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Characterizing Nonlinear Fluid Flow in 3D Printed Rock Fractures: Effects of Roughness, Aperture, and Intersection Angles

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Abstract

Understanding fluid flow behavior at fracture intersections is vital to geothermal energy extraction, underground water flow, and CO_2 storage. Here, laboratory experiments were performed to study the effect of surface roughness, intersection angles, and aperture on nonlinear flow behavior in simple fracture networks. A FormLabs (3B+) 3D printer was used to fabricate 8 samples of 38.1mm in diameter and 59.43mm or 54.9mm in length with 2 intersecting fractures of 10° and 40° respectively. The surface roughness of the fractures was based on laser profilometry measurements from two induced mode 1 rock fractures, with a joint roughness coefficient (JRC) of 5 (smoother) and 10 (rougher). The mean apertures of 1mm and 0.7mm for JRC values of 5 and 10, respectively, with an induced mismatch of 1mm. Hydraulic tests were conducted on the intersecting fractures for a range of constant flow rates (20 to 50 ml/min) using a horizontal hydrostatic core holder, and a confining pressure of 1 MPa. The differential pressure was measured to determine the velocity and Reynolds number, Re, to assess the fluid flow behavior through the intersecting fractures.

Re was observed to range from 4.7 to 25.30. An increase in the intersection angle resulted in a decrease in Re, while an increase in roughness results in an increase in Re. The relationship between hydraulic gradient and flow rate is well-described by Forchheimer's law and the Izbash equation, with a high R^2 value of 0.99. The Izbash exponent is observed to increase with the angle of fracture intersection for both JRC values, indicating a deviation from Darcy flow behavior as the fracture intersection angle increases. This suggests that other factors, such as inertial effects, become more influential in governing the flow rate through a fractured medium. Similarly, the Forchheimer coefficient "b" also increases with the angle for both JRC values, indicating that at higher fracture intersections, there is a greater resistance to flow that is attributed to inertial forces. The contribution of viscous forces represented by the Forchheimer coefficient "a" exhibits some variation with respect to the fracture angle and JRC value, lacking a clear and consistent trend. Understanding this behavior is important for the prediction and management of fluid flow through fractured geological formations.

Objectives

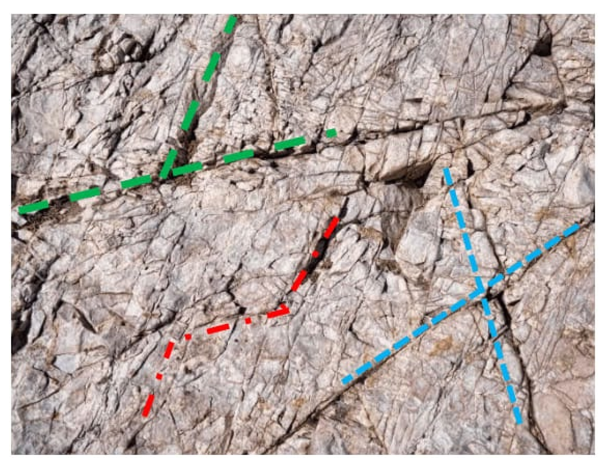

Fig. 1. Fractures in a rock outcrop highlighting the most common naturally occurring: the blue is the X-crossing fracture, in red the Z fracture, and green is the Y fracture

The study aims to achieve the following objectives:

- Gain insights into the dynamics of fluid flow within fractured rock masses.
- Explore and quantify the effects of surface roughness on fluid flow behavior.
- Investigate the interplay of surface roughness, aperture, and contact areas in shaping transport processes
- within fractured rock systems.
- Assess the impact of varied fracture crossings on flow behavior and its consequent effects on transport within
- fracture networks.
- Evaluate the influence of intersections on the overall fluid flow dynamics.

Methodology

Numerical models preparation:

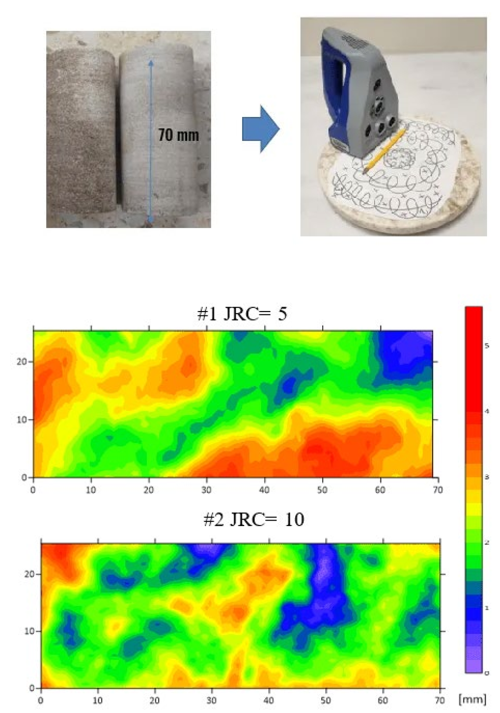

Fig 2. Rough surfaces preparation.

To authentically replicate the surface roughness observed in natural rock fractures, a specialized fracture model was devised. This model integrates anisotropy along with variable aperture sizes and asperity contacts. The construction of these fracture models involved a sequence of numerical procedures. Commencing with an "uplift" movement of 1 mm and 0.7 mm, the process was further advanced by a "shear" movement. This particular movement entailed the displacement of the upper surface along the X direction, incorporating a shear displacement of 1.0 mm. These sequential steps were iteratively executed to generate individual fracture models with precision and accuracy.

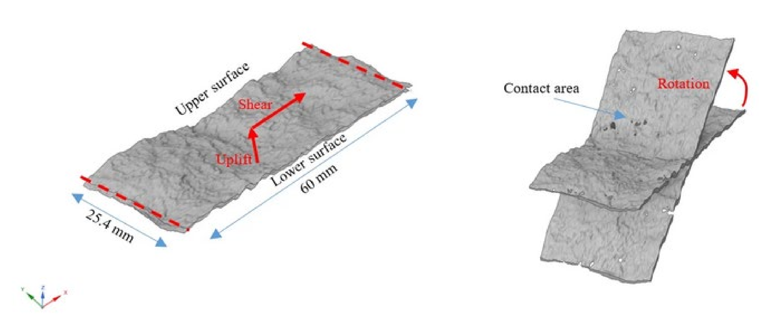

Fig 3. Numerical generation of 40 degrees X-crossing fractures.

Physical 3d printed models preparation:

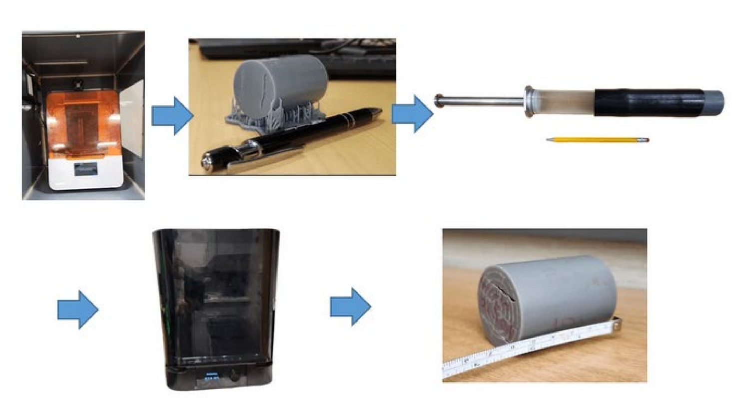

Fig 4. 3d printing procedure.

Laboratory Experiments

To precisely determine the flow rate, we employed a syringe pump (BTSP 175-15) with a resolution of 0.0001 mL/min for injecting fluid in our experimental setup. The pump delivered the fluid into the model, and the resulting effluent at the outlet was collected and weighed using an electronic balance. Rigorous cross-verification of the effluent and injection rates was conducted to ensure a consistent flow rate devoid of any leaks. The hydraulic pressure difference between the inlet and outlet was measured by a differential transducer (EJX110A, Yokogawa) with a resolution of 10 Pa. Each 3D-printed sample was encased in a rubber sleeve and positioned within the hydrostatic core holder (HYC 700B, VINCI). To maintain sample integrity, a confining pressure of 150 psi was applied. Subsequently, we initiated a constant flow rate of 50 mL/min into the model to purge air until saturation was attained. Following this, the flow rate was reset to 0, and a fluid flow test was carried out with incremental flow rates. The flow rates of distilled water varied between 0 ml/s and 50 ml/s, with a viscosity of 0.001 N s/m^2 at room temperature.

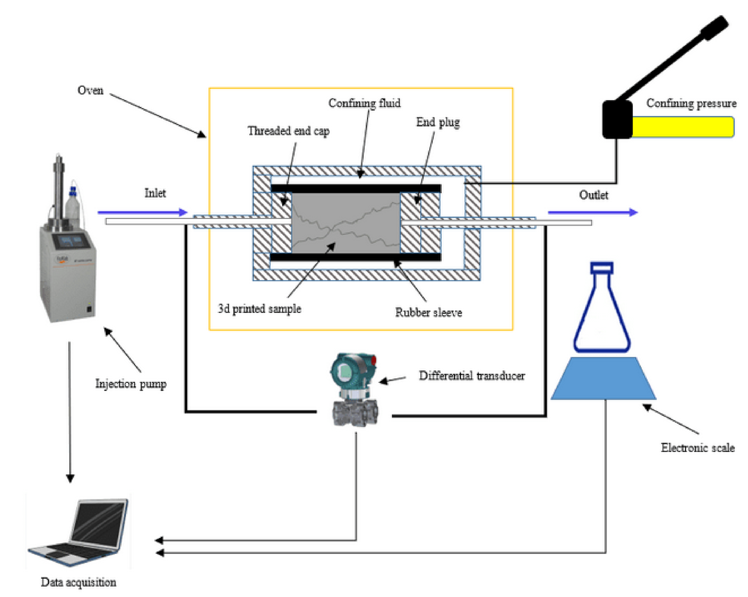

Fig 5. Schematic view of the system designed to test the fluid flow

Conclusion

In conclusion, this study delves into the critical realm of understanding fluid flow behavior at fracture intersections, shedding light on its significance in applications such as geothermal energy extraction, underground water flow, and CO2 storage. Employing laboratory experiments with 3D- printed fracture samples, this research investigates the impact of surface roughness, intersection angles, and aperture on nonlinear flow behavior in simple fracture networks. The hydraulic tests conducted reveal intriguing patterns, indicating that an increase in intersection angle correlates with a decrease in Reynolds number (Re), while heightened surface roughness leads to an increase in Re. The observed deviations from Darcy flow behavior, as indicated by the Izbash exponent and Forchheimer coefficient trends, underscore the growing influence of factors like inertial effects at higher fracture intersections. These findings hold crucial implications for predicting and managing fluid flow in fractured geological formations, emphasizing the nuanced interplay of various parameters in governing such systems.

Acknowledgment

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Results

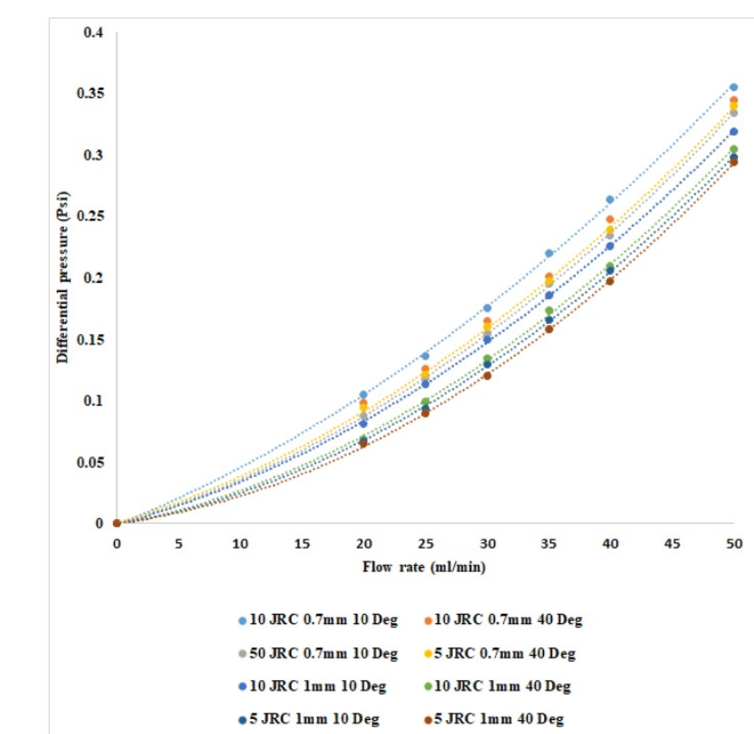

Fig 6. Differential pressure vs flow rate for different roughness

To assess the fluid flow parameters two equations have been employed :

Izbash equation :

$$-\nabla P = \lambda Q^n$$

Where :

where λ and n are empirical coefficients determined by regression analysis

and

Forchheimer equation:

$$-\nabla P = AQ + BQ^2$$

Where:

where

− ∇P is the hydraulic gradient, and Q is the fracture flow rate. (AQ) is the linear viscosity and (BQ) is the nonlinear inertia.

The results of the Izabash exponent (n) and the Forchheimer parameters (a and b) for the different X-shaped rough fractures are summarized in the following tables :

	10 JRC		5 JRC	
	0.7 mm			
	Angle 10	Angle 40	Angle 10	Angle 40
Izbash exponent, n	1.35	1.38	1.458	1.403
Forchheimer a (s/m)	80.6	48.53	58.35	50.462
Forchheimer b (1/m)	1140.8	2393.1	3051.1	4561

	10 JRC		5 JRC	
	1 mm			
	Angle 10	Angle 40	Angle 10	Angle 40
Izbash exponent, n	1.4872	1.6151	1.6421	1.653
Forchheimer a (s/m)	100.46	102.13	88.5	20.9
Forchheimer b (1/m)	3952.5	6274	6295.1	11516