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# COUPLED AIR-WATER FLOW THROUGH FRACTURED SANDSTONES

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## ABSTRACT

In two-phase flow within a rock mass, where both air and water phases flow together, the accurate flow measurement of each individual phase is important in numerical analyses. The increased quantity of water phase decreases the relative permeability of the air phase, and vice versa. The relative permeability is important to analyse the risk of groundwater inundation and gas outbursts particularly in underground excavations. Two-phase flow (i.e., water and air) behaviour through naturally and artificially fractured standard rock cores is investigated using the high-pressure triaxial equipment developed by the authors. Findings of this study show that the individual flow rate components of two-phase flow linearly increase with the increase in inlet fluid pressure, which suggests the applicability of a modified Darcy's law, using the relative permeability factor, in unsaturated flow. When the relative permeability of one phase increases, the relative permeability of the other phase decreases. The flow rate decreases with the increase in confining stress for both single and two-phase flow situations. However, this reduction of flow rate becomes marginal, once the confining stress is exceeded above a certain value.

## INTRODUCTION

The experimental investigation of multiphase flow in fractured rock media is important in many branches of science and engineering. These include mining, petroleum engineering, underground nuclear storage plants and groundwater hydrology. The strength and stability of jointed rock media depend mainly on properties of the structural features and the characteristics of the permeating liquids. The role of water-gas permeability on the induced effective stresses is of paramount importance in sub-surface jointed. Usually, multiphase flow can either be two-phase or three-phase flow. In mining engineering, two-phase flow of water and gas mixtures is common, whereas, three-phase flow (e.g., water + air + oil) is encountered in petroleum engineering. In the past, two-phase flow models in porous media has been studied by various researchers (Narasimhan and Witherspoon, 1978; Schrefler and Zhan, 1993; Kueper and Frind, 1991), however, limited work on unsaturated flow through fractured rock media is published. Some attempts to analyse coupled hydro-mechanical behaviour can be found in literature with respect to gas-water flows (Pruess et al., 1990; Rasmussen 1991; Fourar et al., 1993; and Fourar, 1995). Rasmussen (1991) investigated the fracture flow under conditions of partial fluid saturation. Pruess (1990) conducted a numerical analysis based on relative permeability of two-phase flow subject to pressure difference between air and water in real rock fractures. In Fourar's work, no attempt has made to study the influence of stress (axial, confining pressure) and deformation characteristics of the idealised fracture.

A fractured rock mass contains a large number of discontinuities, which constitute planes of weakness in the rock mass. They are either isolated or exist in the form of interconnected networks, which often carry different fluids including organic gases, air and water. Depending on their orientation, interconnectivity and aperture, individual fractures carry different quantities of flow rates. Analysing flow through a single joint provides a better understanding of flow deformation characteristics and their interaction between each phase. In a single joint, two-phase flow can be in the form of stratified flow, mixed flow or bubble flow. Factors such as velocity of the individual fluid phases, flow path, joint geometry, joint apertures and their roughness and fluid properties (e.g., viscosity and density) will determine the type of flow pattern within a joint.

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It is important to note that the theories and mathematical models developed for multiphase flow in pipes cannot be employed in confidence for flow analysis through joints, because of the complex nature of hydro-mechanical aspects associated with relatively rough joints.

The relative permeability coefficient is measured using the most common technique, i.e., steady state method. In this approach, the measurements are made, based on the hydraulic head or controlled discharge through the specimen. From authors' experience, it is more reliable to employ controlled hydraulic head method. In this paper, the results of two-phase flow through fractured sandstone rock specimens subjected to different boundary conditions of confining stress, axial stress and inlet fluid pressures are presented. Moreover, the applicability of Darcy's law to unsaturated flows is discussed, with regard to different confining pressures and inlet fluid pressures.

## THEORY

Over the past four to five decades, for simplicity, fractures have often been simulated as smooth and parallel joint walls, for the convenience of developing mathematical models to analyse fluid flow data (Baker, 1955; Louis, 1969; Engelder & Scholz, 1981; Brown, 1987; ITASCA, 1996). Flow through a single discontinuity is usually expressed in terms of a cubic law, which is based on laminar flow between smooth parallel plate walls. After extensive laboratory studies, Witherspoon et al. (1980) and Iwai (1976) suggested that the cubic law could still be used for rough, natural joints at low confining stress. However, at comparatively elevated stress, a significant deviation from the cubic law was noted, because of the increased contact area of the joint surface. For steady state flow through a parallel wall fracture with aperture, the flow rate ( $q$ ) is often expressed in terms of the joint aperture and hydraulic head based on Darcy's law for saturated, laminar and incompressible flow, as follows:

$$q = A \left( \frac{k}{\mu} \right) \left( \frac{dp}{dx} \right) \quad (1)$$

where,  $\mu$  = dynamic viscosity of fluid (Pa.sec),  $dx$  = length of joint (m),  $k$  = fracture (intrinsic) permeability ( $m^2$ ),  $A$  = cross sectional area of the fracture ( $m^2$ ),  $q$  = flow rate ( $m^3/sec$ ) and  $p$  = pressure difference (Pa)  
The fracture permeability ( $k$ ) is given by:

$$k = \frac{e^2}{12} \quad (2)$$

where,  $e$  = mean hydraulic aperture.

Darcy's law may be extended to unsaturated flow by introducing a relative permeability factor ( $K_r$ ) in Equation (1), as expressed below.

$$q = K_r \left[ A \left( \frac{k}{\mu} \right) \left( \frac{dp}{dx} \right) \right] \quad (3)$$

By combining Equations (2) and (3), the cubic theory for unsaturated flow through a smooth parallel plate joint walls is formulated by:

$$q = K_r \left[ \left( \frac{e^3 d}{12\mu} \right) \left( \frac{dp}{dx} \right) \right] \quad (4)$$

where,  $d$  = fracture width.

## EXPERIMENTAL PROCEDURE

Prior to testing, the fractured sandstones specimens were mapped using the digital co-ordinate profiling apparatus (Figure 1). Having placed the specimen on the mould which sits on a rigid surface, the probe of the machine is lowered to the surface to obtain x, y and z co-ordinations of the joint surface. These co-ordinations are then analysed by the computer to generate the 3-D surface profiles as shown in Figure 2 for typical specimens. Two specimens, one with an artificial fracture (SS1) and the other having a natural fracture (SS2) were used for characterising the permeability and strength-deformation properties. Both

specimens were in 55mm in diameter and 110mm in length. The tests were carried out using the newly designed two-phase, high-pressure triaxial equipment as shown in Figure 3 (Indraratna and Ranjith, 1999). The test procedure adopted is briefly discussed below.



Figure 1: Mapping of joint profiles using the digital coordinate profiling apparatus

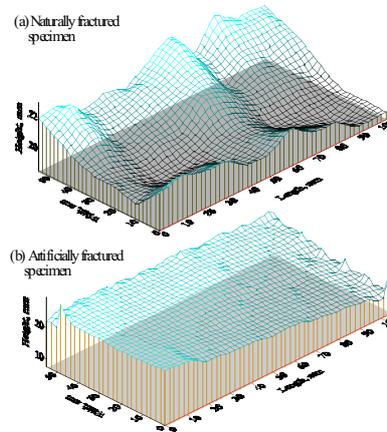


Figure 2: Surface profiles of fractured rock specimens

After smoothening both ends of the rock specimen, it is then covered by a polyurethane membrane, and subsequently placed on the bottom seat of the triaxial cell. In order to measure the lateral deformation of the rock specimen, two specially designed clip gauges are mounted at 1/3 length of the specimen on the membrane. Using two horseshoe clamps, the membrane is tightened to the top and bottom seating so that no fluid flow through the membrane and the specimen takes place. The spiral tube is fixed to carry fluid flow from the specimen to the outlet. Oil is filled inside the cell from the top to the air bleeding hole, and then the top and bottom bases are tightened by six bolts. In order to ensure no trapped air inside the cell, oil is further pumped in to the cell using a hydraulic jack. The specimen is first saturated with one fluid phase, and then the second phase is forced through the specimen. The readings of the inlet air and water pressure transducers, corresponding outlet pressure transducer, cell pressure transducer, volume change device, axial and lateral deformations are monitored continuously, and displayed digitally on the instrumentation display unit prior to recording by the datalogger. Once the water and air mixture passes through the dreschel bottle, airflow rates and water flow quantities are recorded by the film flow meter and the electronic weighing scale, respectively. Flow quantities of both phases and the stress-strain behavior of rock specimens were monitored for various boundary conditions of various cell pressures, inlet fluid pressures and axial stresses.



Figure 3: Experimental setup for Two-Phase, High pressure Triaxial Apparatus.

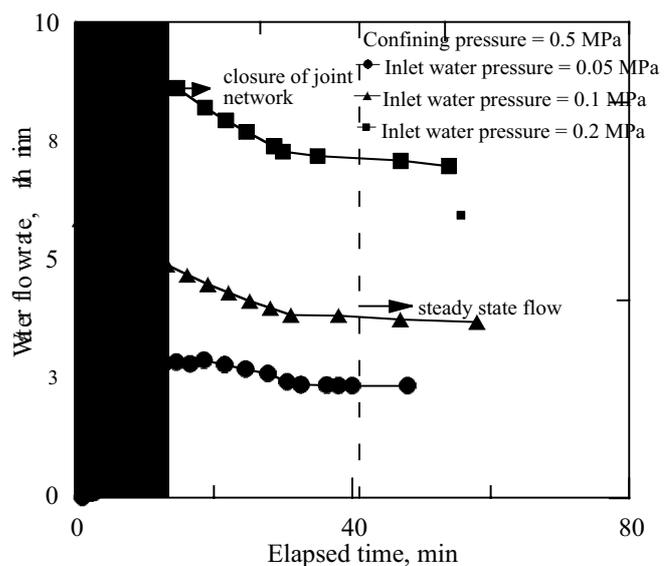


Figure 4: Transient conditions of water flow for different inlet pressures.

## RESULTS AND DISCUSSION

### Effect of Initial Saturation

The fractured specimen is initially saturated with one phase (i.e., either water or air). Figure 4 shows the time taken to fully saturate the specimen with water at a given confining pressure of 0.5 MPa, and at varying inlet water pressures. The flow rate increases during the first 10 minutes, but subsequently decreases followed by a nearly constant flow rate after about 30 minutes. The decrease in flow is attributed to the closure of joint apertures. In order to obtain transient conditions of two-phase flow, the air flow is gradually injected to the water-saturated specimen while maintaining the inlet water pressure at 0.1MPa. The transient conditions of two-phase flow are shown in Figure 5. Water flow tends to decrease initially and followed by constant flow rate after 40 minutes. The air flow rate increases during the initial 20 minutes and then becomes almost constant (i.e., 60 ml/min), as the inlet air pressure becomes stable at 0.06 MPa. The data in following Figures 6-8 are related to the steady state flow condition, as will be discussed later.

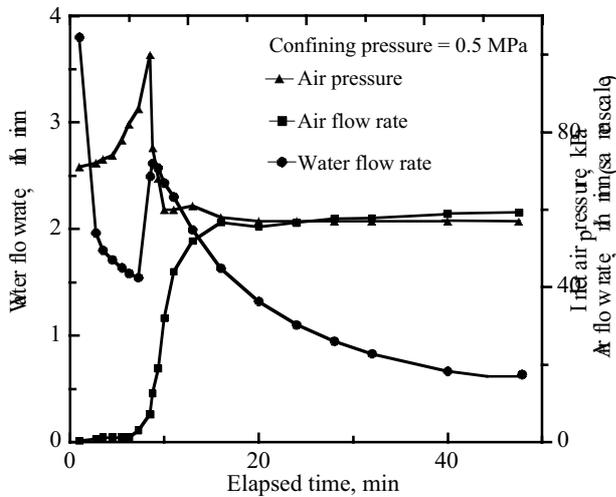


Figure 5 : Effect of air flow on water saturated specimen.

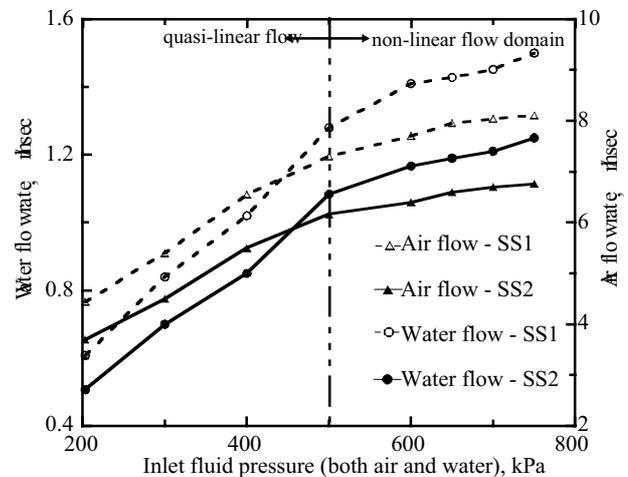


Figure 6 : Effect of inlet pressure on two-phase flow rates through fractured specimens.

### Role of Inlet Fluid Pressure on Two-Phase Flow

The steady state flow rate was measured at zero capillary pressures (i.e.,  $p_a = p_w$ ) for both artificially fractured (SS1) and naturally fractured specimens (SS2). The two-phase flow rate through artificially fractured specimen is expected to be larger than that through a naturally fractured specimen, because a natural fracture usually has a undulated, hence rough surface (see Figure 2). As expected, water and air flow rates increase with the increase in inlet fluid pressures. However, at elevated fluid pressures, flow rate becomes non-linear with the increase in inlet pressures (Figure 6). This is not surprising as the hydraulic gradient is a polynomial function of the velocity of each fluid phase. These results indicate that Darcy's law can still be employed using the relative permeability factor in the analysis of two-phase flow at small inlet fluid pressures, irrespective of the fracture type.

### Role of Degree of Saturation

The tests were designed for two stages: (a) the specimen was initially saturated with water at a given inlet water pressure, then introducing the air phase, and (b) water phase was injected to the initially air saturated specimen. The relative permeability (Equation 4) against normalised inlet fluid pressure is shown in Figure 7. For initially water-saturated specimen, the normalised inlet fluid pressure is defined as the inlet air pressure divided by the inlet water pressure (i.e.,  $p_a/p_w$ ), whereas for the initially air-saturated specimen, the ratio of water pressure divided by the air pressure (i.e.,  $p_w/p_a$ ) was considered. When the ratio  $p_a/p_w$  increases, the relative permeability of air ( $K_{ra}$ ) increases exponentially, while the water permeability ( $K_{rw}$ ) decreases. The opposite trend occurs for the increase in  $p_w/p_a$ . The results indicate that the relative permeability of both phases becomes equal when the inlet fluid pressure ratio tends to 1.25, and  $K_{ra}$  tends to

become unity when  $p_a/p_w$  approaches 2. This represents the situation where the degree of saturation of air becomes 100%.

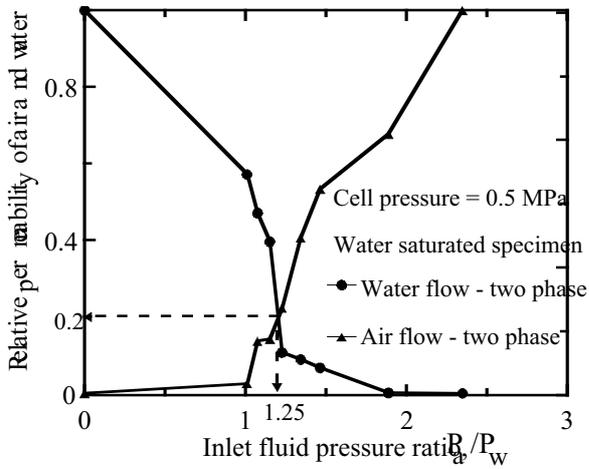


Figure 7a: Relative permeability of air and water for initially water saturated specimen.

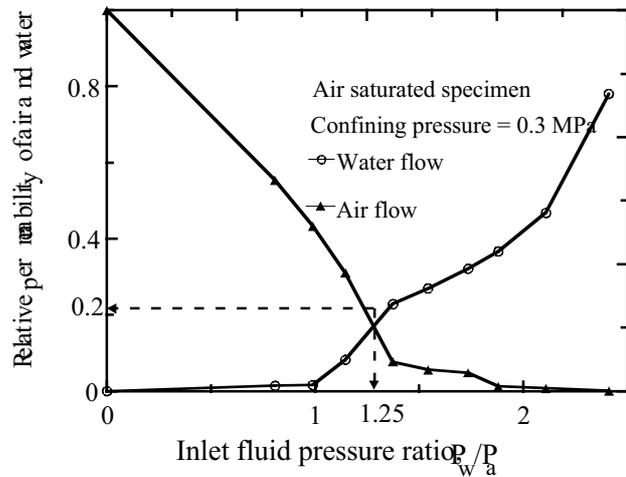


Figure 7b: Relative permeability of air and water for initially air saturated specimen.

### Role of Confining Pressure on Two-Phase Flow

At zero capillary pressures (i.e.,  $p_a = p_w$ ), two-phase flow rate decreases with the increase in confining pressure, because of the deformation of fracture (Figure 8). This trend has been observed by many researchers in the past for fully saturated fluid flow through specimens. At elevated stress, a nearly constant flow rate is observed, which represents the joint has approached to its minimum aperture.

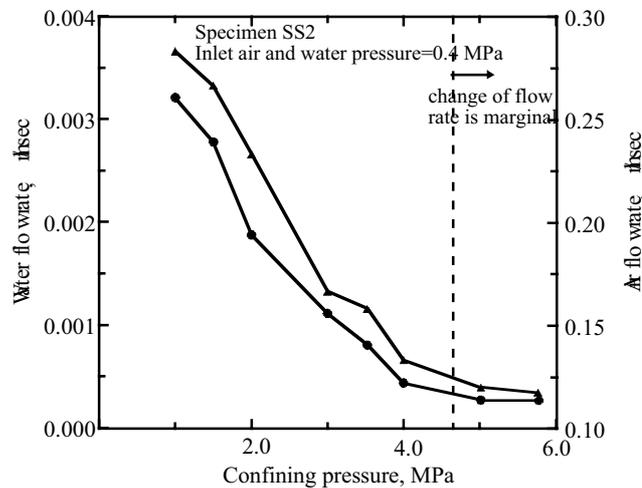


Figure 8: Effect of confining pressure on two-phase flow.

### CONCLUSION

In this paper, a laboratory study of the two-phase permeability of fractured sandstone specimens was discussed. From the test results, the following conclusions can be drawn. The approximately linear relationships observed between the individual flow components and the corresponding inlet fluid pressures suggest that the applicability of the modified Darcy's theory based on the relative permeability factor is acceptable for flow through rock fractures. However, at elevated fluid pressures, the validity of this modified theory diminishes for two-phase flow. When the inlet pressure of one phase increases, its relative

permeability increases exponentially while decreasing the relative permeability of the other phase. Findings of this study show that the relative permeability of both phases becomes equal when the inlet fluid pressure ratio approaches approximately 1.25. The relative permeability becomes unity when the specimen is fully saturated with one fluid. Moreover, this study shows that the role of confining pressure on two-phase flow is as important as in fully saturated flows, because the magnitude of flow is directly related to the joint deformation effected by the confining pressure.

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