International Journal of Rock Mechanics & Mining Sciences 73 (2015) 139–155

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Experimental and visual analysis of single-phase flow through rough fracture replicas

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ARTICLE INFO

Article history:
Received 26 August 2014
Received in revised form
31 October 2014
Accepted 6 November 2014
Available online 29 November 2014

Keywords:
Fracture roughness
Fractal dimension
Single phase flow
Transmissivity
Flow visualization

ABSTRACT

Single phase water flow experiments were performed on seven tightly-closed, rough model fractures. Each model has mirror-image transparent upper and opaque lower walls reproduced from the original single fractures created by laboratory indirect tensile tests of different rock types. The experiments were conducted under both non-loading and normal loading conditions as well as in two opposite injection directions. Surface roughness of model fractures was quantified using variogram fractal dimension.

While a short linear portion was distinguished in the beginning, pressure versus injection rate curves showed nonlinear characteristic at higher values. This nonlinearity was attributed to the predominance of fracture expansion compensating the turbulence effect. This was the case regardless of injection direction and loading. The compensation of turbulence effect developed earlier for rough fractures compared to the smooth parallel plate model and was longer for the fractures with higher fractal dimensions. Transmissivity values showed a decrease with increasing fractal dimensions and normal loading, and also exhibited directional-dependent behaviour. The percentages of water-invaded wet planar areas showed a tendency to decrease with increasing fractal dimension. This relationship was more obvious with a higher correlation when the fractal dimension was replaced by the ratio of fracture surface area to the apparent fracture area, which was used as another parameter to quantify the roughness. The percentage of the dry planar areas that do not involve any flow could be as high as 20% and is controlled by tortuous flow channeling.

1. Introduction

Individual fractures in a rock mass constitute a network of fractures by intersecting each other and fluid flow in the network is predominantly controlled by them. Hence, understanding the flow in a single fracture is prerequisite for modelling flow throughout more complex entire fracture network [1–8]. Fluid flow through a single rock fracture is commonly approximated by the analogy of parallel plate model where laminar flow between two perfectly smooth parallel plates separated from each other by a constant distance is assumed. According to this model, the permeability in the fracture, k_{fr}, is defined as [9,10]:

$$k_{fr} = \frac{b^2}{12} \tag{1}$$

where "b" defines the separation distance between the plates, and it is called aperture.

On the other hand, Darcy's law is used to express the relationship between the rate (Q [m^3/s]) and pressure drop (ΔP [Pa]) in a porous medium [11,12]:

$$Q = -\frac{kA}{\mu}\frac{\Delta P}{L} \tag{2}$$

where k [m^2] is the permeability of the medium, A [m^2] is the cross-sectional flow area, μ [Pa s] is the viscosity of the fluid, and L [m] is the medium length over which the pressure drop takes place. If the permeability of a rock is just caused by a single fracture due to impermeable rock matrix, the parameter k in Eq. (2) can be considered as the fracture permeability. In this case, the product of the fracture width (w), perpendicular to the flow direction, and the fracture aperture (b) are substituted as cross-sectional area of fracture in Eq. (2). If the expression in Eq. (1) is substituted into Eq. (2) by taking cross-sectional flow area of fracture as $A = wb$ [2,8,13], then the following relationship between the rate and pressure drop is obtained:

$$Q = -\frac{\Delta P}{L\mu}\frac{wb^3}{12} \tag{3}$$

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http://dx.doi.org/10.1016/j.ijrmms.2014.11.002
1365-1609/

where the volumetric flow rate, Q, varies as the cube of the separation distance (aperture), b, between the plates [9]. The term kA in Eq. (2) is equal to the term $wb^3/12$ in Eq. (3) and they are called fracture transmissivity with a unit of [m^4] [2]:

$$T = kA = \frac{wb^3}{12} \tag{4}$$

The transmissivity yielded by the parallel plate model, i.e., no tortuosity of fracture surface is considered, is known as the cubic law [2,14,15].

Darcy's law is a linear expression and considered to be applicable for laminar flows in porous media [11,16,17]. Similarly, the cubic law (Eq. (3)) derived from Darcy's law also exposes a linearly proportional relationship between the flow rate and pressure drop of a flow through two parallel flat (or smooth) plates. In reality, rock fractures present considerable roughness on their facing surfaces. The aperture is a critical parameter controlling the effect of roughness on the hydraulic properties of a single fracture. This effect could be slight [14] or negligibly low [15] if the aperture is large. In reality, however, the apertures are so small that the roughness critically affects the fluid flow characteristics. In this case, the validity of the cubic law should be questioned [18,19]. In an attempt to take the roughness effect into consideration, a friction factor was introduced and included the ideal cubic law [18].

In the case of flow between two rough fracture surfaces, different flow regimes can be observed. Although some laboratory water flow tests through rough fractures exposed linear dependency between the flow rate and pressure [3,8], non-linear flow behaviour has commonly been experienced in experiments or simulations by different investigators [7,20–24]. When flow behaviour is non-linear, the approximate value or range of the Reynolds number around which the transition from laminar flow to turbulent regime occurs is about 500 for smooth parallel-walled fractures [25], between 650 and 700 for a pair of artificially-roughened parallel plates [22], between 1 and 10 for different geological materials of porous media [26], about 10 for a natural sandstone fracture [20]. Existence of weak inertia regime between 1 and 10 and observation of the Forchheimer-type flow above approximately 20 were also reported by Zimmerman et al. [20]. Over the range between 2.8 and 14.3, a quadratic flow behaviour was reported by Konzuk and Kueper [7] for a tensile fracture of a dolomitic limestone block.

Rough surfaces of a fracture may entirely contact and perfectly interlock each other over the whole fracture without any considerable void space, forming a tightly closed joint with no aperture, theoretically [27]. Or, the relative displacement of the adjacent walls of this pre-existing closed fracture in vertical (normal) or horizontal direction (shearing or faulting) may result in constant or variable aperture structure, respectively. Sheared surfaces usually contact each other at some local zones and void spaces of different sizes and shapes surround these zones [28]. Hakami and Larsson [29] and Drazer and Koplik [30] studied the hydro-mechanically coupled behaviours of such fractures with mechanically-displaced adjacent walls.

As summarized above, unlike a pair of smooth parallel plates of a uniform aperture, real rock fractures mostly exhibit a wide variety of quite complex geometries. The terms "roughness", "contact areas", and "aperture structure (constant or variable)" describe the major geometrical parameters for the characterization of rock fractures. These parameters cause flow to exhibit channelled character, generally following one or more twisted paths with many inflection points. This property of the channeled flow paths is expressed by the term "tortuosity". From the numerical studies using electrical analog technique [31] and 3D lattice gas methods [32], the parallel plate model was found as an oversimplified approach for rough fracture flow since the effects of fracture geometrical parameters are not taken into consideration. Tsang [31] reported that actual flow rate for a fracture can be three or more orders of magnitude lower than the value predicted by the parallel plate assumption. Zimmerman and Bodvarsson [2] classified the possible causes of deviation under two categories. At low flow rates, geometrical fracture parameters control the flow showing the least resistance to the flow due to the largest aperture. This resulted in the rectilinear streamlines of the parallel plate model to depart from linearity. At sufficiently high velocities, the turbulence effect becomes critically important.

Chen et al. [13] emphasized that roughness, contact areas, and tortuosity may cause inertial losses, variations in flow velocity and direction because of constrictions and obstructions, and initiation of turbulence due to localised eddy flow formation. These features may result in non-linear behavior of single phase flow. Brush and Thomson [33] expressed that contacting rough fracture walls with variable aperture results in a three-dimensional, non-uniform, tortuous flow field. In accordance with the classification by Zimmerman and Bodvarsson [2], they also added that this complicated flow pattern can produce non-negligible inertial forces even though the flow field is laminar and causes flow to be non-linearly dependent on the imposed hydraulic gradient.

Similar conclusions were also reached from the experimental and numerical works of Murata et al. [34] and Murata and Saito [6]. They showed that roughness and contact areas make the flow path tortuous and this causes deviations from the cubic law. The validity of the local cubic law was also questioned by Oron and Berkowitz [35] and Berkowitz [36]. The adequacy of the cubic law for rough rock fractures was remarked by Berkowitz [36] as an open question due to the difficulty in obtaining reliable data of aperture.

In conjunction with the above summarized works, to clarify the deviation from the cubic law one needs to experiment with the flow processes on fracture models representing the nature of the surface roughness realistically. In an effort to incorporate this, several studies used natural fractures or synthetically created tensile fractures or replica models reproduced from the both types in their single phase flow experiments [3,6–8,13,20,29,34,37,38]. Another group of studies, on the other hand, performed single phase flow experiments on artificially roughened parallel rock plates and semi-fracture models [39,40] or idealized fracture models with simulated roughness [21–23].

2. Objective of the study and methodology

As it is seen, considerable attention was given to understand how fluid flow in a single rock fracture is governed. A general agreement reached in literature is that realistic fracture samples; i.e., the replicas of original fracture surfaces are needed to clarify the effect of roughness on single phase flow, especially deviations from the cubic law, identification of flow regimes (laminar and turbulence), and channel flow [19,21–24]. In his pioneering review paper on the hydraulic properties of rock fractures, Berkowitz [36] pointed out the surface roughness as one of the unresolved issues in flow phenomena through single fractures. A variety of fracture samples were used in literature such as a natural fracture [37], a natural granite fracture [3], a replica of a natural fracture [38], three natural granite fractures [13], five replicas from the fractures of a sandstone [41], a dolomitic limestone tensile fracture [7], replicas of three granite fractures [29], three granite tensile fractures [8]). Although valuable analyses on different aspects of flow in fractured media were provided in these studies, no direct correlations to the quantitatively defined roughness parameters have been reported yet. Furthermore, the lack of lithological diversity in the selection of fracture samples restricts the generalization of the results.