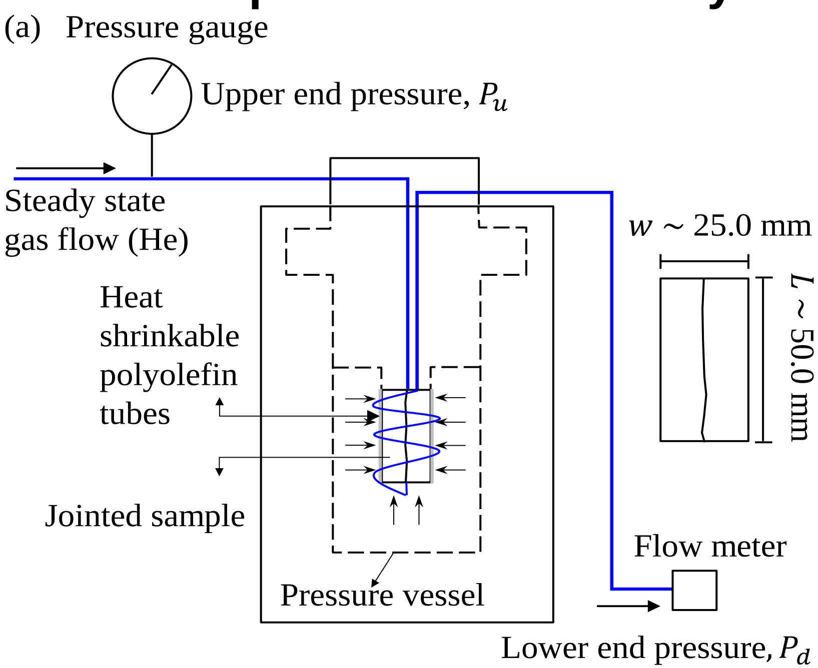
5. YOKO 2 measurement system

(Dong et al. 2010)

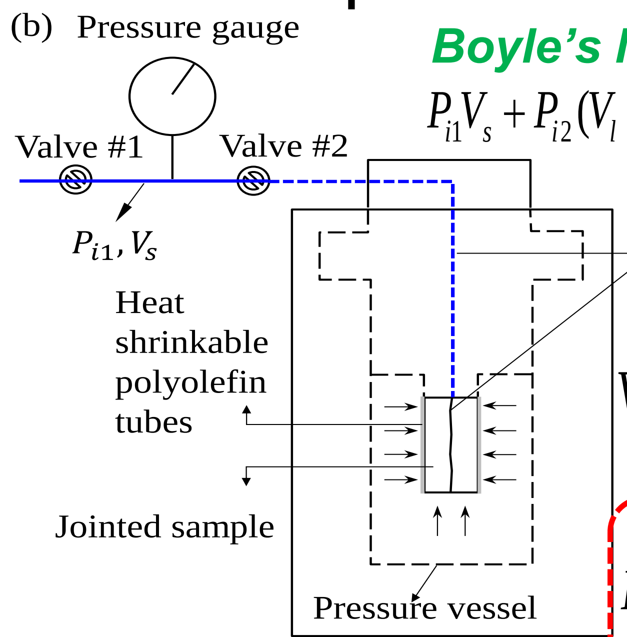
Soil and Rock Mechanics Research Group at NCU, Taiwan.

Maximum confining pressure: 200MPa

Stress- dependent Permeability



Stress- dependent Porosity



Boyle's law:

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

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

$$E = \frac{V_p}{A_f}$$ **Mechanical aperture (E)**

V_p: joint volume(m^3)

A_f: joint area (m^2)

For compressible flow (gas):

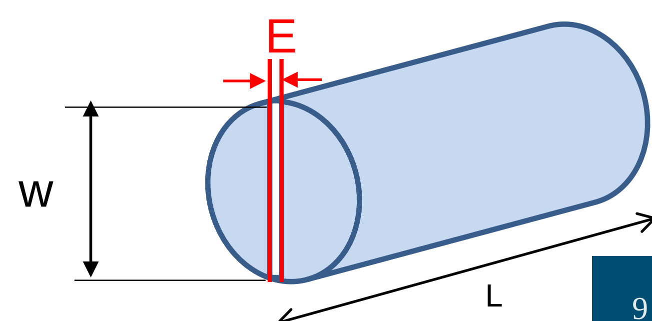
(Schrauf and Evans,1986)

$$Q = \frac{e^3 \rho g w}{12\mu}\frac{\left(P_u^2 - P_d^2\right)}{2P_d L}$$

Hydraulic aperture (e):

$$e^3 = \frac{24\mu L P_d Q}{w(P_u^2 - P_d^2)}$$

Q: volumetric flow rate (m^3/s)
e: hydraulic aperture (m)
ρ: helium gas density (kg/m^3)
g: acceleration of gravity (m/s^2)
w: joint width (m)
μ: viscosity (Pa.s)
P_u: upper pressure (Pa)
P_d: atmospheric pressure (Pa)
L: joint length (m)



1. **Generate fracture 2D profiles**
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Conclusion

Advantages

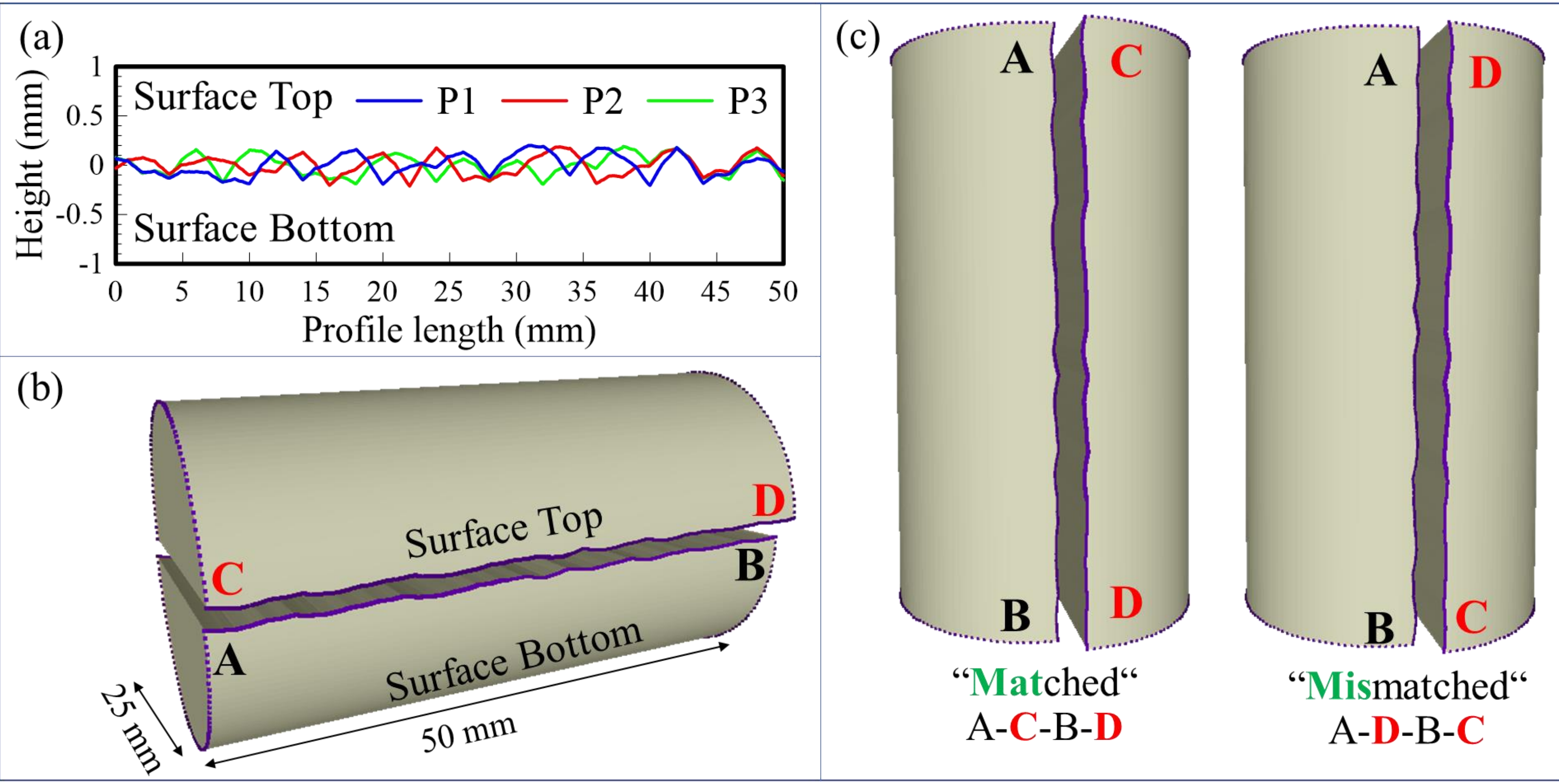
Constraint system:
Surface roughness,
Repeatability of samples
and experiment results

Limitations

Printing period, Printing direction

Sample Creation

3 generated rough fracture surfaces **(JRC = 3.5)**



3D view of cylinder single joint sample P1_Mat_ABDC

Scanned results of the printed samples

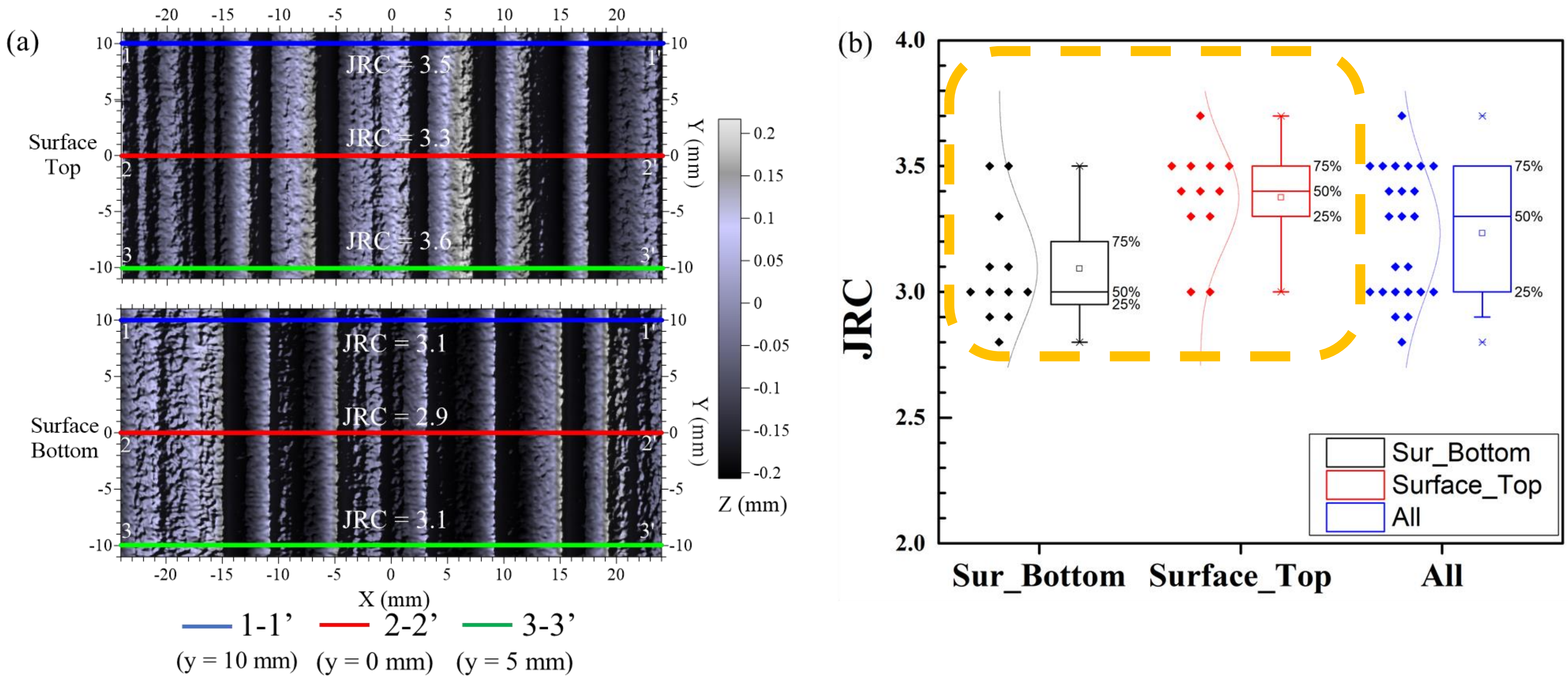
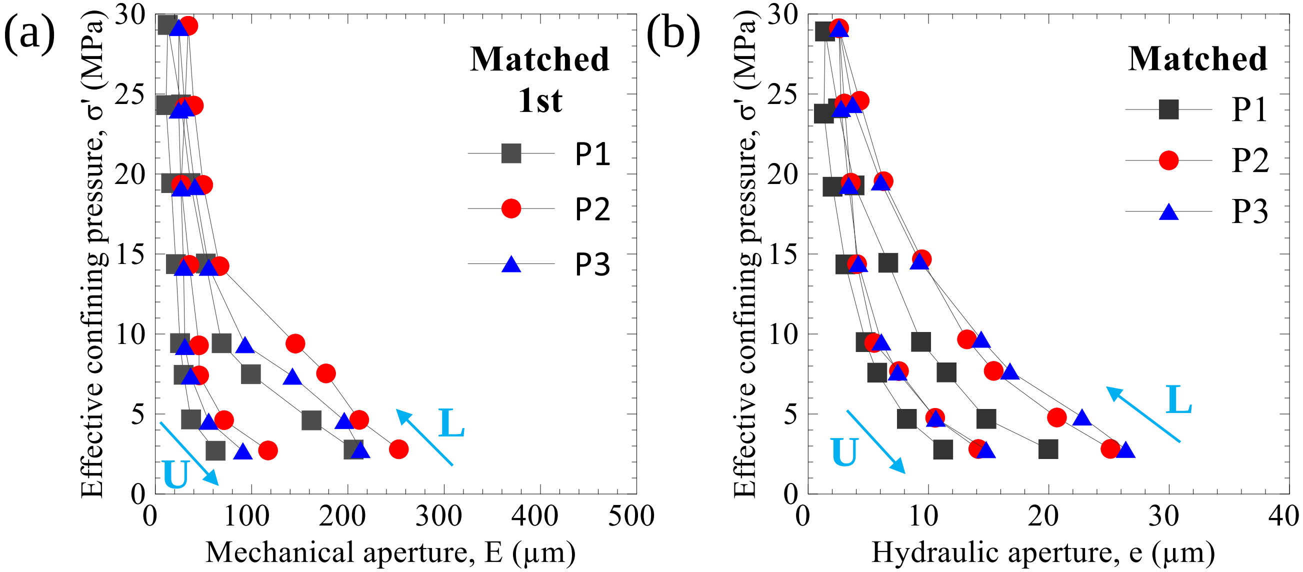


Figure . (a) Scanned results of 3D-printed fracture surfaces (from P1_Mat_E1)

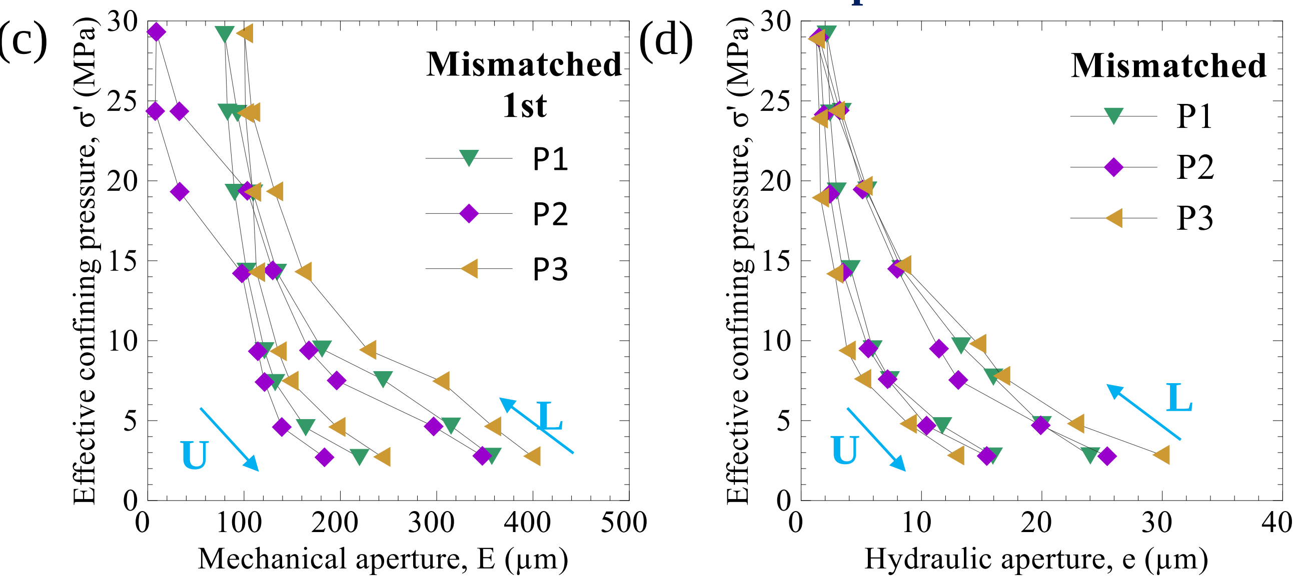
(b) Boxplots for mean JRC all samples, with the central red line representing the median, and the box edges and whiskers denoting the interquartile, and the 5th to 95th percentile range, respectively

Experimental results

E vs σ' Matched samples e vs σ'



Mismatched samples



E vs σ'; e vs σ'

- *nonlinear relationship*

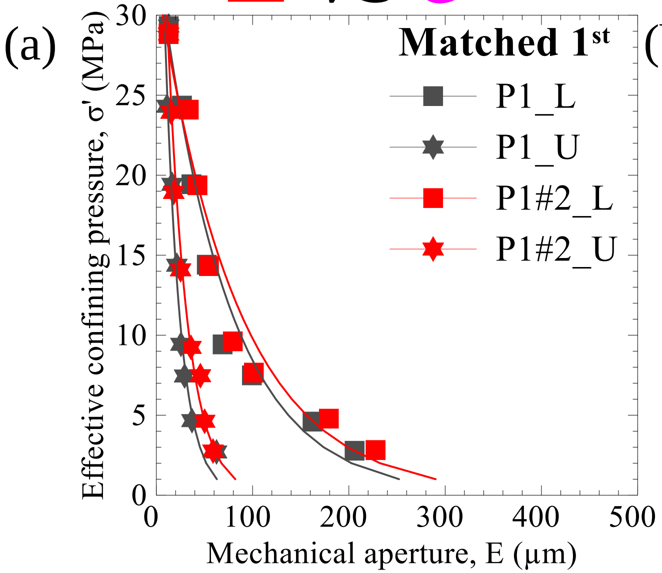
σ' ↑ { E ↓ ; e ↓ }

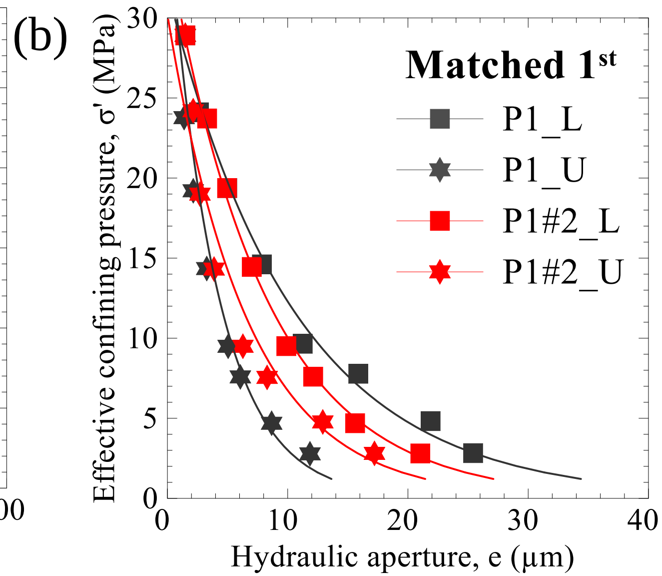
- **Factors affect: ???**

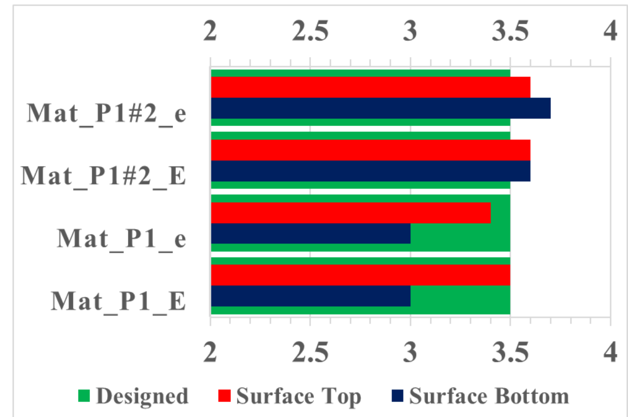
- **P2_Mis** *displays noticeably lower E*

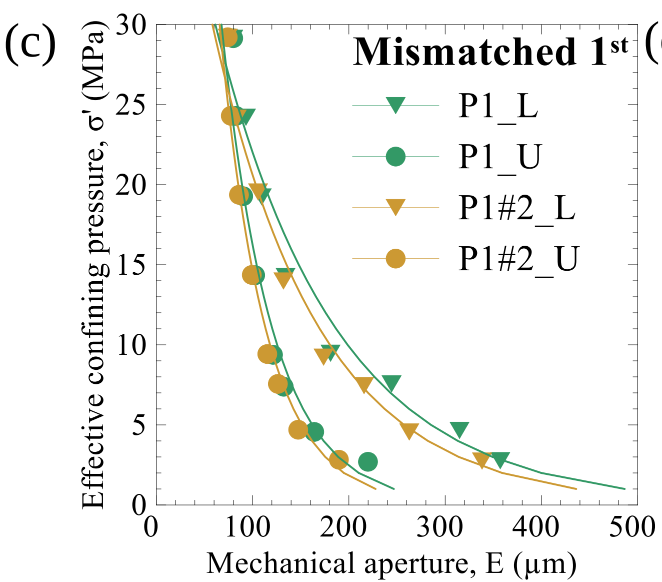
Reproducibility

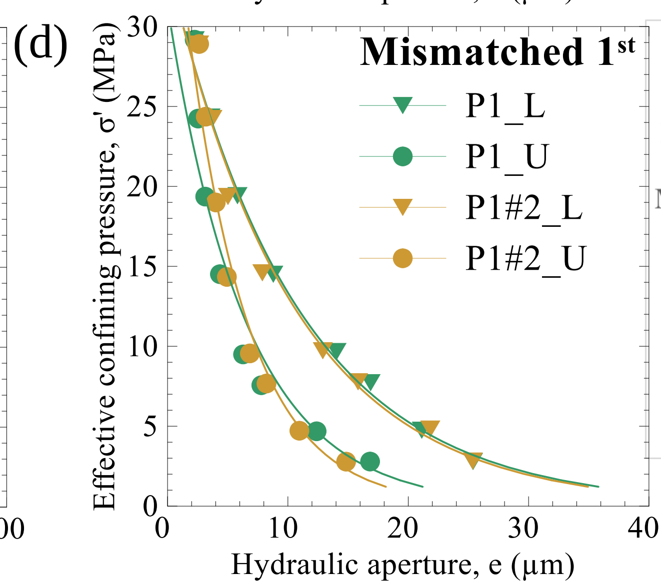
E vs σ' *e* vs σ'

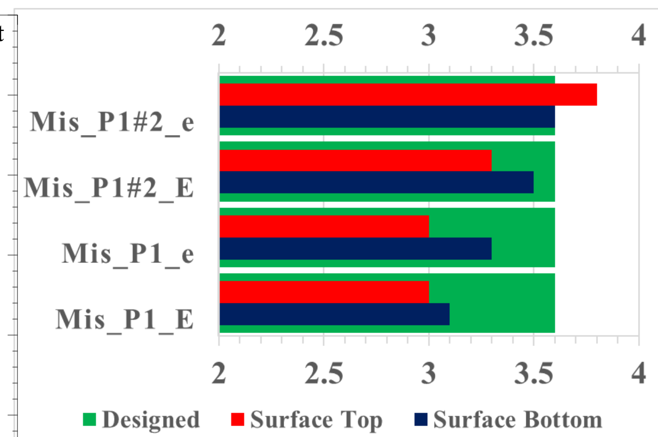












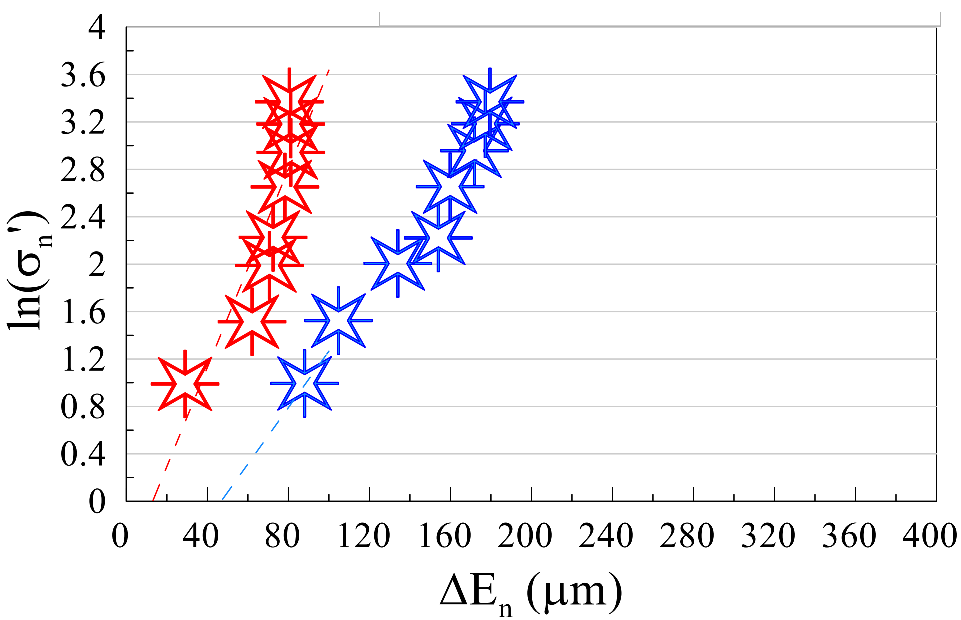
Semi-logarithmic closure law *(Evans et al., 1992)*

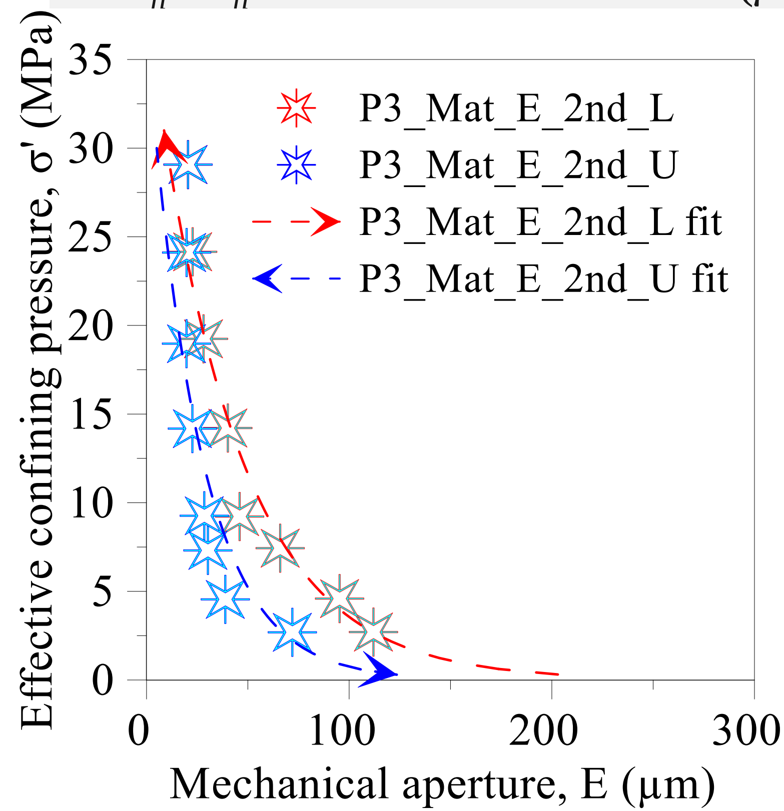
$$\ln(\sigma_n') = \ln(\sigma_n^{ref}) + \Delta E_n * (\mathrm{d}k_n / \mathrm{d}\sigma_n')$$

Fit_Loading Eq: $E_i - \ln\left(\sigma_n' / \sigma_n^{ref}\right) \Big/ \left(dkn / \sigma_n'\right)$

In which:

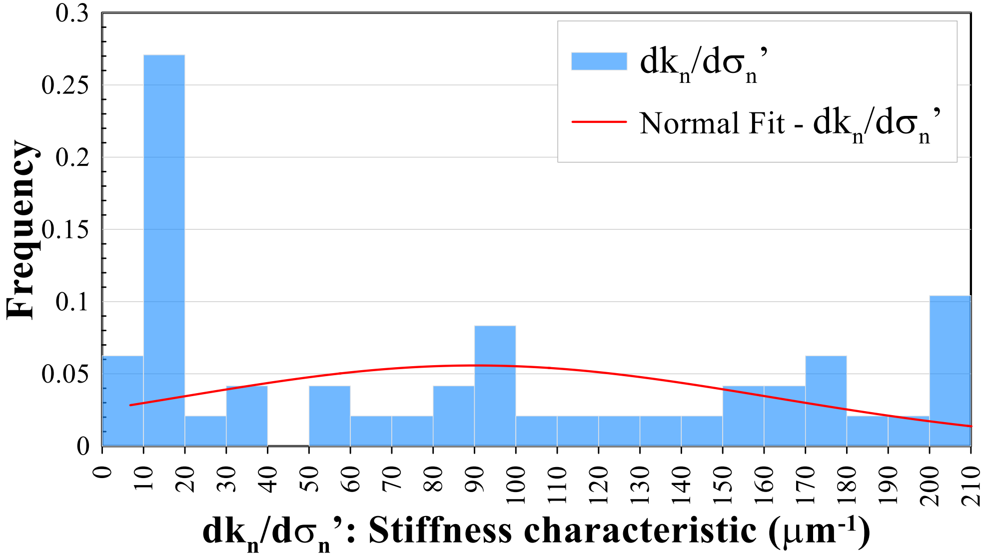
- σ_n' : effective stress (*MPa*)
- σ_n^{ref} : reference effective stress (*MPa*)
- E_i : initial aperture at σ_n^{ref} (μm)
- ΔE_n : Joint closure (μm)
- $dk_n/d\sigma_n'$: Stiffness characteristic (μm^{-1})

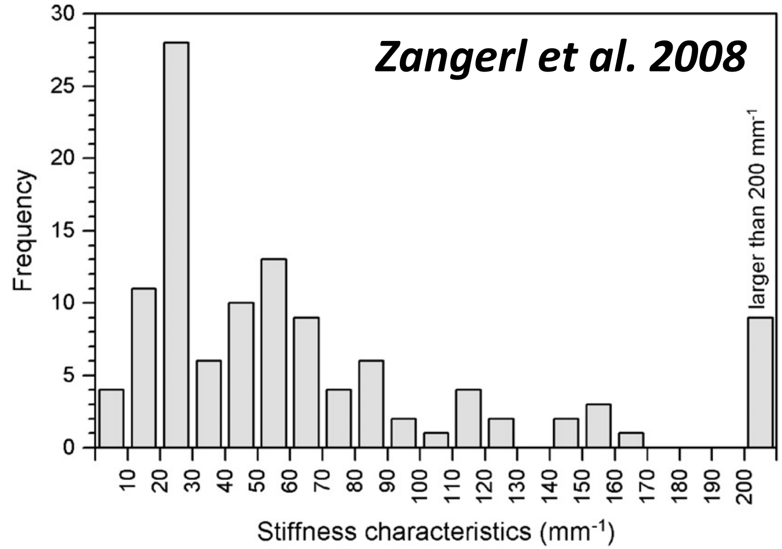




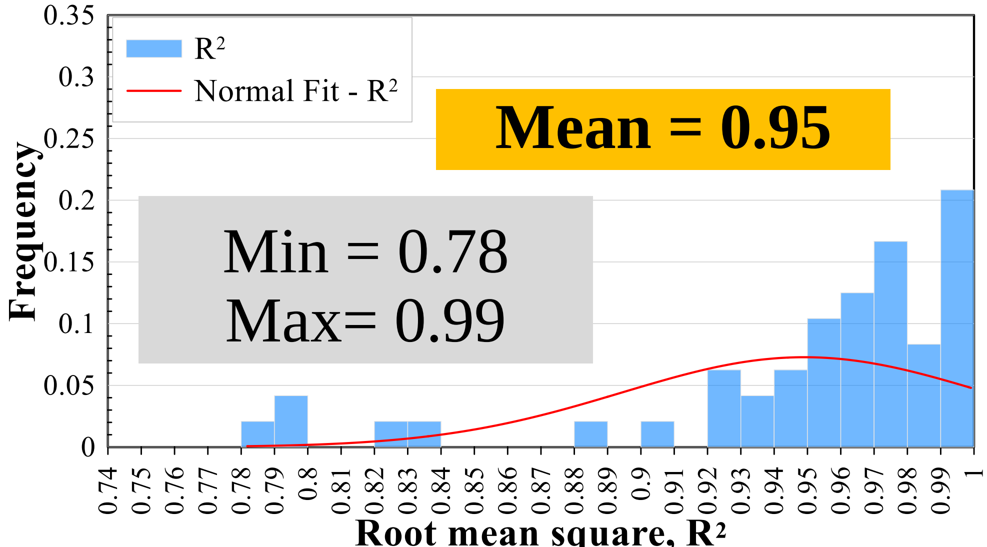
Applicability to natural fracture stiffness

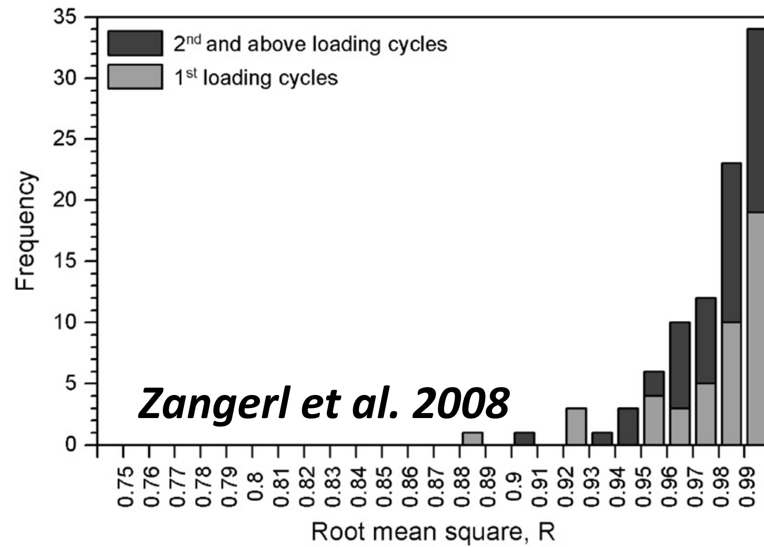
Semi-logarithmic Histogram





R^2 Histogram



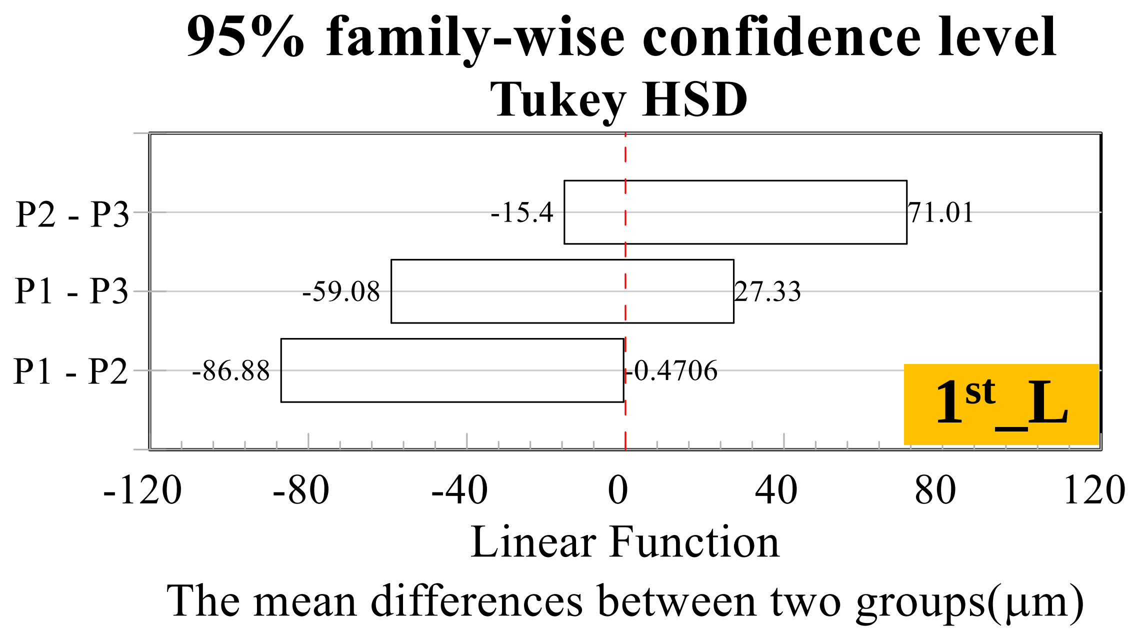


ANOVA test MAT samples

Compare E

Post hoc Test Tukey HSD

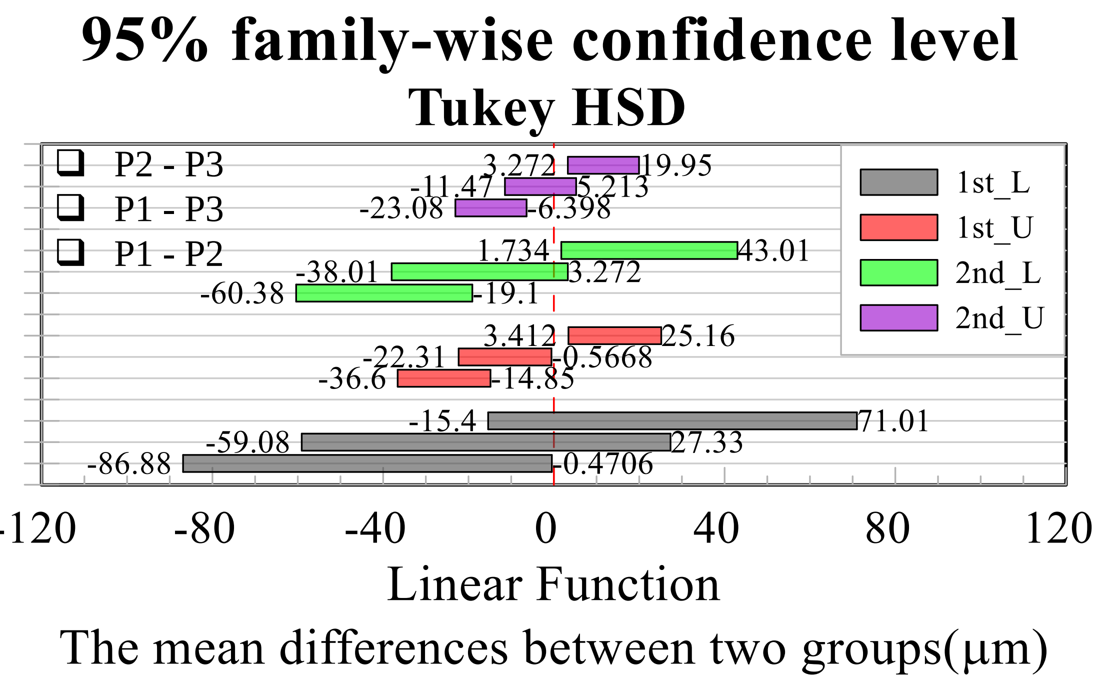
Data analyzed	Sig. results
P2 – P3	**p = 0.344**
P1 – P3	**p = 0.777**
P1 – P2	**p = 0.046**



- ❑ P2 mean is **significantly different** at the 5% level of significance for P1

ANOVA test MAT samples

E



- P2 mean is **significantly different** at the 5% level of significance between P1 and P3 (at **1st_U**, **2nd_L**, **2nd_U**)

e

Data analyzed	ANOVA results
1st_L	p=0.337
1st_U	p=0.288
2nd_L	p=0.111
2nd_U	p=0.335

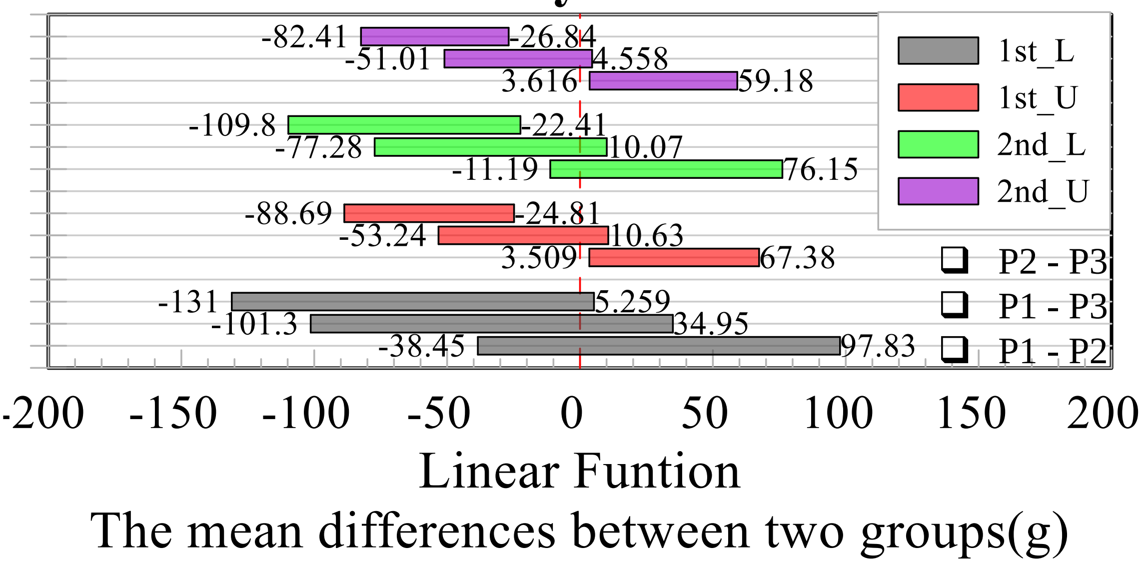
- Sig>0.05 => There are **no statistically significant different** in hydraulic aperture.

ANOVA test MIS samples

E

95% family-wise confidence level

Tukey HSD



- P2 mean is **significantly different** at the 5% level of significance between P1 and P3 (at **1st_U**, **2nd_L**, **2nd_U**)

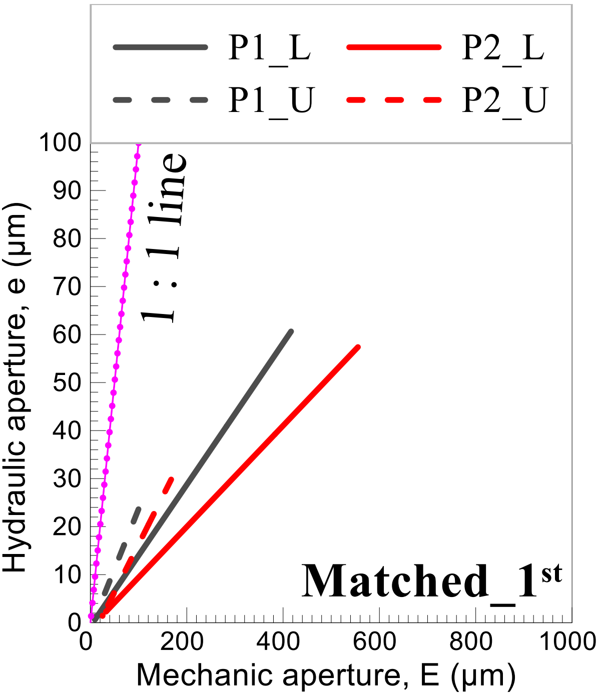
e

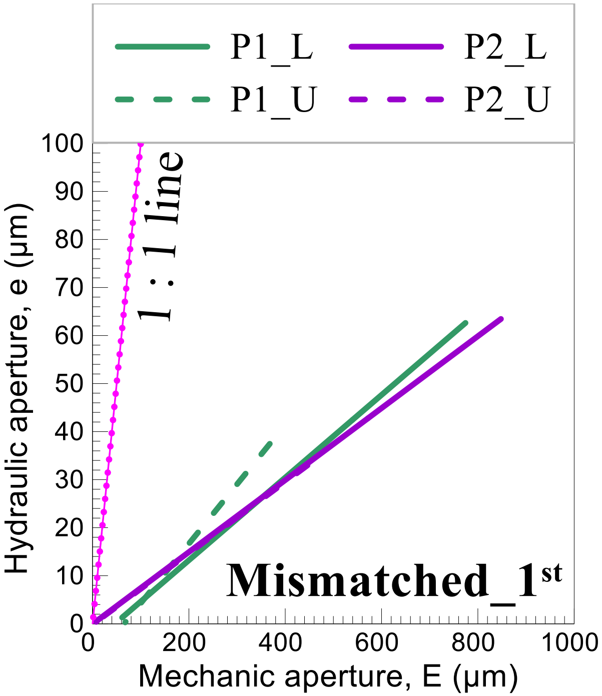
Data analyzed	ANOVA results
1st_L	**p=0.966**
1st_U	**p=0.151**
2nd_L	**p=0.135**
2nd_U	**p=0.143**

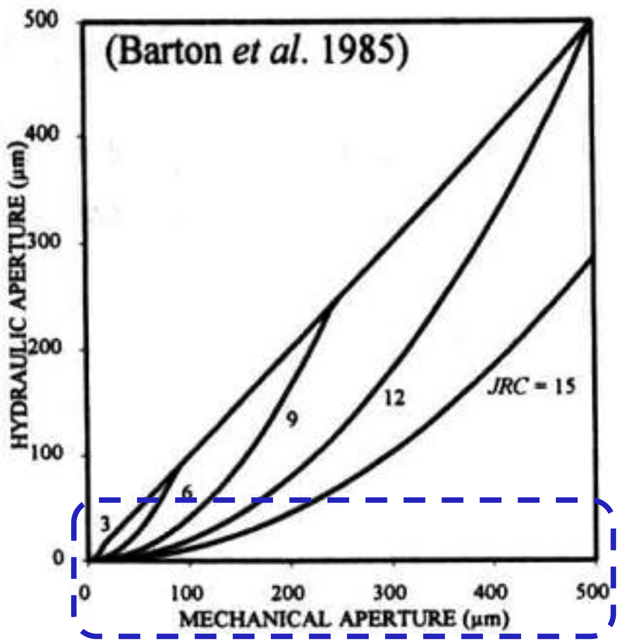
- Sig>0.05 => There are **no statistically significant different** in hydraulic aperture.

***** e vs E relation

1st cycle



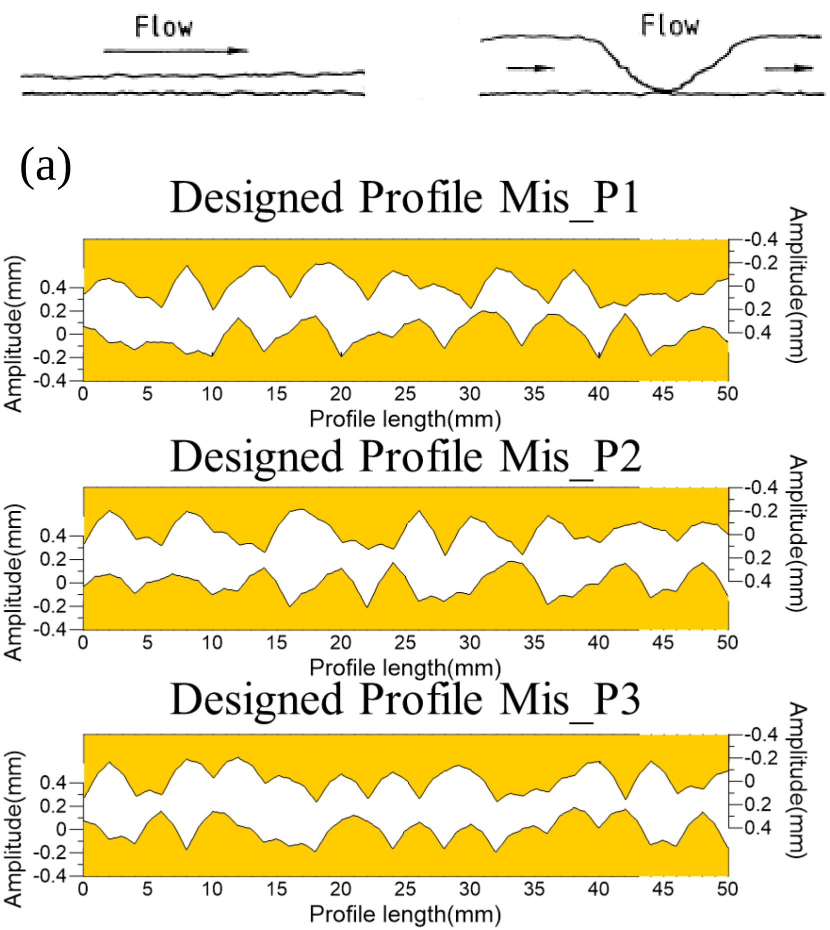




≡ JRC

≠Profiles

E ≠ e



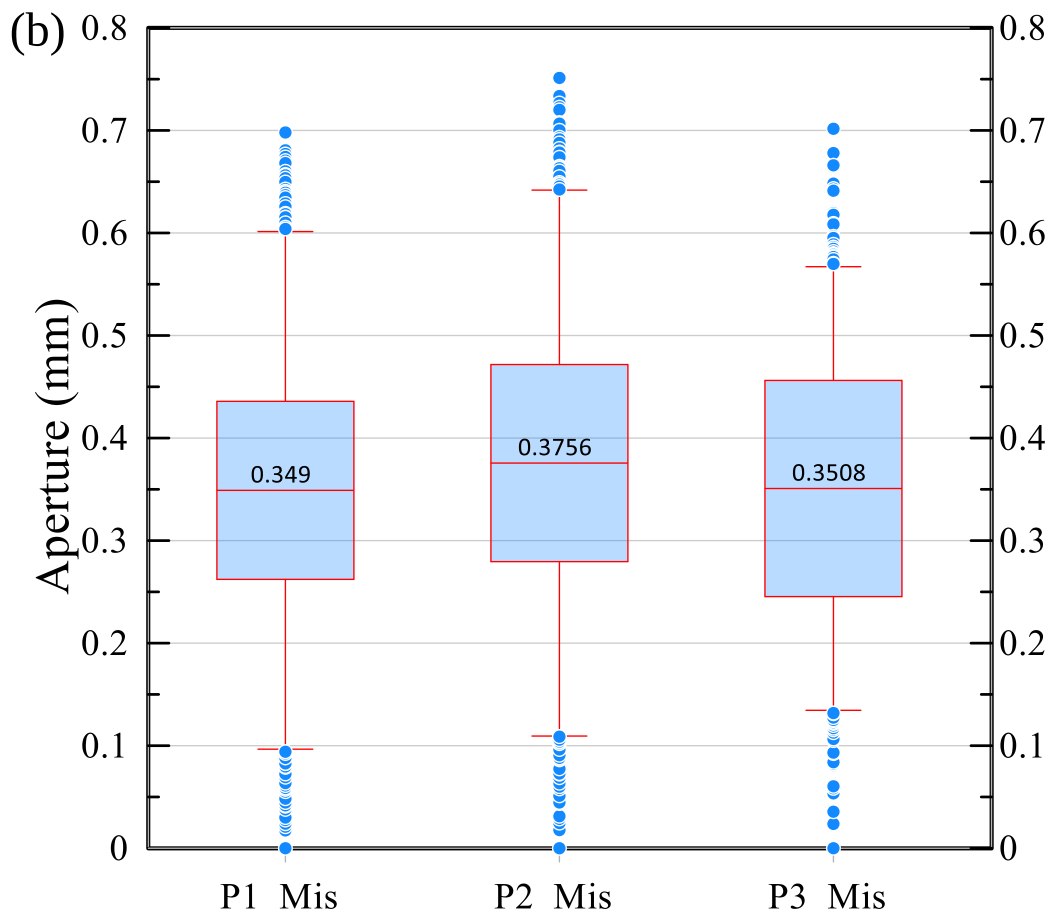
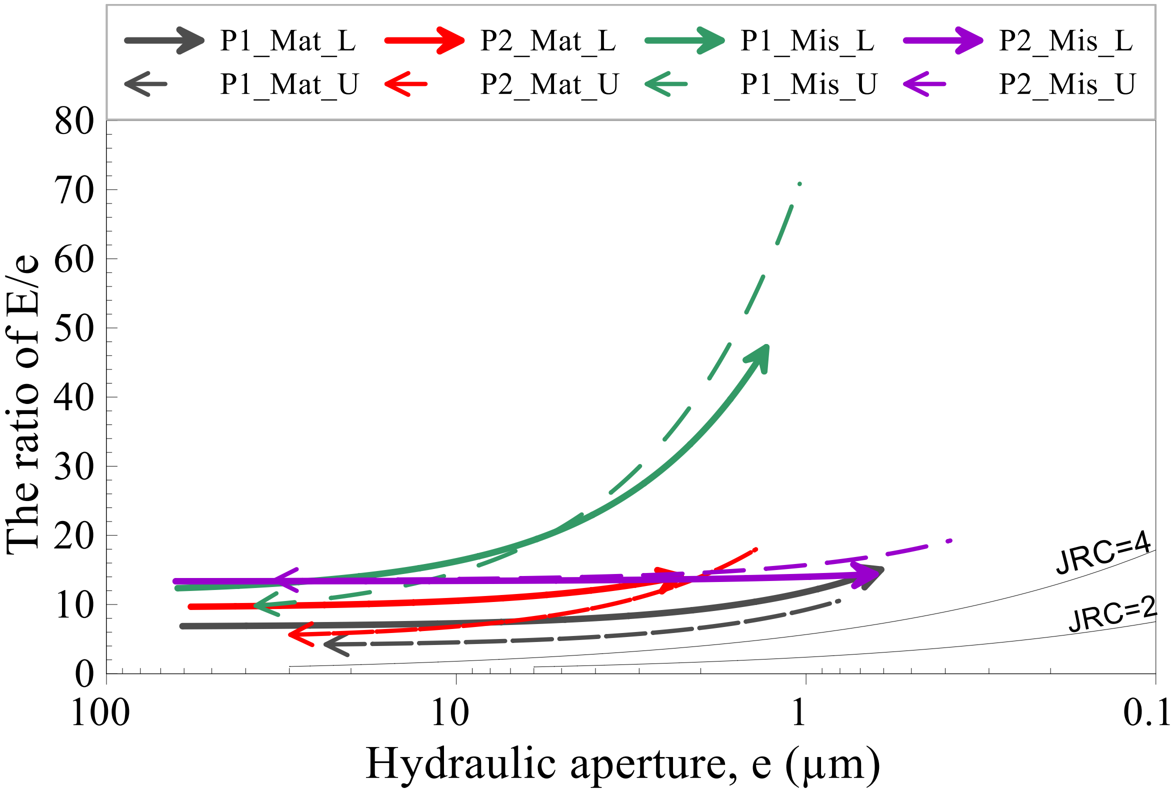


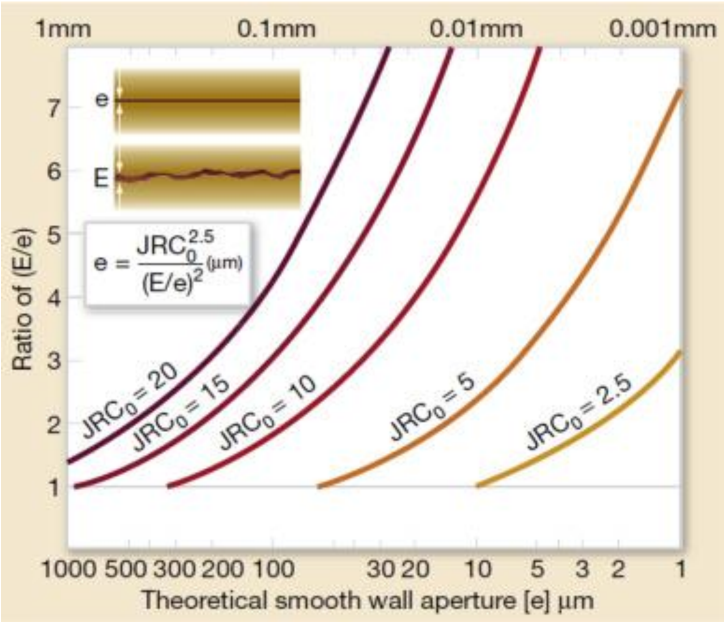
Figure . (a) Fracture aperture along the mismatched surfaces

(b) Boxplots for each mismatched profile , with the central red line representing the median, and the box edges and whiskers denoting the interquartile, and the 5th to 95th percentile range, respectively

***** e vs E relation

1st cycle





(Barton et al. 2019)

≡ JRC
≠Profiles

E_{Mis} ≠
e ≅

- Same **JRC, ≠ Profiles** => **E≠, e ≅ (Mat and Mis)**
- The experimental results indicate that there are still uncertainties when using JRC to predict the relationship of E and e.
- 3D printed samples can be used to improve the understanding of natural subsurface fracture flow.
- E – e relation to other 3D-printed or natural joints requires further research


Thank you