

SITE CHARACTERIZATION OF JOINT PERMEABILITY USING THE HEATED BLOCK TEST

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INTRODUCTION

The isolation of nuclear waste in a mined rock repository poses unique problems in site characterization. The ultimate barrier to radionuclide migration to the biosphere is the joints and major discontinuities that are pervasive at least to several kilometers depth. Modelling the potential effects of these joints on near-field conditions requires that the thermal, mechanical and hydraulic properties of joints are coupled. Acquisition of joint data is therefore a more demanding problem than at any previous time.

Tunneling and mining experience, physical models (Barton and Hansteen, 1979) and numerical models (Voegele 1978, Wahi et al. 1980) demonstrate the possibility of significant shear displacement along joints exposed by an excavation. This process is enhanced by anisotropic stress distributions, by transient thermal loading and by dynamic loading from earthquakes. If the relevant joints are rough, with high wall strength, stability will not necessarily be reduced by the shearing process since roughness-induced dilation will lock the joints in some finite displaced position. The only serious consequence of this process is the joint aperture strain. Permeability may be enhanced around the repository and shaft. According to the present studies a significant shear displacement may be as little as 0.2 mm.

Model studies of flow in a rough joint replica sheared at very low stress reported by Maini (1971), indicated that joint permeability could increase as much as one order of magnitude in the first 2 mm of shear displacement, and a further one order of magnitude in the next 4 mm of shear displacement. Although these effects would be reduced at realistic levels of normal stress, their influence could have important influence on repository sealing requirements.

The effect of temperature on joint permeability has not been an area of extensive research, although this deficiency is rapidly being adjusted. Tests by Nelson (1975) on single fractures in sandstone subjected to a relatively low confining pressure (0.1 MPa) indicated initial increases in permeability to 60°C, followed by significant reductions when increasing the temperature further to 100°C. In-situ tests conducted in Stripa granite by Lundström and Stille (1978) using water temperatures of 10°C and 35°C indicated a 50% reduction in joint permeability, despite the reduced viscosity of water at the higher temperature. Unfortunately there was no coupling of permeability measurements with the full-scale and time-scaled heater experiments, and no possibility of controlling the total normal stress acting across the joints during the flow tests.

Ambient tests of joint permeability as a function of normal stress or aperture have been widely reported. There appears to be considerable discrepancy in the interpretation of results. Some authors (e.g. Witherspoon et al. 1979a) have suggested that the cubic law relating aperture and flow rate is valid even for rough fractures in intimate contact. Other authors (e.g. Kranz et al. (1979) and Walsh (1981)) have explained the measured flow reductions caused by tortuosity and roughness, by a modification to the law of effective stress.

The possibility of a scale effect on joint permeability has been suggested by Witherspoon et al. (1979b). At present, the data base is too limited and diverse to make definite conclusions. It is often unreasonable to try to compare the permeabilities of rough, fresh artificial fractures (a typical test configuration) with weathered natural joints of different roughness, since the degree of aperture closure under a given stress level will vary in each case. Recent work (Barton, 1981a) suggests that scale dependent joint permeability will probably not be a significant factor under conditions of pure normal closure, but will be observed when shearing occurs. This is due to the scale-dependent dilation that occurs when joints of different length are sheared, as shown in a major test program reported by Bandis (1980).

HEATED BLOCK TEST

The pressing need for large scale coupled thermo-mechanical-hydraulic test data prompted Terra Tek's current 8 m³ block test, performed under contract with the Office of Nuclear Waste Isolation. The site is located in gneiss, about 150 metres underground in a test adit in the Colorado School of Mines experimental mine in Idaho Springs.

The 2x2x2 metres block is located in the floor of the test adit. Loading is applied on four vertical sides with flatjacks. The base is attached to the surrounding rock mass. The vertical sides of the specimen were formed by line drilling. The extreme hardness of the quartz lenses in the gneiss caused unexpected difficulties with hole alignment, and diamond coring of the slots was required.

The surface of the block is instrumented with some 30 pairs of Whittemore bolts for recording strain and/or displacement across joints, four Irad strain metres, and five surface strain gauge rosettes. Deformation occurring across the block as a whole is registered with horizontal DCDT rod extensometers. Deformations within the block are monitored with MPBX borehole extensometers. Stress levels are monitored using a variety of instruments. Four vertical holes are used for cross-hole dynamic modulus determination. Data acquisition is accomplished by means of a computer controlled system which stores the readings on magnetic tape and is supplemented by manual readings of certain instruments.

A unique feature of the test facility is the line of heaters crossing the center of the block, shown schematically in Figure 1. The nine boreholes contain

linear heaters, equally spaced 40 cm apart. The combination of heaters and flatjacks has permitted joint permeability to be measured under normal stress or combined shear and normal stress, at any rock temperature in the range 12°-74°C. At the highest temperature the rock reaches 140°C in the heater plane. The block was subjected to a variety of load and temperature paths as detailed in the test matrix shown in Figure 2.

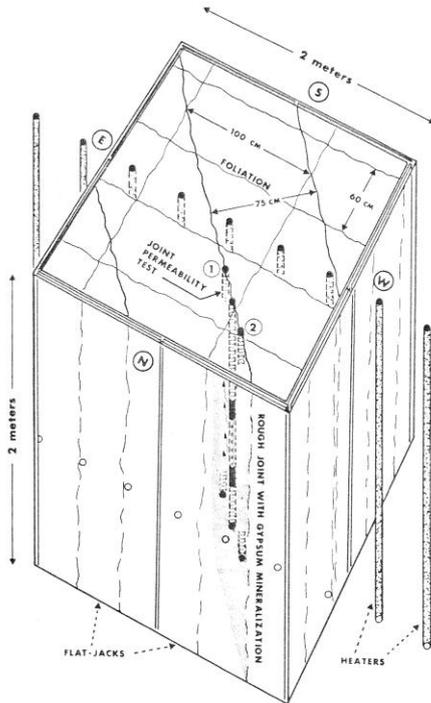


FIGURE 1. Schematic view of test block showing the line of heaters, the permeability test location, and the mean joint frequency and orientation.

The major mineralized diagonal joint (Figure 1) chosen for permeability testing was subjected to pure normal stress under the equal biaxial load cycles. Under the two uniaxial tests the joint was subjected to proportional shear and normal stress, with a shear reversal between the N-S and E-W tests.

SUMMARY OF BLOCK STRUCTURE AND JOINT PROPERTIES

Joint mapping in the roof and walls of the test adit surrounding the block reveals three sets of significant joints (i.e. continuity >2 metres). Each is steeply dipping or vertical. The mean spacing of the three sets is shown schematically in Figure 1. The block size index (ISRM 1978) is approximately 75 cm, the volumetric joint count approximately 4.8 joints/m³ (medium size blocks), and the RQD approaches 100%. Significant horizontal or sub-horizontal jointing is not in evidence. There are probably at least 30 discrete, interlocked blocks of rock within the 8 m³ test block.

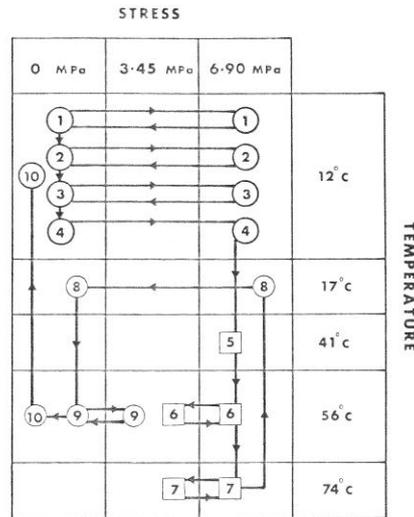


FIGURE 2. Test matrix for the present series of block tests.

- 1. Equal biaxial, cycle to 6.9 MPa
 - 2. N-S uniaxial, cycle to 6.9 MPa
 - 3. E-W uniaxial, cycle to 6.9 MPa
 - 4. Equal biaxial, load to 6.9 MPa
 - 5. Equal biaxial, 41°C
 - 6. Equal biaxial, cycle, 56°C
 - 7. Equal biaxial, cycle, 74°C
 - 8. Equal biaxial, unload, 17°C
 - 9. Unconfined, 50°C, and 55°C cycle
 - 10. Unconfined, ambient
- (AMBIENT)
(HEATING AND COOLING CYCLES)

When interpreting the test results and attempting to extrapolate our results to other environments, it is helpful to have a quantitative characterization of the jointing that can be used in numerical modelling. For this reason, extra care was taken with characterization of the set of diagonal joints, which were the subject of this study.

The diagonal joints are hydrothermally altered, with gypsum mineralization and iron staining of the joint walls. By contrast the foliation joints show little evidence of alteration or weathering. The roughness of all the joints was recorded in numerous locations using a 15 cm long contour gauge, and was also measured over longer base lengths. Visual estimation of the joint roughness coefficient (JRC) using Barton and Choubey's (1977) set of profiles, was supplemented with self-weight tilt tests of jointed pieces of drill core (Figure 3). These cores were obtained from the permeability test holes, which were drilled down the plane of the major diagonal joint. The various estimates of JRC were converted to natural block size values using the methods derived by Bandis et al. (1981).

The compressive strength of the joint walls (JCS) was measured with a Schmidt hammer. The diagonal joints proved to be markedly weaker than the other two

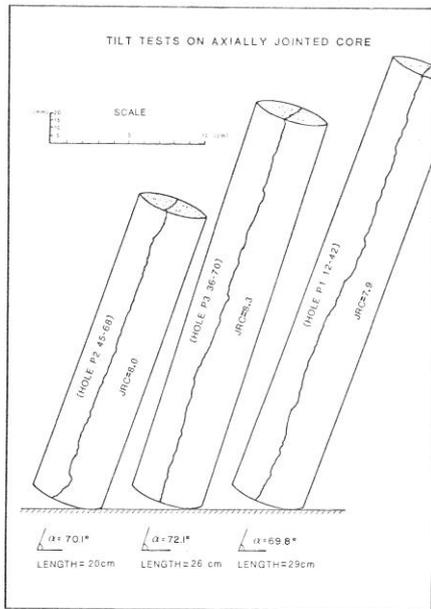


FIGURE 3. Characterizing the diagonal joints drilled from the three permeability test holes, P1, P2 and P3.

joint sets, due to alteration. These values were again converted to natural block size values.

Significant properties for interpretation of joint strength and deformability are listed below:

| Diagonal joints | Estimated full-scale values | | |
|-----------------|-----------------------------|----------|----------|
| | JCS | JRC | ϕ_r |
| | 50-65 MPa | 6.7-10.0 | 25° |

Peak friction angles (ϕ') for the diagonal joints which are loaded in shear during the uniaxial tests, are given by the following equation (Barton and Chouhey, 1977):

$$\phi' = JRC \log (JCS/\sigma_n') + \phi_r \quad (1)$$

where σ_n' = effective normal stress
 ϕ_r = residual friction angle

These parameters are used to model the complete shear stress-displacement and dilation behavior of joints (Barton, 1981b). Other recent work by Bandis (1980) has shown that JCS and JRC also control the normal stiffness and closure of joints. Consequently, the joint permeability measured during the various load paths will also depend on these parameters.

MECHANICAL CONSTRAINTS OF A CONTINUOUS BASE

The two metre cube of rock was isolated from the surrounding rockmass on four sides, but the base was continuous. Analysis showed that for deformation in the elastic range, the upper 80% of the block would be essentially unaffected by a continuous base, i.e. down to a depth of some 160 cm, strains would be uniform.

During uniaxial loading the high shear stresses developed on the diagonal joints tend to deform the block beyond the elastic range. However, this initial tendency is strongly resisted by the stiffening behavior of the underlying rock mass. In effect, only a portion of each diagonal joint is subject to shear, making shear resistance high. Figure 4 indicates the estimated range of peak shear strength, assuming that the base of the block was a frictionless boundary. The N-S and E-W uniaxial load paths shown in the same figure did not cause gross shearing along the diagonal joints due to the restraint of the continuous base. In reality the strength envelopes should be displaced several MPa to represent the cohesive, stiffening effect of the underlying rock mass.

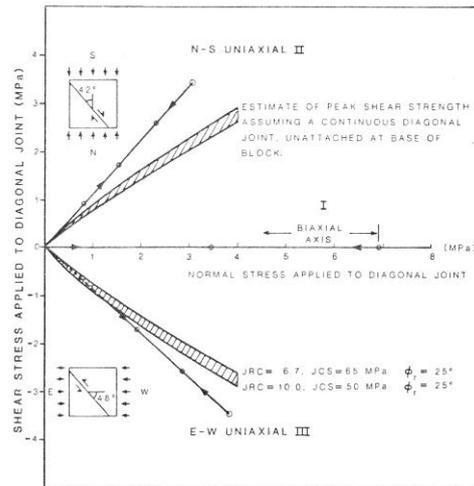


FIGURE 4. Comparison of biaxial and uniaxial load paths with the shear strength of the diagonal joints, assuming the block was bounded by a frictionless base.

The measured shear displacements experienced by the major diagonal joint during the N-S and E-W uniaxial load paths are shown in Figure 5. The N-S test is the first shearing event, and it is resisted by an initial shear stiffness of 4.8 MPa/mm. This increases rapidly as shear displacements approach 0.2 mm. Despite these mechanical constraints, joint permeability was clearly affected by these aperture strains, small as they appear.

JOINT PERMEABILITY AS A FUNCTION OF STRESS

Joint conductivity was monitored by injecting water along the major diagonal joint. This was done utilizing double packers located in a central hole drilled coaxially down the joint (Figure 1). The flow section was at a depth interval of 66-109 cm. Flow rates were monitored at the bottom of parallel boreholes drilled each side of the vertical injection hole. Hole No. 1 was 18.5 cm from the injection hole, hole No. 2 was 24 cm in the opposite direction.

Analysis of the drill core recovered from these holes indicates that due to its roughness and local undulations, the diagonal joint is not intersected by hole No. 2 in the depth interval 70-130 cm. Flow rates were correspondingly low towards this hole, and at

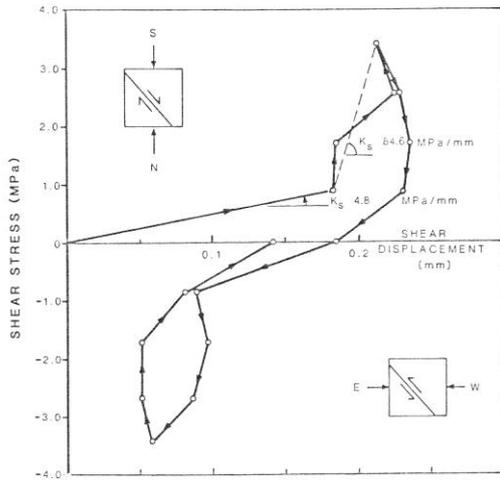


FIGURE 5. Shear displacement of the diagonal test joint is limited by the continuous base. Reversal is only partial during E-W loading.

some stress levels the flow rate fell below measurable levels (i.e., $<0.001 \text{ cm}^3/\text{sec}$). Consequently only the flow rates towards hole No. 1 are analyzed here. It is estimated from the core analysis that a section of the injection interval (95-105 cm) is non-conducting, and a section of observation hole No. 1 (103-109 cm) also non-conducting, due to the undulating joint passing outside the boreholes locally. This means that the measured flow rates may be some 10-15% less than representative for the joint as a whole.

The flow rate was measured by a depth indicator installed in the observation holes. The pressure gradient was assumed to be approximately linear, and equal to the injection pressure divided by the distance between the two holes. Injection pressures used in the ambient tests were 0.14, 0.24 and 0.34 MPa (20, 35 and 50 psi).

Figure 6 summarizes the results of the first three ambient permeability tests. The numbers 1 through 8 indicate the order of testing. Theoretical smooth wall apertures (e) and permeabilities ($e^2/12$) can be calculated from the following well known equation for linear flow between parallel plates:

$$q = \frac{de^3}{12\mu} \cdot \frac{dP}{dy} \quad (2)$$

where dP/dy = pressure gradient
 μ = absolute viscosity ($1.24 \times 10^{-5} \text{ gm.sec/cm}^2$ at 12°C)
 d = width of flow path
 q = flow rate

Table 1 summarizes the most significant data from the three first ambient tests.

The permeability of the joint when it was virtually unloaded by drilling four slots round the sides of the block, was equivalent to that of a smooth wall aperture (e) of 60.7 microns. Each of the three ambient load paths reduced this to between 27.1 and 30.3 microns at the highest stress level. Subsequent biaxial

loading to 6.9 MPa prior to heating the block also produced an equivalent aperture of the same magnitude; 30.0 microns. The relationship between these theoretical smooth wall aperture changes, and the change of real joint aperture measured during the various load cycles is discussed later.

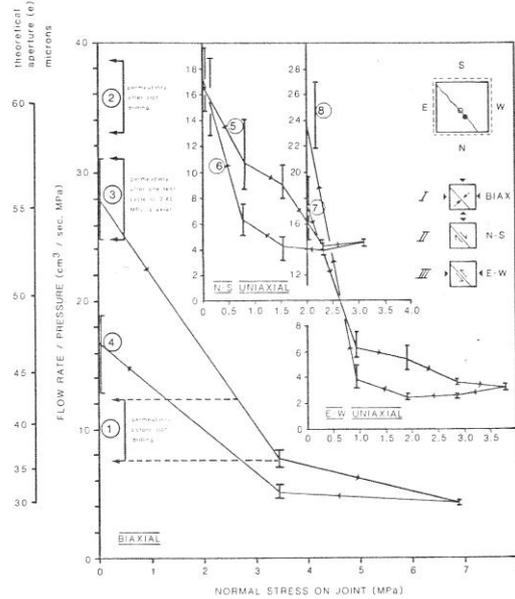


FIGURE 6. Effect of normal stress on flow rate and on the theoretical smooth wall aperture (e) (1 micron = 0.001 mm). Ambient tests.

Table 1

Stress Dependency of Joint Permeability
 Rock Temperature = 12°C

| Stresses on Joint | | e (micron) | K (darcys) |
|---------------------------------------|--------------|-----------------|-----------------|
| σ_n (MPa) | τ (MPa) | | |
| Pre-slot drilling (in-situ stress) | | 38.6 | 124 |
| Post-slot drilling | | 60.7 | 307 |
| 1. Biaxial | | | |
| 0 | 0 | 55.7 | 259 |
| 6.9 | 0 | 29.7 | 73.5 |
| 0 | 0 | 46.9 | 183 |
| 2. N-S uniaxial | | | |
| 0 | 0 | 46.9 | 183 |
| 3.1 | 3.4 | 30.3 | 76.5 |
| 0 | 0 | 47.6 | 189 |
| 3. E-W uniaxial | | | |
| 0 | 0 | 47.6 | 189 |
| 3.8 | 3.4 | 27.1 | 61.2 |
| 0 | 0 | 52.7 | 231 |

1 micron = 0.001 mm; 1 darcy = 10^{-8} cm^2

JOINT PERMEABILITY AS A FUNCTION
OF STRESS AND TEMPERATURE

The rock temperature gradients established during the various heating cycles were monitored with 80 thermocouples located in boreholes throughout the block. The rock temperature at the permeability test interval was interpolated from two thermocouples located 50 and 75 cm from the heater plane. Twenty-one days heating at an output of 500 watts per borehole heater, established a quasi-steady state gradient, giving a rock temperature of 55° at the test interval. A further twelve days at 700 watts per heater increased this to 74°C. Cooling to near-ambient temperature (17°C) took 33 days.

Various flow tests were performed to investigate the effect of mismatching the rock temperature and the water temperature at the injection side of the test. It was found that the calculated smooth-wall flow apertures (e) were more consistent when the rock temperature was used to estimate the viscosity of the water, in place of the injection water temperature. There was evidence for suspecting that cold water injected into a hot rock joint caused aperture increase. Efforts were therefore made to preheat the water to the rock temperature. A mismatch of 5° or 10° did not appear critical since the heat capacity of the rock, combined with the slow flow rates, were sufficient to guarantee flow temperatures equal to rock temperatures.

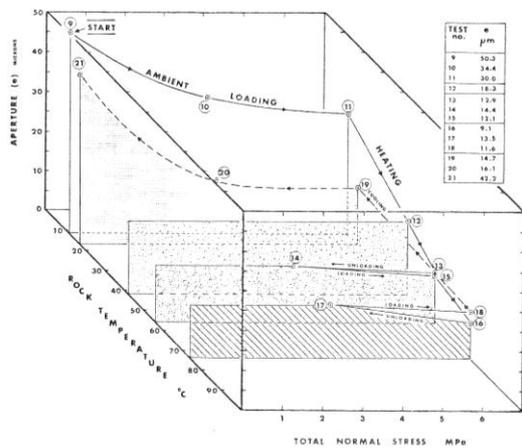


FIGURE 7. Biaxial loading at elevated temperature, showing the effect of coupled "hydrothermomechanical" behavior.

The test matrix shown in Figure 2 indicates the sequence of "hydrothermomechanical" tests (Nos. 4 through 8) performed following the three ambient tests. The three variables: flow (or aperture), rock temperature, and total normal stress show remarkable interdependence, as shown in Figure 7. The tightest smooth-wall aperture of 30.0 microns achieved at ambient temperature (12°C) and under a total normal stress of 6.9 MPa was reduced to 18.3 μm at 41.4°C and to 9.1 μm at 73.6°C. Thus increased temperature alone reduced joint permeability by an order of magnitude from 75 darcys to 6.8 darcys.

This remarkable reduction of flow aperture (which could not possibly be achieved at ambient temperature

without exceptionally high stress levels) is interpreted as improved mating of the opposed joint walls. The diagonal joints are quite rough, and they were undoubtedly formed at elevated temperature, though how high is uncertain. A roughness profile of a joint measured at ambient temperature will not exactly match a profile measured while the joint is at elevated temperature, due to thermal expansion. Our elevated temperature and pressure partially recreate formation conditions. The improved mating of the asperities is almost maintained by pressure alone during cooling, probably due to the high shear strength of the tightly mated walls. Significant lack of fit was not re-established until the aperture rebounded from 16.1 to 42.2 μm, which occurred somewhere between 3.45 MPa and 0 MPa (points 20 and 21 in Figure 7).

The inversion of the load cycle at 74°C (points 16, 17 and 18) is further evidence that temperature may have a more powerful influence on aperture (e) than pressure. After unloading to 3.45 MPa, a reloading to 6.9 MPa was insufficient to "reclose" the joint to the same extent. The table below suggests that the scatter of flow data is insufficient to invalidate this conclusion, despite the diminutive apertures involved

Table 2

Sample of Experimental Scatter From Three Sets of Flow Data

| Test No. (Figure 7) | Mean e (μm) | Range (μm) | σ (MPa) |
|------------------------|-------------|------------|---------|
| 16 | 9.06 | 8.6-9.8 | 6.90 |
| 17 | 13.5 | 13.1-14.1 | 3.45 |
| 18 | 11.6 | 11.5-11.7 | 6.90 |

The final sequence of heated flow tests shown in Figure 2 (Nos. 9 to 10) were conducted on the unconfined side of our loading matrix. The starting point was No. 21 on Figure 7, with T = 16.5°C, σ = 0 MPa and e = 42.2 μm. This aperture increased to 48.2 μm at 50.5°, presumably due to the thermal expansion of the roughness profile, which was not in this case in intimate contact with its mating half due to the absence of confinement. The aperture (e) returned to 41.9 μm at 55°C. A load cycle to 3.45 MPa (equal biaxial) at 56°C induced significantly better fit, with (e) closing to 17.5 μm. The subsequent unconfined test allowed the aperture to rebound to 36.5 μm. It appears that the "hydrothermomechanical" closure effect is only achieved when there is coupling of both temperature and pressure. This is quite logical when conditions under which joints were formed are visualized.

COMPARISON WITH REPORTED DATA

Witherspoon et al. (1979b) considered that the four thick curves shown in Figure 8 were potential evidence of a scale effect on fracture permeability. Our in-situ ambient data for the natural mineralized joint shows close agreement with the Pratt et al. (1977) in-situ data for a joint in granite, and apparently lends support to this scale effect hypothesis.

However, several aspects of the hypothesis are suspect. Chief of these is the attempt to compare artificial, unweathered tension fractures (Iwai, 1976 and Witherspoon et al., 1977) with natural weathered joints. Bandis (1980) has shown that joint apertures tend to be larger when joints are weathered, with low

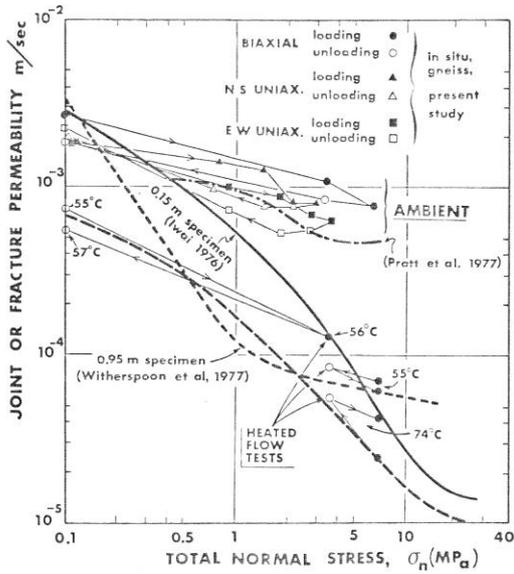


FIGURE 8. Comparison of ambient and heated flow tests performed in the present block test, with data presented by Witherspoon et al. (1979b).

JCS values. In addition, the closure measured under a given level of normal stress is found to depend on the values of JCS, JRC and the initial aperture. Weathered joints and artificial fractures are therefore likely to exhibit different permeability-stress relationships even at the same scale, unless their properties (JRC, JCS) are matched. Temperature "matching" is also important.

Intuitively, samples of different size taken from the same joint would not seem likely to exhibit different permeabilities if subjected to the same normal load paths, since pure normal closure is likely to depend on the properties of the small steeply inclined asperities at all scales.

However, when shearing of the joint is an added variable, the scale dependent properties of JRC and JCS must be considered (Bandis et al., 1981). The reduction of these two parameters with increasing sample size immediately introduces a potential permeability scale effect. The reason for this is seen in Figure 9, which illustrates the recent development of dilation modelling for different joint sample sizes taken from the same joint (Barton, 1981b). Increasing the size of sample causes delayed dilation, and seems sure to guarantee a major scale effect on permeability if significant shearing occurs.

An extremely interesting point emerges from the comparison of joints and artificial fractures shown in Figure 8. The artificial fractures were generated and presumably flow-tested at nearly the same ambient conditions in the laboratory. In contrast, the natural joints in gneiss and granite were undoubtedly formed at elevated temperature and pressure. Our results show that when joints are flow-tested at elevated temperature and pressure, mating of the joint walls apparently approaches the degree of mating achieved

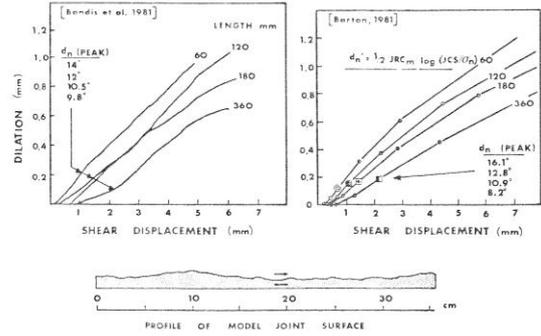


FIGURE 9. The delayed dilation exhibited by larger samples of the same joint (Bandis et al., 1981) suggests scale dependent joint permeability when shearing occurs.

when flow-testing an artificial fracture at its formation temperature.

ROUGHNESS AND TORTUOSITY EFFECTS

In many of the joint or fracture permeability tests reported in the literature, the true joint aperture is unknown. Results are therefore expressed as in this study, by an equivalent smooth wall aperture (e) derived from equation 2, or from an equivalent formulation for radial flow. This "cubic law" formulation was derived for open, non-contacting, smooth parallel surfaces.

In a recent article, Walsh (1981) utilizes the analogy of heat flow in a sheet with non-conducting cylindrical inclusions, to deduce that the permeability K_1 of a joint with points of contact is related to K_0 of an equivalent joint with an unhindered flow path as follows:

$$\frac{K_1}{K_0} = \frac{1 - A_1/A_0}{1 + A_1/A_0} \quad (3)$$

where A_1 = area of contact points
 A_0 = total area of joint

An analysis of contact area measurements by Iwai (1976), Barton and Choubey (1977) and Bandis (1980) indicates that a simple estimate of A_1/A_0 both for normal closure and limited states of shear is as follows:

$$A_1/A_0 \approx \sigma'_n / \text{JCS} \quad (4)$$

where σ'_n is the effective normal stress applied across the joint.

This simple model predicts linear increases in contact area with load, which agrees with a more complicated formulation by Walsh and Grosenbaugh (1979).

According to equations 3 and 4, tortuosity effects alone would result in about 20% reduction of permeability for our altered mineralized joint, when tested under an equal biaxial stress of 6.9 MPa. The combination of tortuosity and roughness results in the smooth wall aperture (e) being smaller than the real aperture (E). By similar reasoning, changes in either parameter (Δe , ΔE) will not be of equal magnitude. Results for $\Delta E/\Delta e$ measured in the present block tests are compared with E/e reported in the literature in

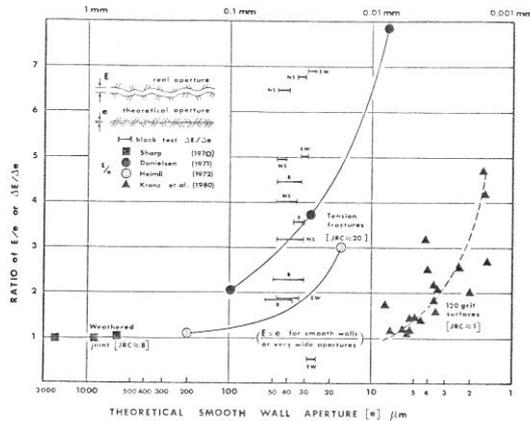


FIGURE 10. Losses due to tortuosity and roughness expressed as the ratio E/e . In-situ block test results are compared with data reported in the literature. B = biaxial, NS = uniaxial, EW = uniaxial.

Figure 10. The mean value of $\Delta E/\Delta e$ for our biaxial tests was 3.0, for a mean value of $e = 40 \mu\text{m}$.

The flow losses due to tortuosity and roughness and the observation of load path dependence has been interpreted by Kranz et al. (1979) and Walsh (1981) as evidence that the law of effective stress may not apply to flow through fractured rocks. The foregoing evidence that $E/e \geq 1$ for rough "closed" joints would appear to be a more reasonable and correct explanation. A recent article by Witherspoon et al. (1979a) has suggested that the cubic law ($e = E$) does hold even for "closed", rough fractures down to $e = 4 \mu\text{m}$. Their conclusions are contrary to the above findings, and may have been influenced by the mathematical technique used to estimate the true apertures, which were not measured directly.

CONCLUSIONS

1. A mineralized joint in gneiss, loaded normally in an 8 m^3 biaxially loaded block, exhibited a four-fold reduction in permeability when loaded from 0 to 6.9 MPa, under ambient conditions (12°C). A subsequent loading test at 74°C to the same stress, produced a thirty-fold reduction in permeability. Increased temperature alone, with no change in the 6.9 MPa normal stress, reduced permeability ten-fold. Temperature does not appear to have a positive effect on joint permeability when the joint is unconfined.
2. It appears important to test joints at elevated temperature during repository characterization, since the mating of joint walls may be artificially limited by ambient testing.
3. Uniaxial loading of the block caused 0.25 mm shear displacement of the test joint. This caused sufficient aperture strain (dilation) to increase the permeability a few percent. The continuous base of the block prevented further shear, dilation and permeability increases under the stress applied.
4. Comparison of measured changes in joint aperture

(ΔE) with calculated changes in the smooth wall aperture (Δe), indicates that $E/e > 1$ for rough, "closed" joints. This is presumably due to the combined effects of tortuosity and roughness, which may be particularly marked for the case of mineralized joints.

5. Excavation and thermally-induced shear strain and the resulting joint dilation seem likely to enhance permeability in the immediate vicinity of a repository. Outside this zone the thermal pulse might have a positive effect in reducing joint permeability. Further studies are recommended for resolving this important question.

ACKNOWLEDGEMENTS

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SITE CHARACTERIZATION OF JOINT PERMEABILITY
USING THE HEATED BLOCK TEST

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ABSTRACT

An instrumented 8 m³ block of jointed gneiss was subjected to biaxial and uniaxial loading under ambient and elevated temperatures using flatjacks and a line of borehole heaters. The tests were performed by Terra Tek in an experimental adit of the CSM mine in Colorado, as part of the ONWI programme for evaluating site characterization test methods for measuring water transport and thermal properties of rock masses. A weathered, mineralized vertical joint intersecting the block diagonally, was subjected to normal closure cycles under equal biaxial loadings to 6.9 MPa (1000 psi). Combined shear and normal closure, and shear reversal, were achieved by the uniaxial loading cycles. Water flow was monitored between a vertical injection hole and a parallel observation hole drilled down the plane of the joint. Rock and water temperatures were varied from 12° to 74°C in the flow test section of the block. Using the ambient (12°C) unconfined joint as datum, permeability reduced by a factor of four under normal stress of 6.9 MPa at 12°C. When temperature (74°C) and normal stress (6.9 MPa) were coupled, the reduction factor was thirty, and when only temperature was increased at 6.9 MPa, the permeability was reduced by a factor of ten. Measured changes in joint aperture (Δe) consistently exceeded the calculated changes in theoretical aperture (Δe) used in the cubic flow law for smooth parallel plates.