Aalto University
School of Engineering

Master’s thesis - Master's programme in geoengineering
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Fluid flow tests for a non- and dislocated rock fracture of Kuru granite and its replicas

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Introduction

- Nuclear waste disposals: a barrier in the bedrock to isolate waste.
- Radionuclides can escape in the worst-case scenario by fluid flow through fracture networks.
- Understanding of fluid flow through fracture networks and single fractures is important for a safer design

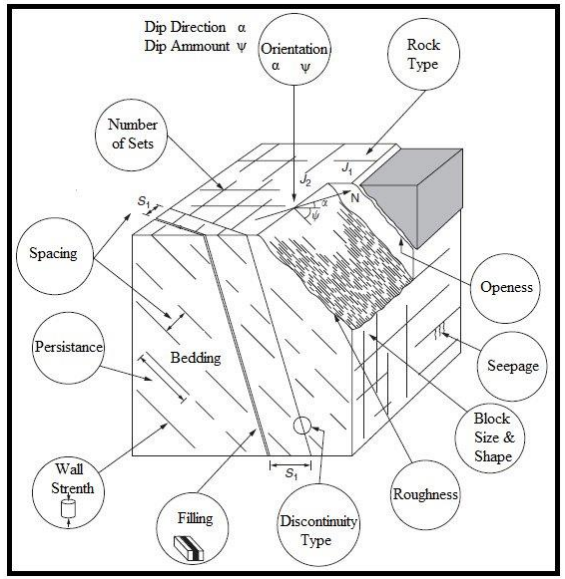
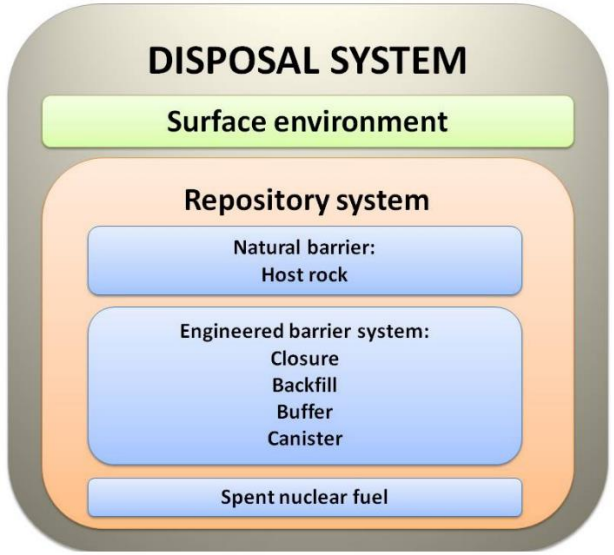


Diagram showing the characteristics of discontinuities in rock masses (Wyllie and Mah, 2017).



The components of the geological disposal system (Posiva Oy, 2012).

Thesis objectives

Dislocation affects fluid flow behavior in rough fractures.

- Developing a fluid flow test method for dislocated fractures.
- Using High-resolution 3D photogrammetry to measure dislocated aperture.
- Using 3D printing to fabricate non- and dislocated physical aperture.
- Measuring fluid flow through real and 3D printed fractures.
- Analyzing dislocation effect on physical aperture distribution and fluid flow behaviour.

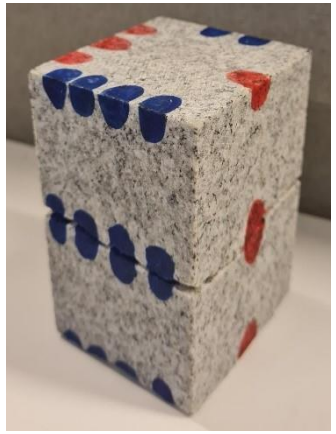
Research questions

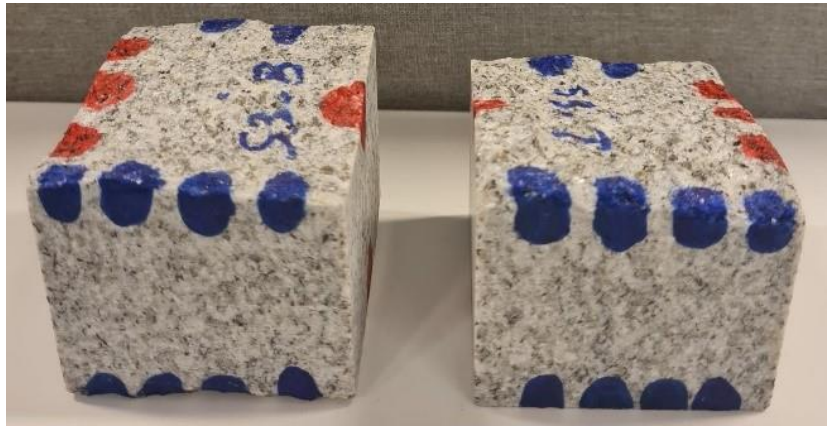
- How does dislocation affect fluid flow behaviour through rock fracture?
- How can photogrammetry and 3D printing be used to produce accurate replicas of fractured rock geometries?
- What limitations exist in using these technologies in fluid flow testing?
- To what extent can the 3D-printed models be generalised to predict fluid movement in naturally fractured rock formations?

Methodology

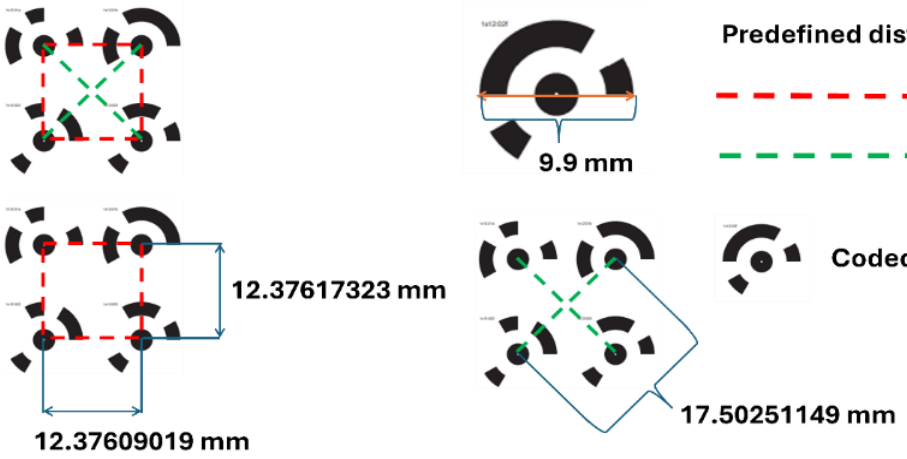
Rock Sample:

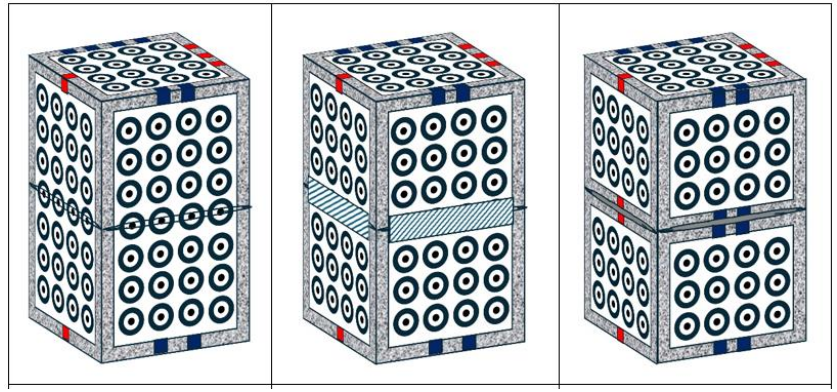
- Rock type: Kuru granite
- Dimensions: 6 cm × 6 cm × 10 cm
- Fracture creation: Tensile fracture





- Circular 20-bit markers, with predefined distances for scaling

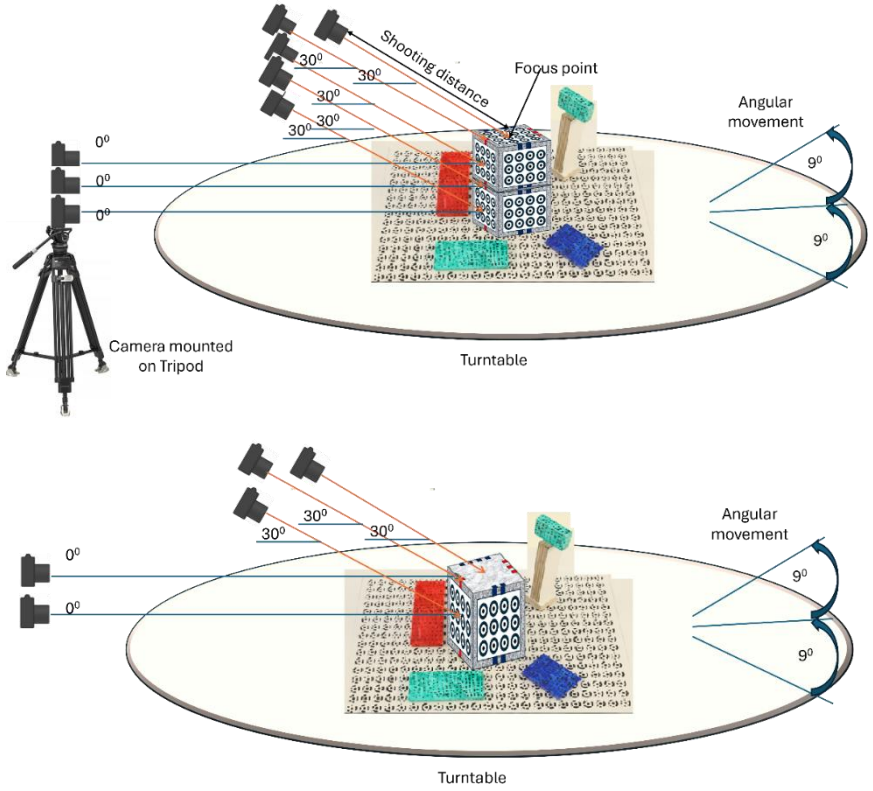




Methodology

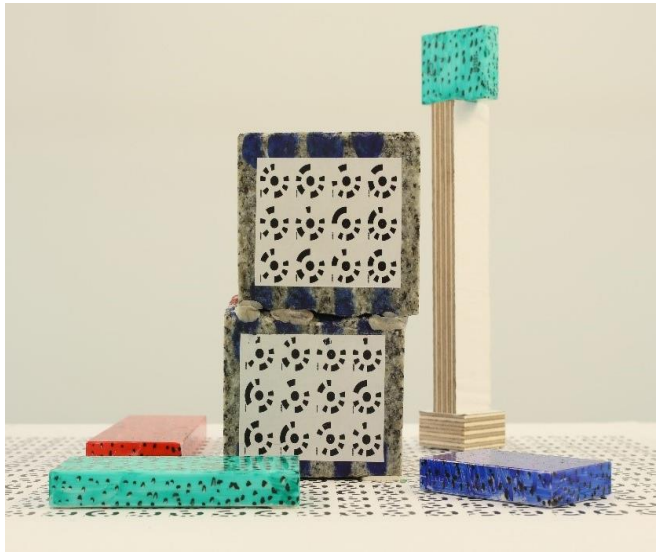
Photogrammetry: A method to reconstruct high detailed 3D models from 2D photos

- A turntable
- Shooting distance: 50 cm
- Shooting angles: 0 ° , 30 ° , 45 ° , and 60 ° angles
- 40 images for each shooting angle with angular movement of 9°
- Four ceramic calibration blocks (25 mm, 50 mm, 75 mm, 100 mm)
- Verifying 3D model accuracy by comparing digital with real dimensions.

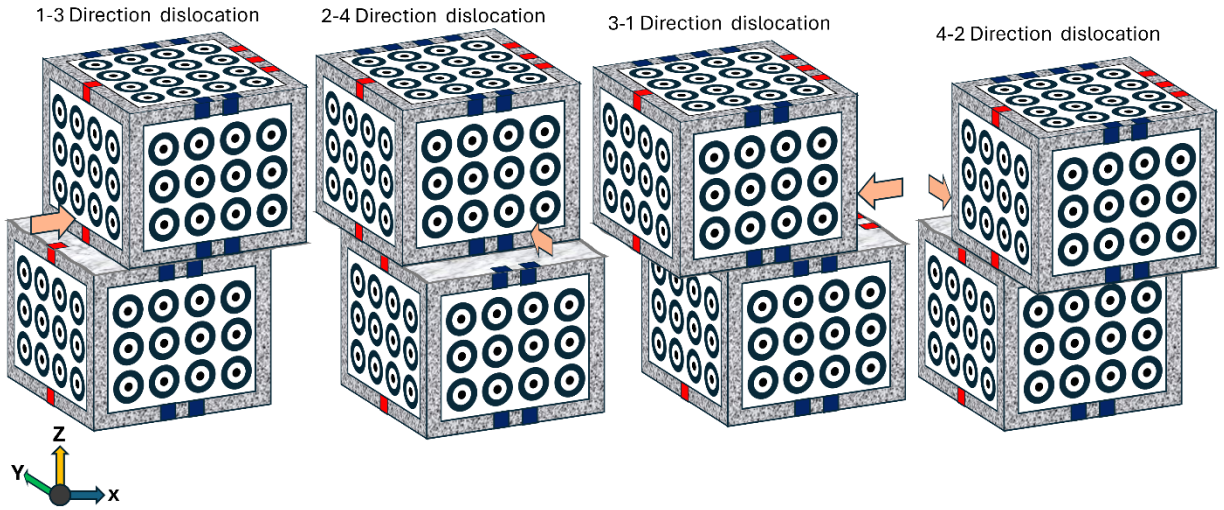


Methodology

Photography of dislocated fractures



- Top half shifted by 1, 2, 3, 4, and 5 mm
- Repeated for directions ±X and ±Y
- Displacements measured using a 10 µm resolution caliper.
- Same procedure as the well-matched used for ones.

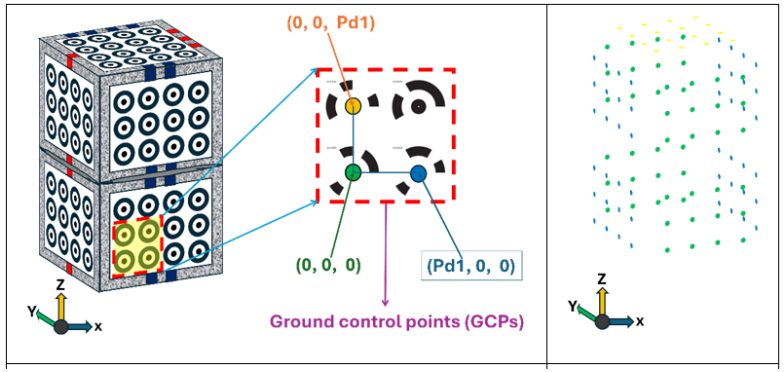


Methodology

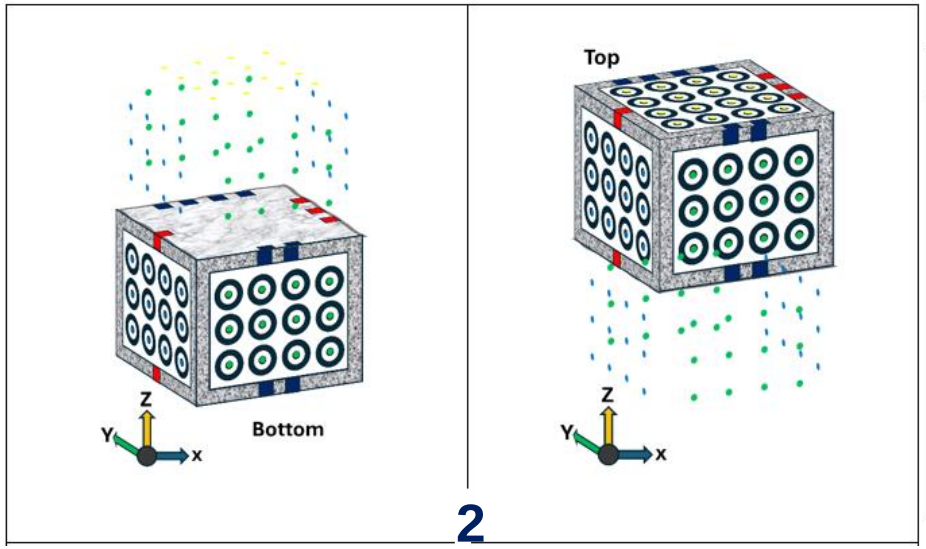
1. 3D models of well-matched and disclocated sample, top and bottom halves reconstructed in RealityCapture 1.4.

2. Predefined distances between markers used for scaling well-matched and dislocated models.

3. Coordinates of markers extracted and used to put the halves in the same coordinate system as well-matched and dislocated samples



1



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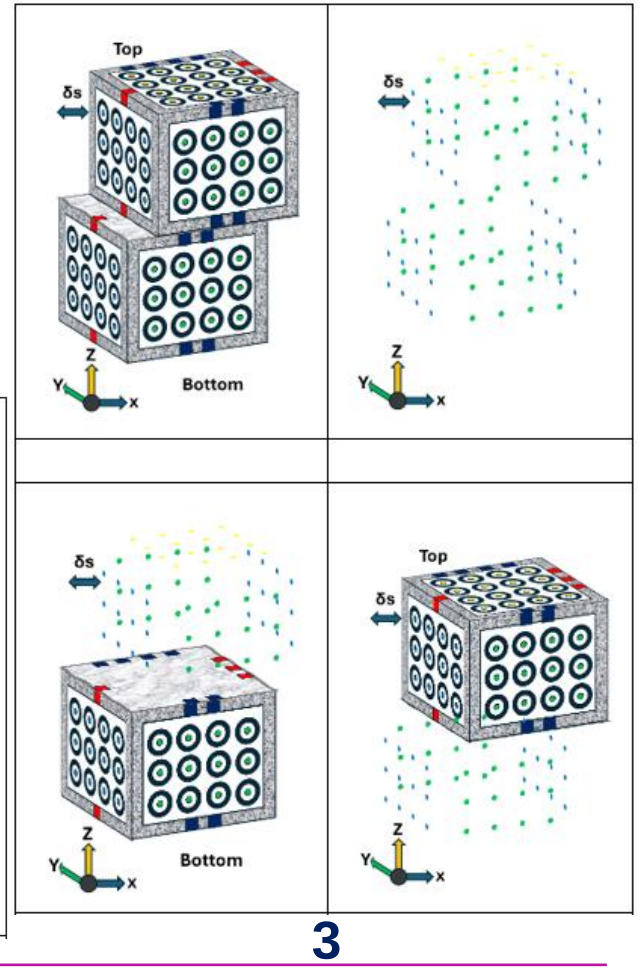
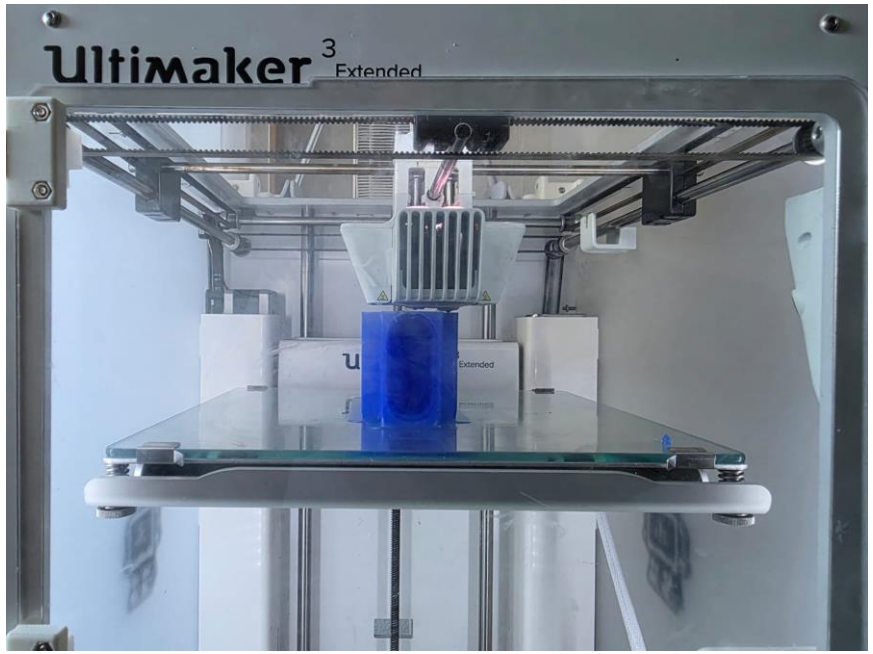


3

Methodology

3D Printing

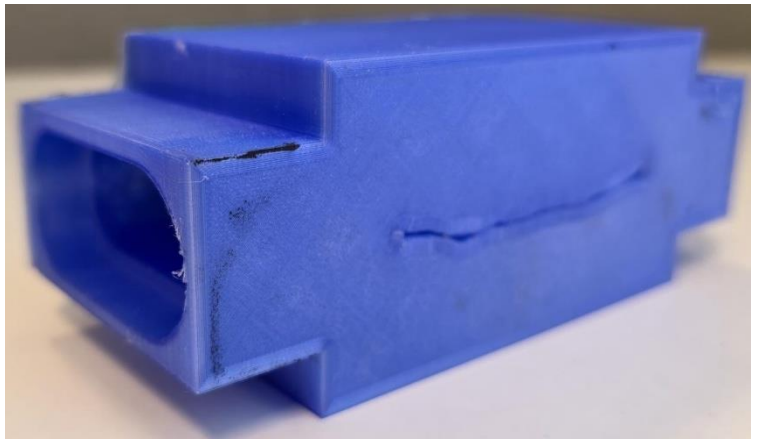
- Printer: Ultimaker 3 Extended Fused Deposition Modelling (FDM) printer, with a 0.25mm nozzle,
- Filament: Polyethylene terephthalate glycol-modified (PET-G).
- Software for printing: Ultimaker Cura 5.7.2
- Software for editing 3D models:
  - CloudCompare (editing and meshing)
  - SOLIDWORKS (editing)
  - Autodesk Mesh Mixers (editing and meshing)



Methodology

Types of 3D printed samples

3D printed replica



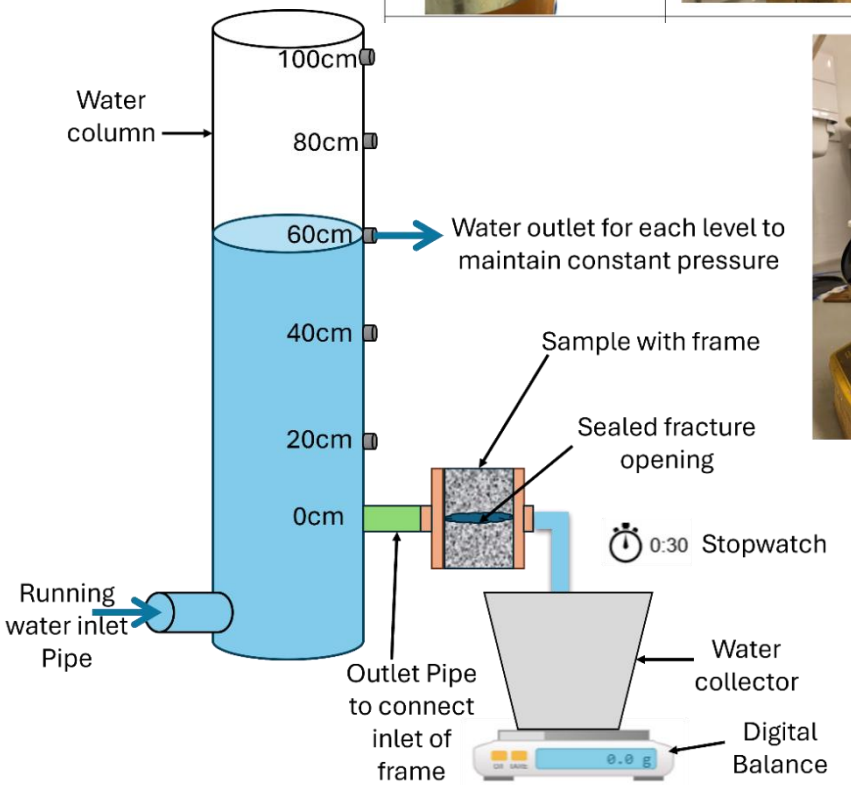
3D printed physical aperture

- Replicas of top and bottom halves

Methodology

Fluid flow test

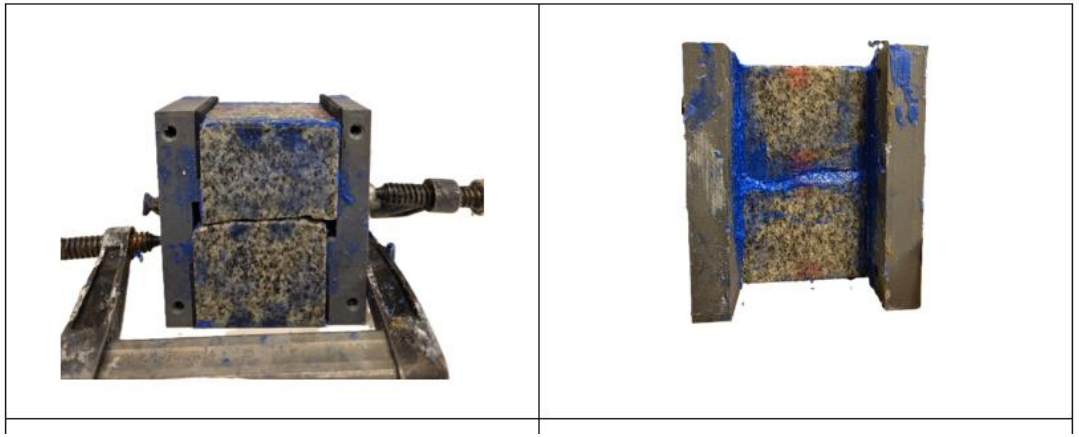
- A water column with a 20 cm interval for different water pressures
- Water in outlet weight measured by a digital balance for a certain time
- Conducted fluid flow tests for different displacements in different directions to evaluate anisotropy
- Using Forchheimer's equation (nonlinear) to calculate hydraulic aperture
- Compared the results of fluid flow tests on real and 3D-printed samples. (well matched and dislocated)

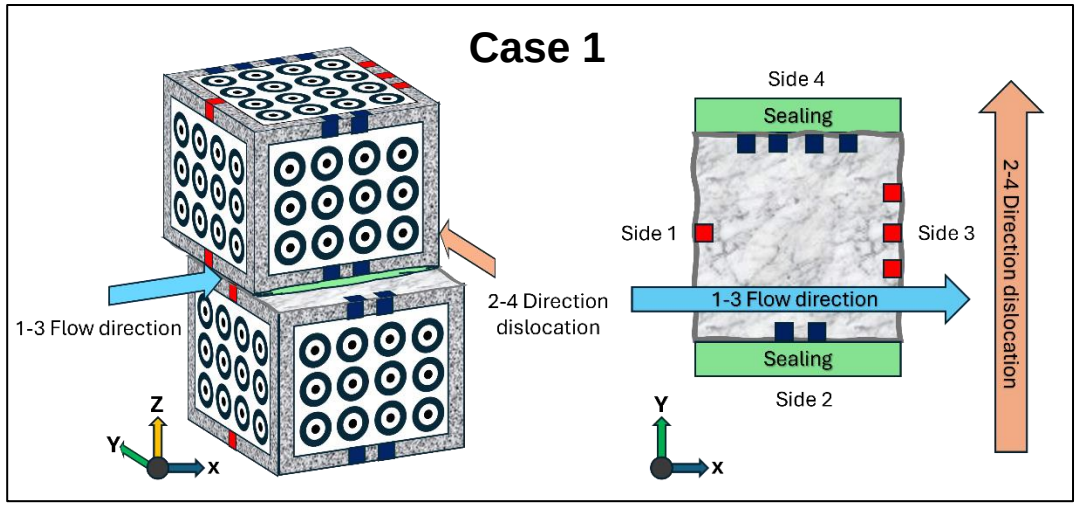


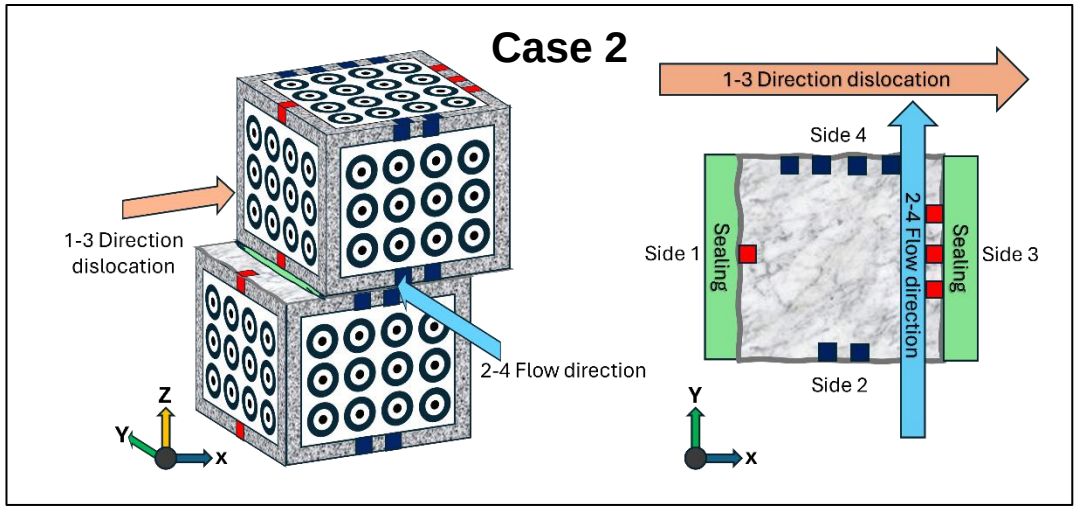
Methodology

Fluid flow test for evaluating the impact of anisotropy

- Fluid flow tested perpendicular to dislocation
- Dislocated in two perpendicular directions
- Fracture sealed along dislocation directions

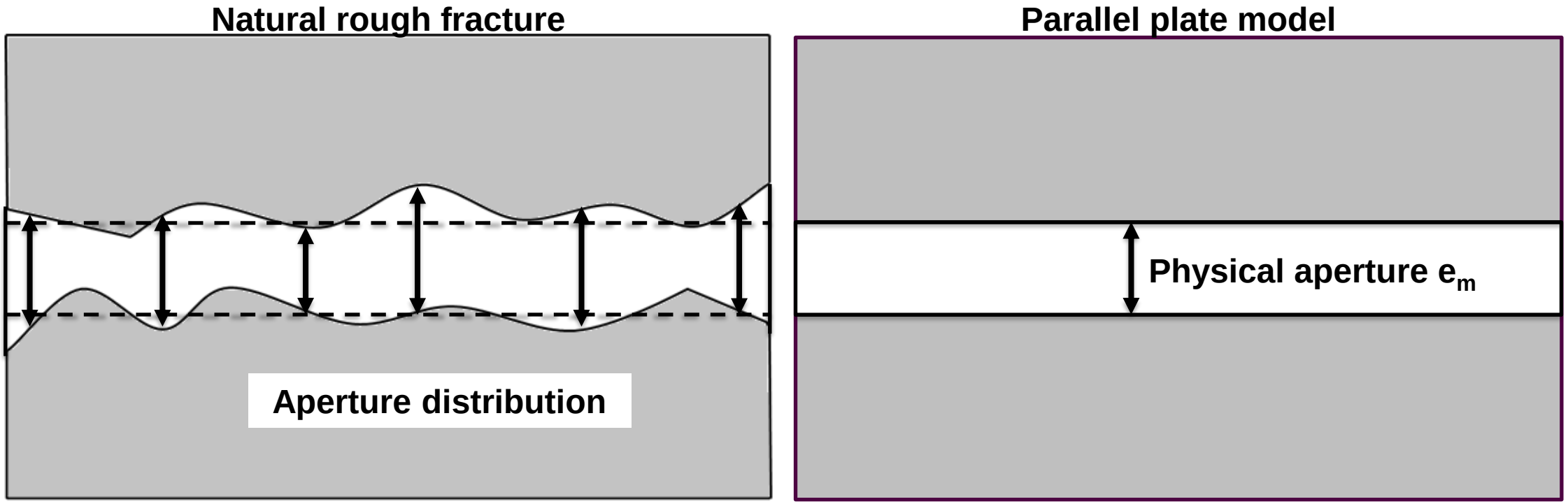






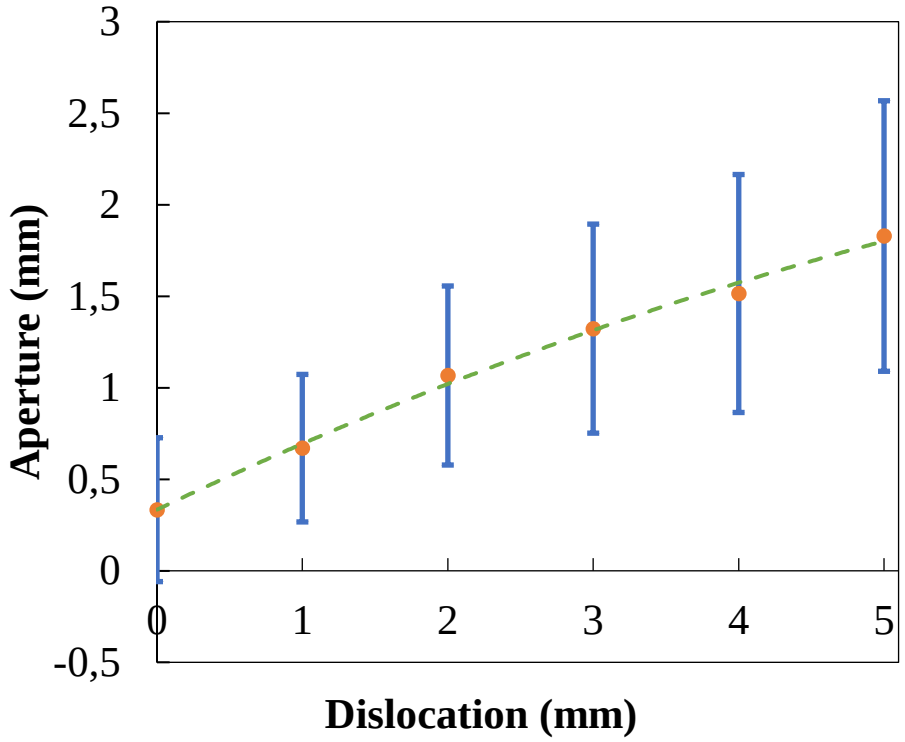
Physical aperture

- Physical aperture: distribution of actual distances between opposing rough fracture surfaces

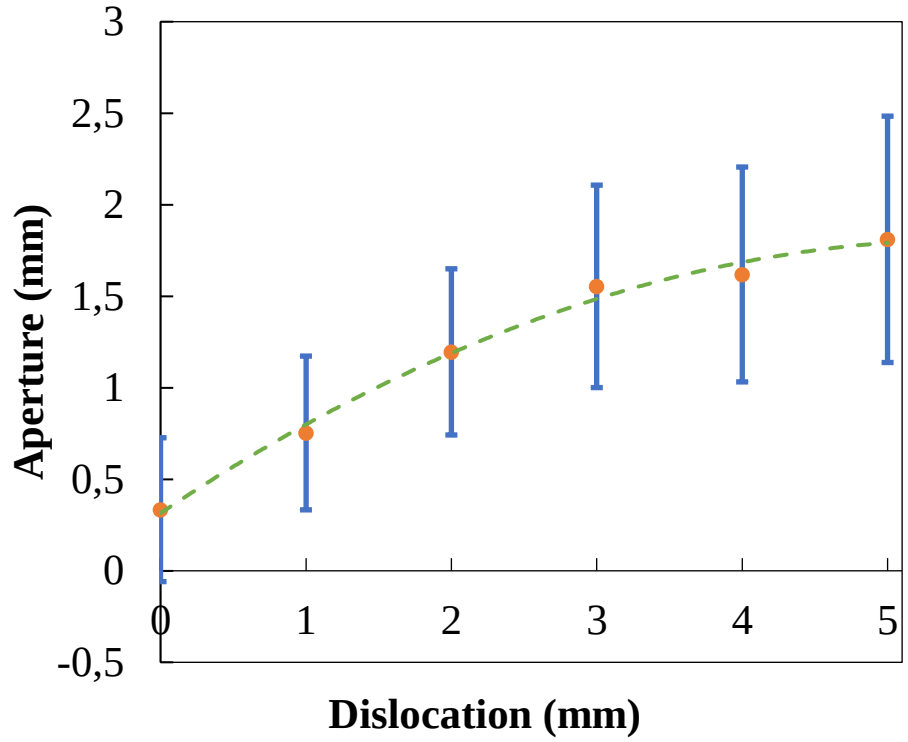


Results

Variation of physical aperture with degree of dislocation



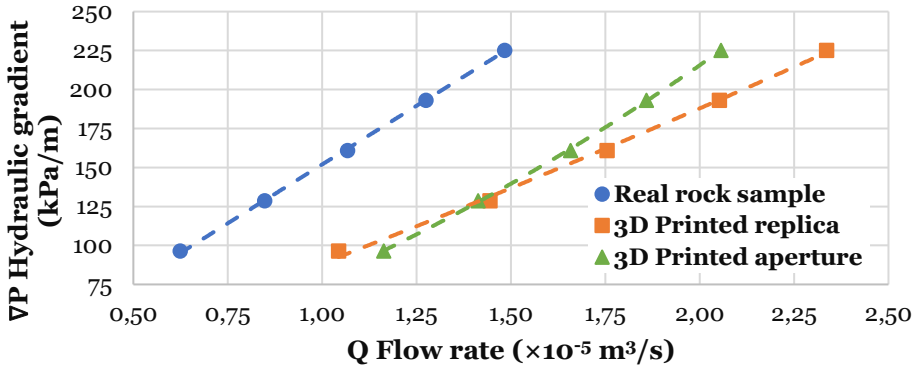
Dislocated in 1-3 direction



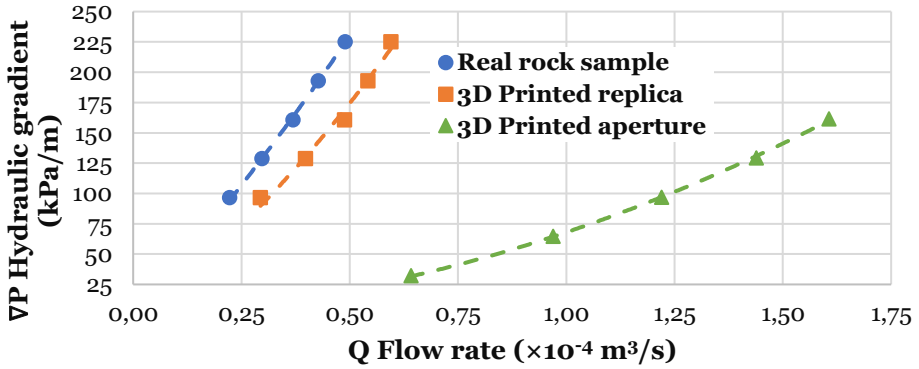
Dislocated in 2-4 direction

Results

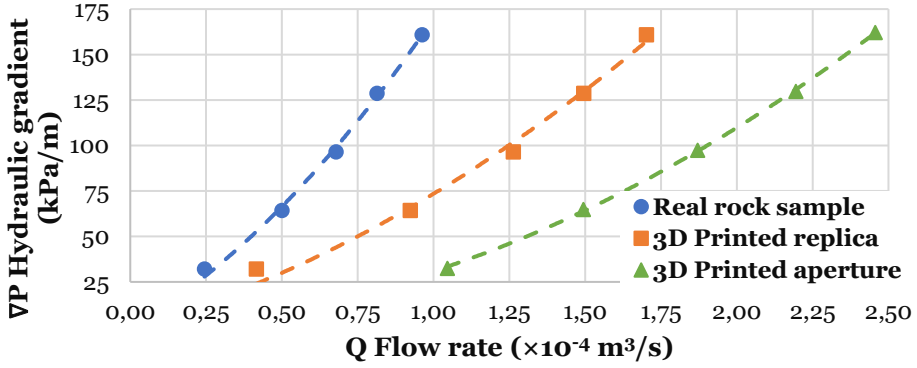
Nonlinear relationship between flow rate and pressure gradient across sample types with dislocation in the 2–4 direction and flow in the 1–3 direction (Case 1)



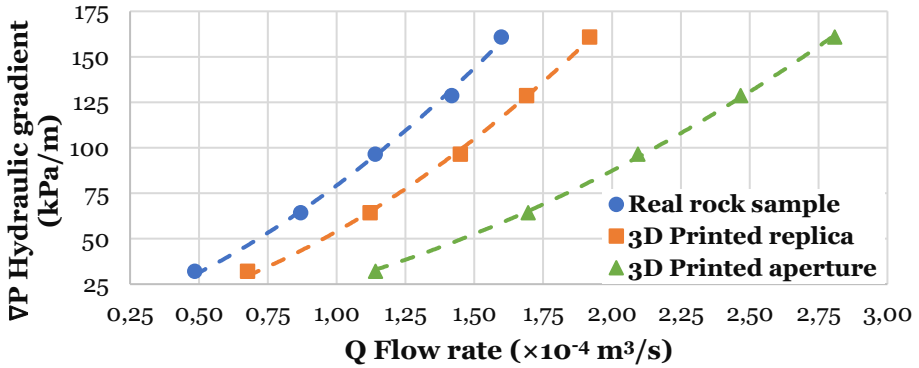
Non-dislocated



1 mm Dislocated



3 mm Dislocated



5 mm Dislocated

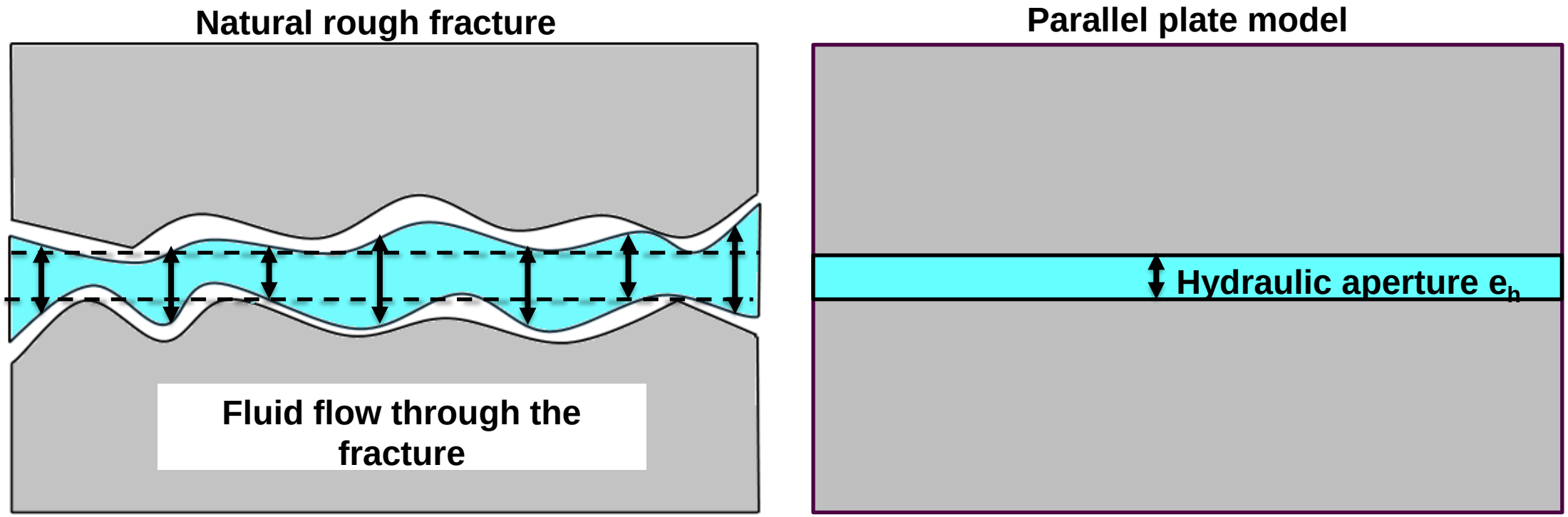
Results

Forchheimer coefficients and calculated non-Darcy coefficients

Flow direction	Dislocated direction	Degree of dislocation (mm)	Real rock sample			3D Printed replica			3D Printed aperture		
			A ($\times 10^8$ kg/m^{5}s)	B ($\times 10^{12}$ kg/m^8)	β (1/m)	A ($\times 10^8$ kg/m^{5}s)	B ($\times 10^{12}$ kg/m^8)	β (1/m)	A ($\times 10^8$ kg/m^{5}s)	B ($\times 10^{12}$ kg/m^8)	β (1/m)
1-3	Well-matched	0	153	12.4	2.29	84.30	52.3	14.38	48.80	295	112.28
	2-4	1	39.50	13.00	5.79	24.40	21	12.91	1.58	5.22	19.45
		3	9.59	7.39	8.08	4.65	2.69	4.76	0.68	2.41	15.01
		5	4.60	3.32	5.65	2.22	3.18	8.80	0.92	1.72	8.43
2-4	Well-matched	0	161	214	38.23	108.00	16.1	3.84	82.00	276	79.04
	1-3	1	40.20	7.35	3.31	26.20	16.7	10.01	5.81	15.90	26.01
		3	7.10	7.82	10.70	4.41	5.01	9.42	1.38	4.18	17.24
		5	3.08	4.61	10.50	2.01	4.31	13.05	0.98	1.51	7.07

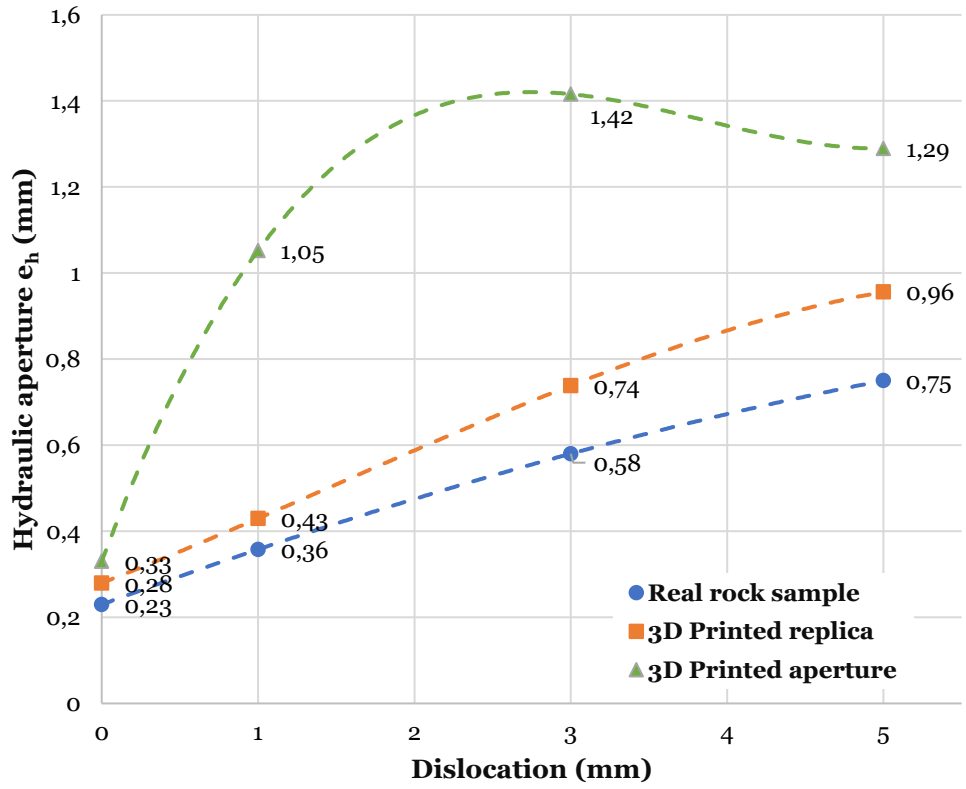
Hydraulic aperture

- Hydraulic aperture: The equivalent aperture between two parallel flat plates that would allow the same flow under the same pressure gradient

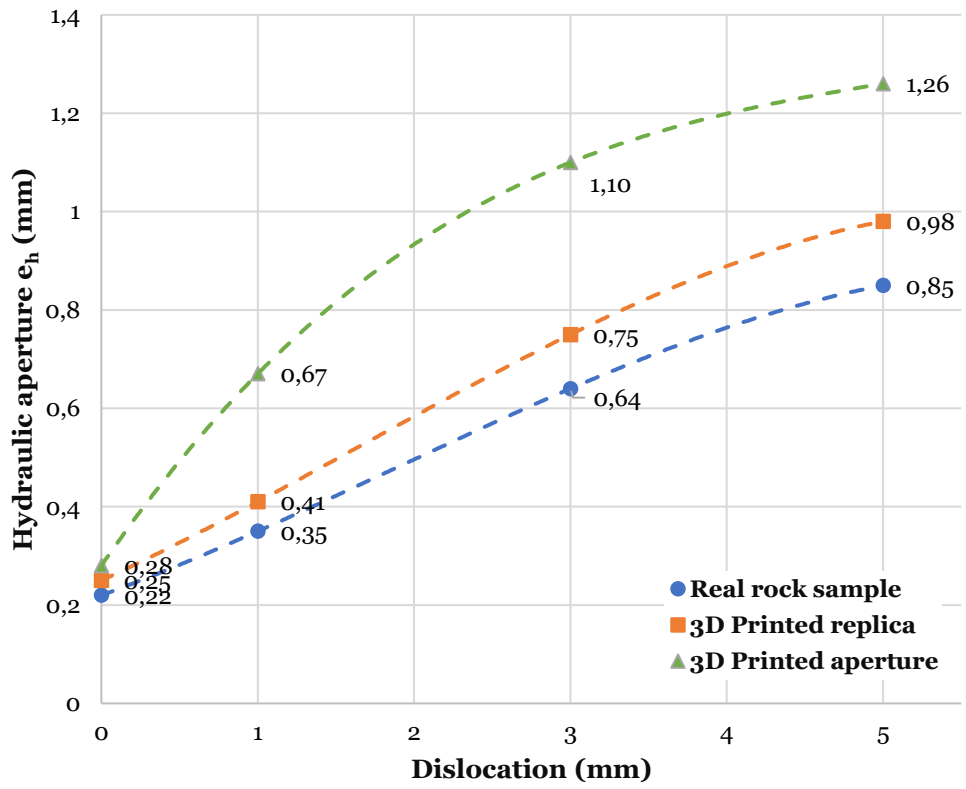


Results

Comparison of hydraulic apertures across sample types and dislocation configurations



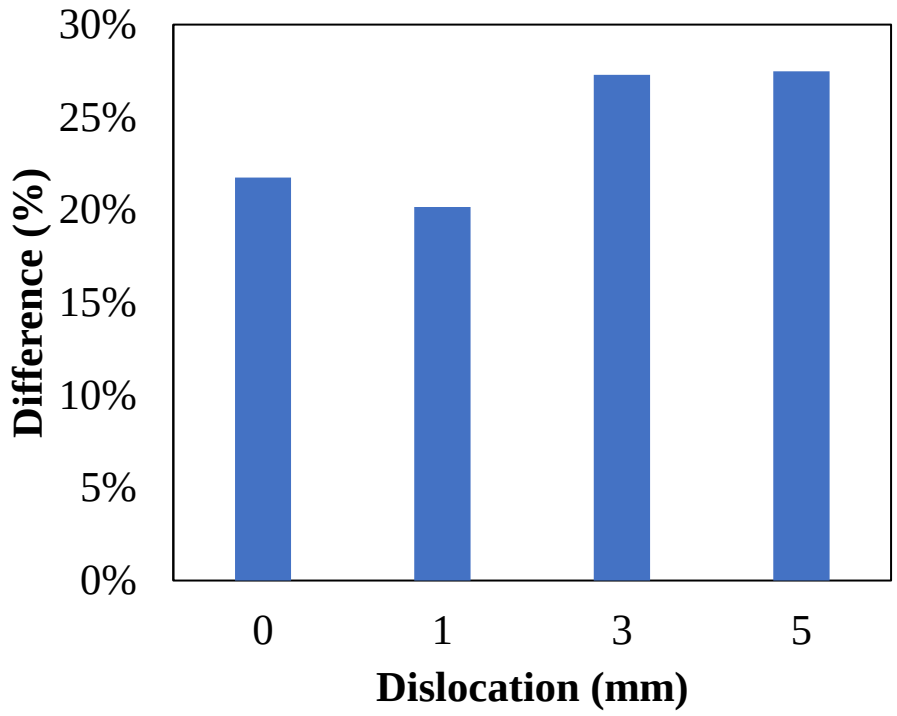
Case 1: Dislocated in the 2-4 direction and the flow in the 1-3 direction



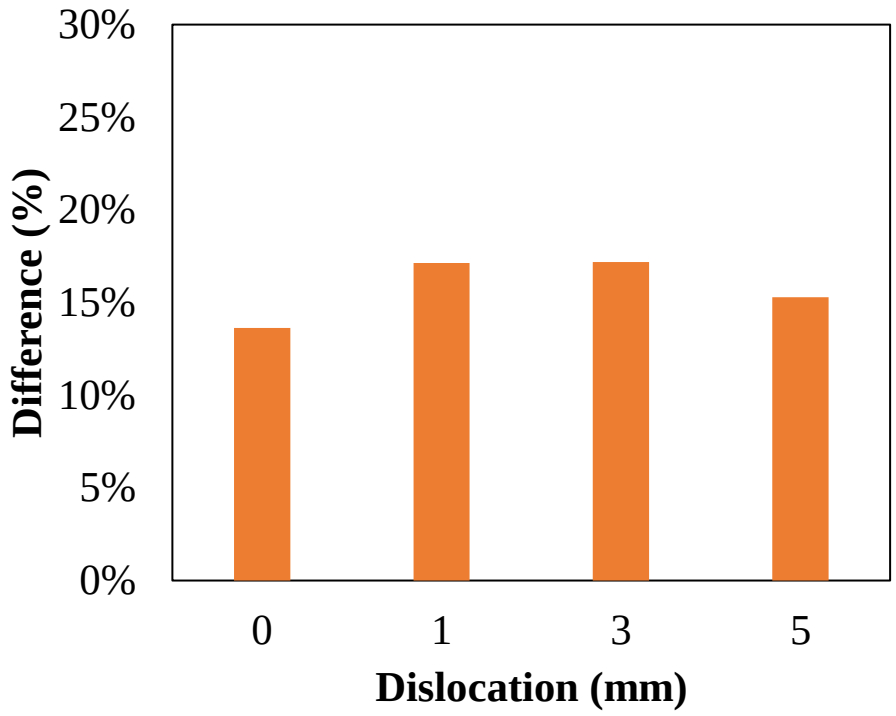
Case 2: Dislocated in the 1-3 direction and the flow in the 2-4 direction.

Results

Percentage differences in hydraulic aperture between the 3D printed replica and the rock sample



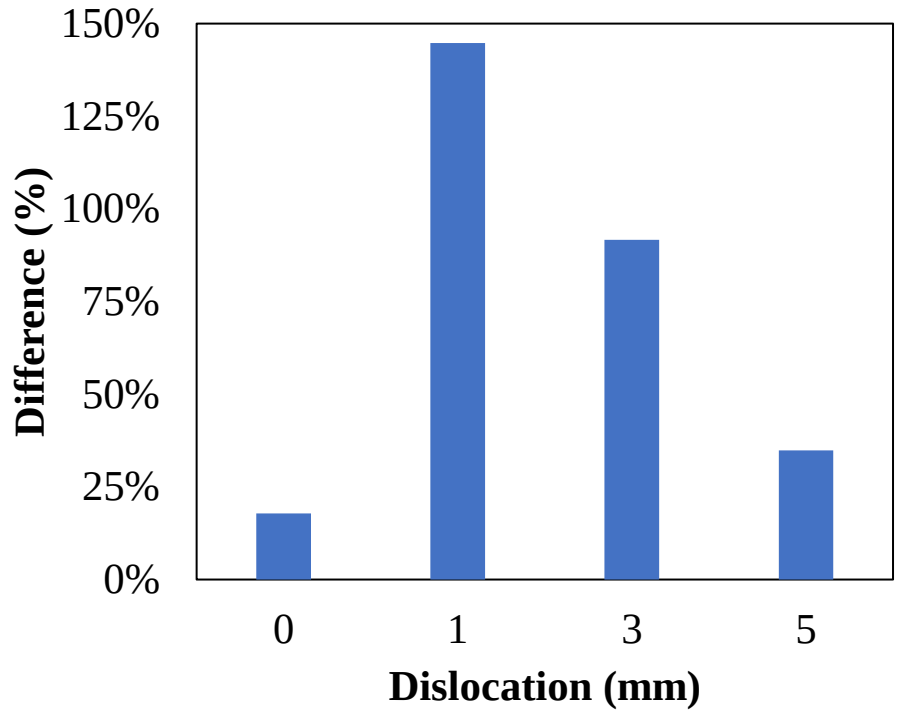
Case 1: Dislocated in the 2-4 direction and the flow in the 1-3 direction



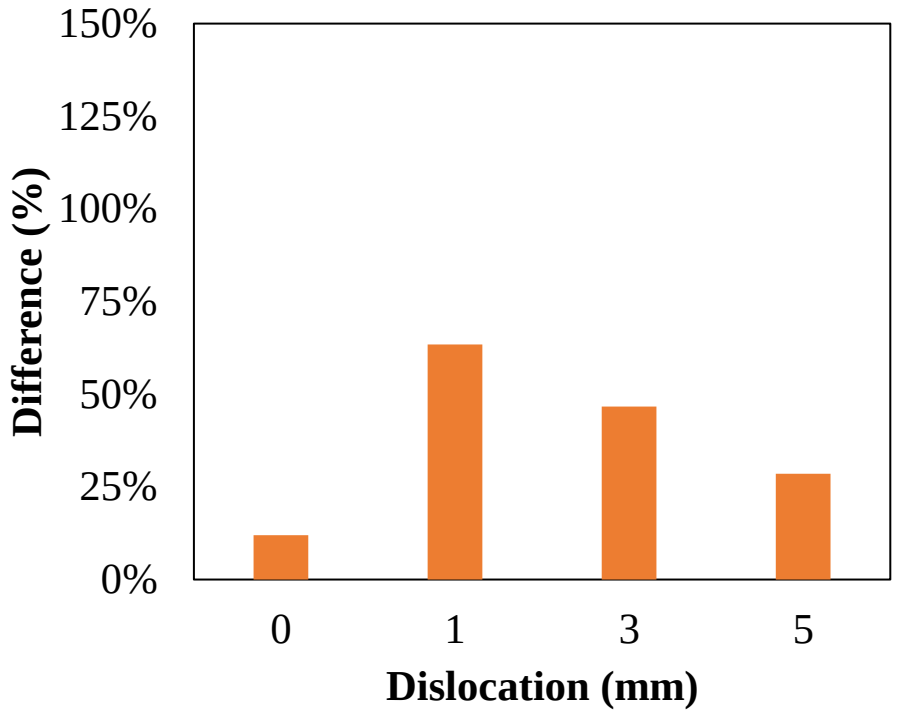
Case 2: Dislocated in the 1-3 direction and the flow in the 2-4 direction.

Results

Percentage differences in hydraulic aperture between the 3D printed physical apertures and the 3D printed replica



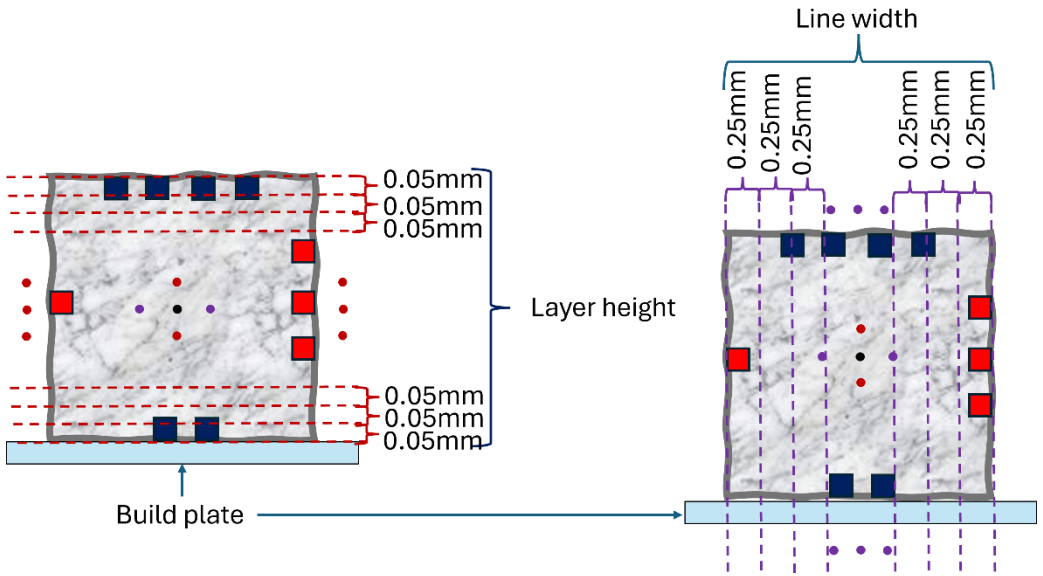
Case 1: Dislocated in the 2-4 direction and the flow in the 1-3 direction



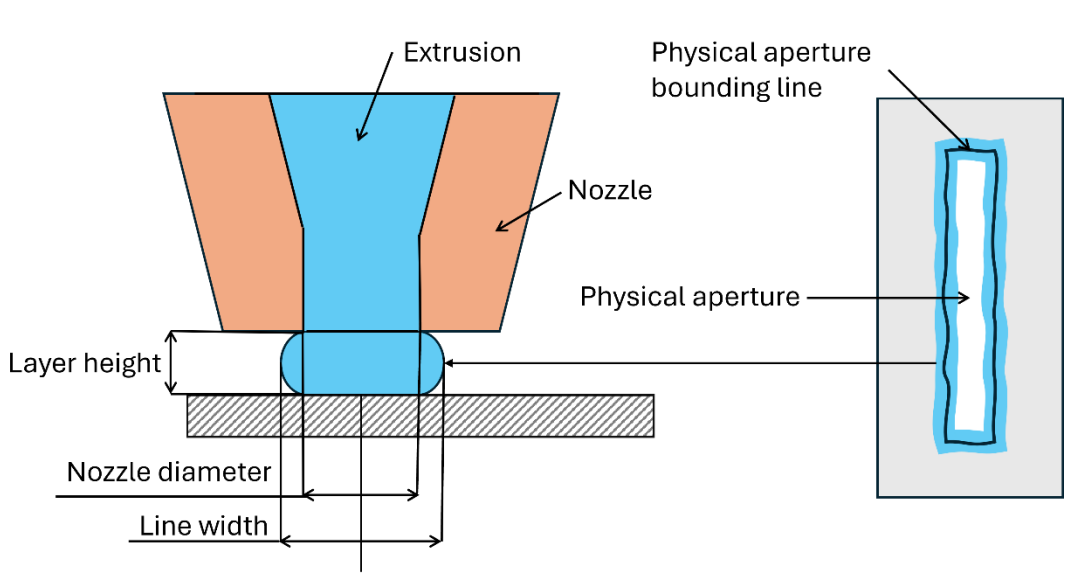
Case 2: Dislocated in the 1-3 direction and the flow in the 2-4 direction.

Results

Limitations in FDM 3D printing



Directional resolution variation in FDM 3D Printing



Nozzle interference resulting in an undersized physical aperture

Conclusion

1. Physical aperture increases nonlinearly with dislocation as fracture surfaces become less mated.

2. Fluid flow is nonlinear and anisotropic, and the Forchheimer equation describes the influence of hydraulic aperture (e_h).

3. Increasing dislocation enlarges the hydraulic aperture, leading to higher flow rates but with anisotropic behaviour.

4. 3D-printed replica shows the same flow trends, but hydraulic apertures are 15–25% higher than the real sample because of limitations in FDM 3D-printing.

5. The uniform 0.4 mm artificial gap adopted in physical aperture reproduction is more effective under well-matched conditions but less accurate with greater dislocation- optimal artificial gap may decrease as dislocation increases.

Future research

1. Proceeding with the same methodology on multiple rock samples of similar and larger sizes for further validation.

2. Conducting fluid flow tests in the direction of the dislocation to better understand anisotropic flow behaviour and how dislocation orientation affects fluid flow.

3. Exploring the influence of 3D printer resolution and slicing tolerances on fracture roughness by using high-resolution and advanced printing technologies.

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Thank You