FLUID TRANSPORT PROPERTIES OF
ROCK FRACTURES AT HIGH PRESSURE
AND TEMPERATURE

Progress Report

For Period July 1, 1979-June 30, 1980

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April 1980

Prepared For

THE U. S. DEPARTMENT OF ENERGY

UNDER CONTRACT NO. DE-AS02-76-ER04504

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ABSTRACT

Flow rates and thus permeability were measured for a variety of effective pressures on artificially prepared joints in Cheshire quartzite. Permeabilities calculated from constant head tests compare with permeabilities calculated from pulse decay tests. Measurement of the change in aperture with effective pressure shows that at effective pressures of less than 20 MPa changes in confining pressure have a larger influence on the aperture than changes in pore pressure. Joint permeability changes with aperture; thus changes in confining pressure are more influential on permeability than changes in pore pressure. Although a "cubic law" model for flow along a joint gives a rough estimate of joint permeability, measurements of the changes in flow rate with aperture suggest that the "cubic law" is inadequate for smooth joints at high pressure. This is so because the effective cross section available for flow changes with pressure in a nonlinear manner.

INTRODUCTION

The rate of flow of a fluid along a nominally closed joint is related to the aperture of the joint. For parallel plates the basic form of the relationship between aperture and fluid flow is a "cubic law" based on the Hele-Shaw model [Harr, 1962]. The flux per unit drop in head can be developed from Darcy's law and simplified as:

$$Q/\Delta h = C d^3 \quad (1)$$

where Q is the flow rate, Δh is the drop in head, d is the joint aperture and C is a function of fluid properties as well as geometry of the flow path [Witherspoon et al., 1980]. The validity of the cubic law has been discussed in a series of papers including those by Lomize [1951], Sharp [1970], Sharp and Maini [1972] and Gale [1975]. Witherspoon et al. [1980] demonstrate the validity of the cubic law for laminar flow along tensile joints with apertures down to 4 μm and effective pressures of 20 MPa. They argue that permeability is uniquely defined by joint aperture and is independent of stress history.

In contrast, Kranz et al. [1979] present data on smooth joints which indicate that stress history does affect the validity of the cubic law. The cubic law gives a rough approximation* of the joint permeability but at high effective pressures (50 to 200 MPa) small changes in aperture do not affect the flow rate per unit drop in head by a cubic law. The purpose of this paper is to present further data illustrating the effect of stress history on fluid flow along joints at high effective stresses (> 20 MPa).

*Figure 9 and Table 2 in Kranz et al. [1979] are in error. The left scale (k) should equal the right scale (k_j) in Figure 9. Likewise, the units for k should equal the units for k_j in Table 2. Experiment 31, for example, should show $k = 0.19$ darcies and $k_j = 1.33$ darcies.

EXPERIMENTAL PROCEDURE

Our experimental procedure for fluid flow tests was much the same as described in Kranz et al. [1979]. Kerosene was the pore fluid and split cylinders were used to model joints. The surfaces of the split cylinders were prepared by polishing cylinder-halves against each other by hand. Changes in joint aperture were measured with a four-armed dilatometer. The experimental apparatus was modified to measure flow rates during constant head tests, whereas Kranz et al. [1979] reported data from pulse decay tests. The pore pressure for the constant flow tests was generated by servocontrolling a double acting Aminco pump. Feedback for servocontrolling the pump was from a BLH pressure cell in the pore pressure system. A constant pore pressure gradient across the sample was maintained with a servocontrolled piston moving within a small pressure vessel that collected fluid passing through the sample. Here again the feedback element was another BLH pressure cell. The signals from the two BLH pressure cells were compared to maintain a constant pressure difference with the signal while driving the Aminco pump as the master. The BLH pressure cells were capable of detecting pressure differences of 0.01 MPa at 200 MPa ambient pressures. Flow rate out of the sample was measured by monitoring with an LVDT the withdrawal of the piston from the pressure vessel collecting pore fluid. Strokes of the Aminco pump were not used to measure flow because of back leaks through ball-check valves.

PULSE DECAY VERSUS CONSTANT HEAD TESTS

The purpose in using a constant head test was to check data using the pulse-decay tests as reported in Kranz et al. [1979]. One suspicion was that Kranz et al. failed to confirm the validity of the cubic law using pulse decay tests because of the transient behavior of flow during the pulse decay test.

The constant head test assumes that Darcy's law holds and there is a linear pressure gradient along the length of the sample. That is

$$Q = \frac{kA}{\mu} \frac{dP}{dL} \quad (2)$$

where Q is the volume flow rate, k is the intrinsic permeability, A is the cross section through which the fluid flows, μ is the dynamic viscosity, L is the length of flow path, and P is the fluid pressure. For the constant head test Q is measured as the rate of flow into the small pressure vessel from the sample. k may be calculated using either the cross section of the sample (9.62 cm^2) or the cross section of the joint whose aperture is estimated using the four-armed dilatometer.

Constant head tests show the same range in permeability as falling head tests for a joint prepared in Cheshire quartzite (Figure 1) where the permeabilities are calculated using the cross sectional area of the sample rather than the joint aperture. The variability in permeability at any effective pressure is in part associated with the preparation of seven different samples for which data are shown. The grinding of surfaces by hand rarely produces a uniform surface finish and, so, the initial surface finishes were probably different from sample to sample. Further vari-

120-grit QUARTZITE

Figure 1. Whole rock plus joint permeability (k) at various effective pressures (P_e) for joints in Cheshire quartzite prepared with 120-grit polishing compound. Constant head data come from four different samples, whereas falling head data come from three different samples (1-4). The range of permeability shown for constant head tests indicates the variability of k for repeated tests during which confining pressure is held constant and hydraulic head is varied. In this plot loading paths and confining pressures are not distinguished.

ability in data arises from hysteresis associated with loading history which is not distinguished in Figure 1 [Kranz et al., 1979]. From this comparison we conclude that both types of tests showed similar flow rates and flow rates varied in a similar manner with similar changes in effective pressure. Likewise we conclude that failure of the cubic law cannot be attributed to the specific details of the pulse decay test.

CHANGE IN APERTURE WITH PRESSURE

Permeability of soil, intact rocks, and jointed rock follows a hysteresis loop when either confining pressure or pore pressure is cycled up and down [Freeze and Cherry, 1979; Kranz et al., 1979; and Witherspoon et al., 1980]. Direct measurement of the aperture in jointed rock shows that the hysteresis in permeability is a direct consequence of the hysteresis in the response of the aperture to changing pore pressure and confining pressure [Kranz et al., 1979; Witherspoon et al., 1980]. The flow rates along joints are, in part, controlled by the cross sectional area of the flow channel.

An example of the effect of changing confining and pore pressure on aperture is shown in Figure 2. The loading path consisted of increasing the confining pressure to 40 MPa then increasing pore pressure to about 39.4 MPa. Pore pressure was then decreased to 0.1 MPa followed by the release of confining pressure. Hysteresis loops are evident for both pore and confining pressure cycles and the top of the confining pressure cycle is offset by the residual amount of the pore pressure hysteresis loop. Despite unloading preceding loading in the pore pressure cycle work was

Figure 2. Joint aperture versus effective pressure. The joint in Cheshire quartzite was prepared with 80-grit polishing compound. By the nature of the experiment, confining pressure is applied before pore pressure and removed after pore pressure.

lost during the cycle. This same behavior is displayed in the conventional sense for the confining pressure cycle where lost work is represented by the area between the loading and unloading curves.

Kranz et al. [1979] present permeability as a function of pressure with the equation

$$dk = -a \, dP_c + b \, dP_f \quad (3)$$

where $b/a < 1$ for jointed Barre granite. The physical reason for $b/a < 1$ is seen in Figure 2. At effective pressures of less than 20 MPa changes in confining pressure have a greater effect on changes in aperture than equivalent changes in pore pressure. A confining pressure of 40 MPa closed the joint in quartzite about 50 μm , whereas the injection of about the same pore pressure re-opened the joint a little more than 20 μm .

Both the confining and pore pressure curves exhibit marked changes in slope when the effective pressure is less than 25 MPa. However, close inspection shows that the change in slope for the confining pressure curve occurs at about 23-24 MPa, whereas the change in slope for the pore pressure curve is somewhat lower (~ 21 MPa). Again, this demonstrates the greater overall capacity for changes in confining pressure to affect joint aperture.

JOINT PERMEABILITY VERSUS EFFECTIVE PRESSURE

Change in flow rate was measured in conjunction with change in joint aperture. To illustrate details associated with change in effective pres-

sure, the permeability may be calculated using the cross sectional area of the sample (9.62 cm^2), a constant independent of pressure, rather than the cross sectional area of the joint, which varies with pressure. Figure 3 shows that the permeability versus effective pressure curves are similar to the joint aperture curves. Consider the pore pressure cycle with confining pressure held constant (dots) during which the effective pressure was first decreased and then increased in a series of steps. The permeability was lower during the initial decrease in effective pressure than upon the return to the same effective pressure. This is equivalent to the slight opening of the joint aperture seen during the pore pressure cycle in Figure 2. Likewise, during the confining pressure cycle with constant pore pressure (squares), permeability was lower during confining pressure changes that lowered the effective pressure. At low effective pressures, permeability changed more rapidly with changing confining pressure (Figure 3). Hence, permeability must be a function of both effective pressure and pore pressure. Although the aperture versus effective pressure curves show a marked change in slope at 20 to 25 MPa (Figure 2), the permeability versus effective pressure curves for the same surface show marked change in slope at less than 15 MPa effective pressure. The changing confining and pore pressure curves for permeability diverge at less than 10 MPa effective pressure.

Assuming that the cross-sectional area of the joint changes linearly with the joint aperture, permeability may also be calculated using the cross-section area of the joint, which is joint aperture times the diameter of the sample. This calculation requires the absolute aperture which can only be estimated [Witherspoon et al., 1980]. For our calculation we assume that at the lowest effective stress, flow follows the cubic law

Figure 3. Effective pressure versus permeability curves for a joint in Cheshire quartzite prepared with 80-grit polishing compound. Data come from constant-head flow tests. Arrows indicate direction of change of either confining or pore pressure. Only one point was taken for permeability during initial application of confining pressure.

where $k_j = d^2/12$. Knowing the flow rate and drop in head for permeability tests at low effective stress, we find the aperture (d_o) which sets the k_j equal to $k = \frac{\mu Q}{A} \frac{dL}{dP}$. Once d_o is found, we calculate k for higher effective pressures using an aperture $d = d_o - \Delta d$ where the change in aperture d is measured experimentally. A plot of k_j vs. k shows that measured fluid flow does not follow the d^3 -law at high pressure (Figure 4). At low effective pressures and wide apertures the d^3 -law is confirmed, as shown by the one-to-one change of k vs. k_j for the confining pressure curve. However, for the two pore pressure curves with narrow apertures there is just a slight increase in joint permeability (k) with increase in aperture versus a dramatic increase in k_j .

Failure of the plot of k vs. k_j to follow a straight line suggests that the cubic law for fluid flow breaks down under the test conditions. This is also seen in a plot of flow rate per hydraulic head ($Q/\Delta h$) versus aperture (d) (Figure 5). At high flow rates and wider apertures, the curves appear to parallel a d^3 -law but at low flow rates and narrower apertures the d^3 -law is inadequate.

DISCUSSION

We have found two principal new results. Firstly, we find that at low pressure permeability approximately follows the d^3 -law, as did Witherspoon et al. [1980], but at much higher pressures, permeability decreases faster with d than as d^3 . Secondly, we reaffirmed the result of Kranz et al. [1979] that pore pressure has a weaker effect on fracture closure (and hence permeability) than does confining pressure.

Figure 4. Plot of joint permeability using the cubic law for fluid flow versus joint permeability using experimental data. Effective pressure was changed by changing either pore pressure or confining pressure with the other held constant.

Figure 5. Experimental data for straight flow through a joint prepared with 80-grit polishing compound in Cheshire quartzite versus aperture. Slope of a cubic law for fluid flow is shown. Circles and squares represent different tests between which the surface was repolished.

One can begin to understand these results by considering the theory of closure of random surfaces of Greenwood and Williamson [1966] which has recently been partially confirmed for rock by Walsh and Grosenbaugh [1979]. This theory has the result that if two surfaces of random topography are in contact under a pressure p , that if the deformation is elastic, the mean aperture d will be

$$d = d_0 - \Lambda \log p \quad (4)$$

where Λ is a constant that depends on the topography of the surface and the elastic constants of the material [Gangi, 1979]. An additional result is that the real area of contact, A_c , is dependent only on the load and not on the nominal area, A , thus

$$A_c = E p A \quad (5)$$

where E is a constant similar to Λ . It is clear from (5) that if W is the effective cross-sectional width available for flow that

$$W = W_n - (E p A)^{1/2} \quad (6)$$

where W_n is the nominal width, and, from (4),

$$W = W_n - (w_0 + \exp \left(\frac{d_0 - d}{2\Lambda} \right)) \quad (7)$$

where w_0 is the contact cross section at zero pressure. Substituting this into equations (2) and (4) of Witherspoon et al. [1980] for linear flow through a crack of separation d , we obtain

$$\frac{Q}{\Delta h} = \left[\frac{w_n - [w_o + \exp(-\frac{d_o - d}{2\lambda})]}{2} \right] \frac{\rho g}{12\mu L} d^3 \quad (8)$$

Equation (4) fits the closure data (Figure 6) within the experimental error when pore pressure is fixed. Equation (8) shows why the permeability decreases faster with d than d^3 (Figure 5). Witherspoon et al. [1980] assumed that w was a constant and introduced a factor f to account for it. We show here (Equation 6) that w is a function of p and hence d .

If A_c is only a function of load, then if a pore pressure P_p is present

$$A_c = E p A - E P_p (A - A_c) \quad (9)$$

and we see why P_p plays a smaller role than p in changing the aperture and permeability. The above result was discussed by Kranz et al. [1979].

Figure 6. Plot of joint stiffness ($\partial P / \partial d$) versus confining pressure (P). Data from loading curve in Figure 2.

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