

ROCK MASS CHARACTERIZATION METHODS
FOR NUCLEAR WASTE REPOSITORIES IN JOINTED ROCK

Gebirgsklassifikationen für Lagerstätten von radioaktiven Stoffen in geklüftetem Fels
Méthodes de classification des massifs rocheux pour le dépôt des déchets nucléaires
dans les roches à diaclases

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SUMMARY:

The planned isolation of nuclear waste in mined rock repositories poses unusual requirements for rock mass characterization. This paper describes recently developed block test methods for characterizing and quantifying the thermal, mechanical and hydraulic properties of rock masses. The heated block test, recently conducted in situ on an 8m³ block of jointed gneiss, provides normal stress and temperature-dependent data such as deformation modulus, joint stiffness, joint permeability, thermal expansion, thermal conductivity and dynamic elastic modulus. Simpler tests conducted on singly jointed blocks or on jointed drill core provide joint roughness data. This is incorporated in recently developed constitutive models which describe the coupling of normal displacement, shear displacement, shear strength, dilation and permeability.

ZUSAMMENFASSUNG:

Die geplante Isolierung von radioaktivem Abfall in abgebauten Gesteinsabfällen stellt ungewöhnliche Anforderungen an Felsgesteinkennzeichnung. Dieser Bericht beschreibt kürzlich entwickelte Blocktestmethoden zur Kennzeichnung und quantitativen Bestimmung der Wärmeeigenschaften und der mechanischen und hydraulischen Eigenschaften der Felsmasse. Der Heißblocktest, der kürzlich "in-situ" auf einem 8m³ großen Block von geklüftetem Gneis durchgeführt wurde, gibt normale Spannungs- und Temperaturabhängigkeitswerte wie Verzerrungsmodul, Verbindungssteifigkeit, Verbindungsdurchlässigkeit, Wärmeausdehnung, Wärmeleitfähigkeit und Dynamik elastizitätsmodul. Einfachere Messungen, die an einzeln geklüfteten Blocks oder an geklüfteten Bohrkernen vorgenommen wurden, geben Kluftrauhigkeitswerte an. Diese sind miteingeschlossen in kürzlich entwickelte zusammenfassende Modelle, die die Kupplung normaler Verlagerung, Scherverlagerung, Scherfestigkeit, Dehnung und Durchlässigkeit beschreiben.

RESUME:

L'isolation projetée des déchets nucléaires dans des dépôts de roche extraites présente des exigences peu commune pour la caractérisation de la masse de roche. Cette étude décrit les méthodes, récemment développées, des essais des blocs pour caractériser et pour quantifier les propriétés thermiques, mécaniques et hydrauliques des masses de roche. L'essai du bloc chaud, récemment conduit in situ sur un bloc de gneiss jointé (de 8m³) fournit l'indication normale qui dépend de la force et de la température par exemple, le coefficient de la déformation, la dureté de la jointure, la perméabilité de la jointure, l'expansion thermique, la conductivité thermique et le coefficient dynamique et élastique. Des essais plus simples qu'on a conduits sur des blocs individuellement jointés ou sur le centre jointé d'un trepan fournissent les indications de la rugosité des jointures. Tout ça est incorporé dans des modèles de base, récemment développés, qui décrivent le couplage du déplacement normal, du déplacement du cisaillement, de la force du cisaillement, de la dilation et de la perméabilité.

1 INTRODUCTION

Characterization of rock masses is usually associated with construction and excavation projects such as dams, tunnels, mines, etc. In general the parameters of most importance are associated with deformation moduli, shear strength and permeability, each a function of stress and orientation. Civil engineering experience suggests that the natural joint sets have most effect on the magnitude of these parameters. Jointing is also responsible for their directional anisotropy.

The planned isolation of nuclear waste in mined rock repositories poses additional problems in rock mass characterization. The extended time scale and the thermal load associated with long-term isolation add to the number of significant parameters that need to be quantified. Numerical modeling of potential groundwater and radionuclide transport through changing stress and temperature regimes demands an advanced level of input data. Particular emphasis falls on accurate joint characterization, in particular on the manner in which the hydraulic, thermal and mechanical properties should be coupled.

2 THE HEATED BLOCK TEST

The schematic block diagram shown in Figure 1 represents the 8 m³ in situ test recently completed by Terra Tek for the Office of Nuclear Waste Isolation. The objective was to demonstrate a suitable method for obtaining appropriate hydrothermomechanical data for modeling and designing a repository in jointed rock. The particular test was performed in jointed gneiss. Flat-jacks were used to apply uniaxial and biaxial loading, and a line of borehole heaters were used to heat the block and to generate a temperature gradient. An extensive suite of borehole instruments were evaluated over a range of stress and temperature cycles, as indicated in Figures 2 and 3. The list below indicates average block temperatures relevant to the joint permeability tests described later.

Ambient 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.

Heating and Cooling Cycles

5. Equal biaxial, 41°C.

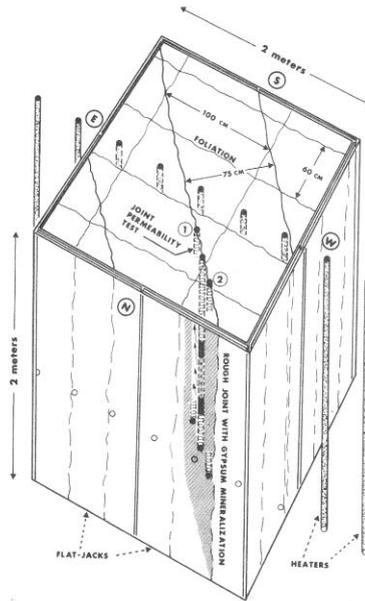


Fig. 1 Schematic of Terra Tek's 8 m³ in situ heated block test in jointed gneiss.

6. Equal biaxial, cycle, 6.9-3.45-6.9 MPa, 56°C.
7. Equal biaxial, cycle, 6.9-3.45-6.9 MPa, 74°C.
8. Equal biaxial, , unload, 17°C.
9. Unconfined, 56°C, cycle, 0-3.45-0 MPa.
10. Unconfined, ambient.

The ability to load and unload or heat and cool the block independently exposed the instrumentation to a large number of operating cycles and pinpointed several areas where improvements to existing instrumentation could be achieved.

2.1 Deformation behavior

The deformability of the block was measured over several different base lengths, ranging from 25 cm with the Whittemore gage, to the full 2 meters dimension using the multiple position borehole extensometers (MPBX). Whittemore gage points were specifically located to measure the deformation across individual joints, and to record the deformation of the intact rock

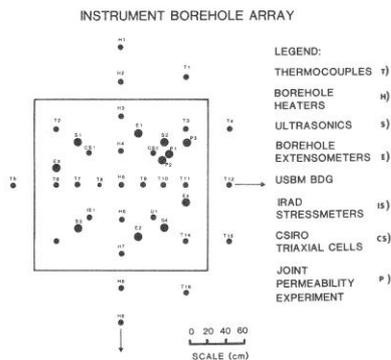


Fig. 2 Borehole instrument array.

between joints. Figure 4 shows a typical stress-strain loop from EW uniaxial loading at ambient temperature. Whittemore gage measurements aligned within $\pm 10^\circ$ of drift E-W were used. Eight measurements at each stress level (1.75, 3.45, 5.25, 6.9 MPa) were averaged to compute the strain values. Six of the eight gages spanned joints. The "S" shaped hysteric loop is typical of much of the loading data obtained on jointed rock, signifying low moduli on first loading and final unloading, and consistently high moduli on initial unloading.

Block deformation could actually be detected visually, by observing the growth and closure of cracks above each flat-jack, round the four vertical sides of the block. These cracks were monitored with several gages. In effect the surrounding rock mass acts as the loading "platen" and deforms outwards, while the block itself shortens, each contributing to the total crack width. An elastic solution given by Poulos and Davis (1973) was used to relate stress level and crack width to the modulus:

$$E = \frac{\Delta P \cdot 1920}{\delta} \quad (1)$$

where E = deformation modulus (MPa)
 ΔP = stress increment (MPa)
 δ = total crack opening (mm)

A value of Poisson's ratio of 0.2 was assumed in deriving the equation. Figure 5 illustrates the results obtained following four ambient load cycles, which had stiffened the block to an effective deformation modulus of approximately 40 GPa.

Unloading loops at 50°C and 80°C showed an interesting reversal of hysteresis which has yet to be satisfactorily explained. Perhaps the most significant result is the tendency for extremely high unloading moduli at elevated temperature and also when cooling.

Observations of joint deformation reported later, indicate that joints interlock tightly at elevated temperature, and remain tightly closed until almost unloaded. This behavior has potentially serious consequences for the long-term hydraulic integrity of a repository, since it is likely to facilitate the development of sporadic large aperture joints during the cooling-unloading phase. This may also be contemporary with the canister failure phase.

2.2 Poisson's ratio

Values of Poisson's ratio for horizontal transverse to axial strain were calculated using Whittemore strain data acquired during uniaxial loading at ambient temperature. The results show the characteristic non-elastic response of jointed rock to uniaxial stress. Individual measurements of Poisson's ratio fell in the range of ≤ 0 to ≥ 2.0 , probably because of shear displacement along joints. Average values ranged from -0.441 to +0.472, the negative values occurring during the reversed shear caused by the EW loading.

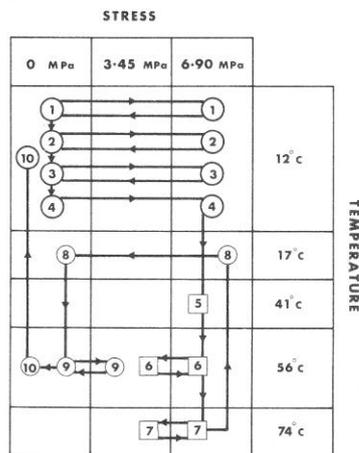


Fig. 3 Test matrix for the present series of block tests.

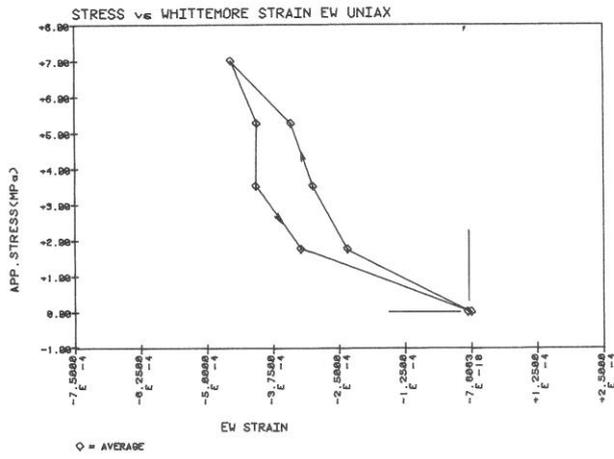


Fig. 4 Typical stress-strain loop obtained from Whittemore points.

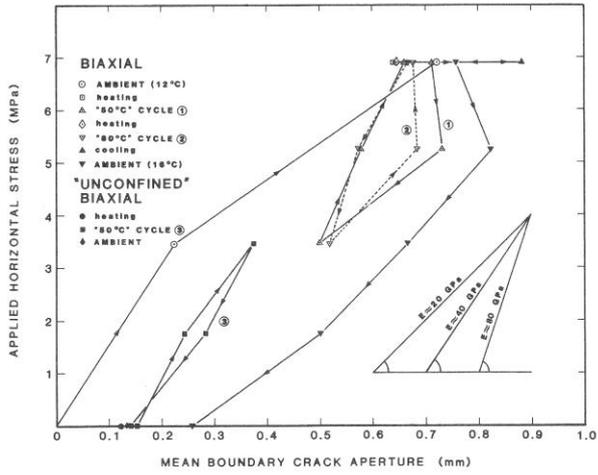


Fig. 5 Block deformation measured from boundary crack monitoring, under elevated temperatures.

Values of Poisson's ratio were also calculated from the vertical strains measured by the two vertical MPBX gauges, during biaxial and uniaxial loading. The following values were obtained during ambient loading:

Biaxial	0-6.9 MPa	0.246
	6.9-0 MPa	0.171
NS uniaxial	0-6.9 MPa	0.063
	6.9-0 MPa	0.058
EW uniaxial	0-6.9 MPa	0.071
	6.9-0 MPa	0.059

The absence of joint shearing is evident in these moderate vertical strains.

2.3 Dynamic elastic moduli

Crosshole ultrasonic velocity (compressional and shear wave) measurements were made in the block at different loads and temperatures. The equipment used to make the ultrasonic measurements is shown in Figure 6.

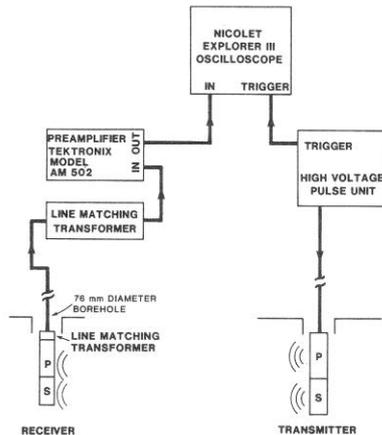


Fig. 6 Diagram of crosshole ultrasonic equipment.

Piezoelectric transducers were bonded to the downhole assemblies, which were in turn mechanically loaded against the side of the borehole at the location of each measurement, to provide acoustic coupling to the rock. The transit time between the transmitted pulse and the received signal was obtained from the oscilloscope display.

Each wave form was also recorded on a magnetic disk built into the oscilloscope, for future reference.

The dynamic Young's modulus and Poisson's ratio were calculated in accordance with elastic theory, using the following equations:

$$E = \frac{\rho V_s^2 (3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2} \quad (2)$$

$$\nu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}, \quad (3)$$

where E = dynamic Young's modulus

ν = Poisson's ratio

V_p = P-wave (longitudinal) velocity

V_s = S-wave (shear) velocity

ρ = bulk density of the rock

Figure 7 shows examples of some of the data obtained during ambient temperature loading. The trend for higher modulus at greater depth in the block, and at higher stress (confinement) levels is apparent. Note also the reduced dynamic modulus on final unloading, a result consistent with the moduli obtained from static measurements.

Laboratory measurements of dynamic Young's modulus on intact samples indicated a small increase with confining stress. For example, the dynamic modulus increased from 72 to 73 GPa parallel to foliation, and from 76 to 77 GPa perpendicular to foliation, over the range of confining stress 0-7 MPa. The dynamic modulus reduced from 69 to 64 GPa in the temperature range 20-140°C, under a confining stress of 7 MPa. The dynamic moduli obtained from the cross-hole ultrasonic tests reflected

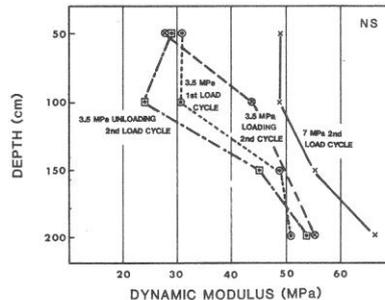


Fig. 7 Dynamic Young's modulus calculated from the ultrasonic data, as a function of depth in the block at different load conditions.

the effect of jointing and blast damage or stress relief. At 50 cm depth in the block values under ambient loading ranged from 10-49 GPa, while at 200 cm depth at the base of the block, where there was presumably improved confinement, values ranged from 27-68 GPa.

Under ambient biaxial loading the average dynamic modulus measured at the highest stress level (6.9 MPa, 1000 psi) was 53 GPa. Under N-S uniaxial loading, the first occasion in which the block was subjected to shear along the diagonal joints, the average dynamic modulus in the lateral (expanding) E-W direction was only 34 GPa. In the loaded N-S direction it remained high at 50 GPa. However, when the shear stress was reversed in the E-W uniaxial test, the average dynamic modulus in the lateral N-S direction was only slightly lower than in the loaded direction (47 GPa compared to 53 GPa). This is presumably due to the re-closing of joints during reversed shear.

Under elevated temperature biaxial loading, the general tendency for increased modulus with depth remained. However, there was a marked increase in the range of modulus values in the E-W direction, parallel to foliation. At elevated temperature, high confinement (6.9 MPa) produced 10-30 GPa increase in modulus in this sensitive E-W direction.

2.4 Thermal Expansion

Thermal property data for intact samples of Stripa (Swedish) granite presented by Chan, et al. (1980), indicate reduced values of Young's modulus, thermal conductivity and Poisson's ratio as rock temperature is increased over the range 20-200°C. The coefficient of thermal expansion increased over the same range of temperature, and proved to be the most important temperature dependent input parameter for realistic numerical modeling of the mechanical response of a rock mass to heating.

Thermal expansion data assembled in Figure 8 indicates that both small and large scale data obtained from the heated block test follow the trends of laboratory data from similar rock types. An initial reduction in (α) at low temperatures measured by the horizontal strain indicator (HSI) gages is probably caused by improved closure of the numerous vertical joints sampled by these gages. The strongly foliated nature of the granitic gneiss is reflected in the relative magnitudes of the expansion coefficients. Those mea-

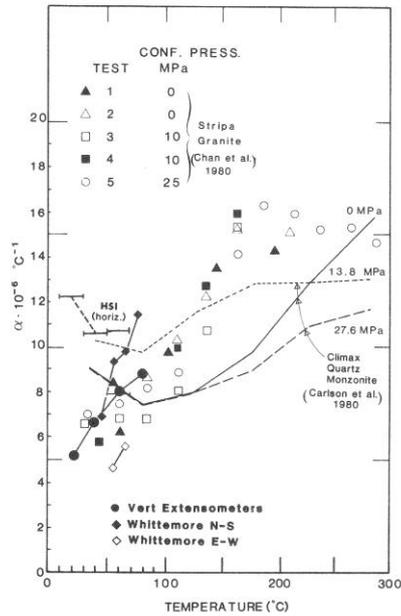


Fig. 8 Overlay of major laboratory tests of (α) as a function of temperature and confining pressure for granitic rocks. Block test results from the rod extensometers, Whittemore pins and HSI gages are plotted for comparison.

sured parallel to foliation (E-W) were 1/3 to 1/2 the magnitude of those measured in the perpendicular (N-S) direction.

2.5 Stress Monitoring Discrepancies

A significant objective of the heated block test was to investigate the performance of several stress gages in a known (applied) stress field, under conditions of cycling stress and temperature. As it turned out, the strongly foliated nature of the granitic gneiss caused considerable discrepancies between applied and measured stress, presumably due to the extremely large strength and stiffness contrast caused by the quartz lenses. Schmidt hammer rebound values reported by Hardin, et al. (1981) indicated rebounds as high

as 96%, which theoretically convert to unconfined compression strengths well in excess of 400 MPa. The strength contrast was certainly evident in the problems experienced in percussive drilling of the slots. Hole alignment was so irregular that the slots eventually had to be diamond cored with overlapping holes, using drill-guides.

Data taken with the USBM three component borehole deformation gage during ambient equal biaxial loading indicated that the applied horizontal N-S and E-W stresses were in a ratio 4:1. This result was incompatible with the known equal stress distribution of 6.9 MPa, and may have been caused by locating the gage in a borehole paralleling a hard quartz lense.

IRAD vibrating wire stressmeters responded to stress changes somewhat differently than they did during laboratory calibration in a 157 mm (6.0 inches) core of gneiss taken from the block. Although installed in the block with special attention given to alignment, the N-S gage perpendicular to foliation was roughly 300% more sensitive than the laboratory calibration, and the E-W gage showed only a 20% sensitivity to the known applied stresses of 6.9 MPa. This is equivalent to the core used for calibration being stiffer, in the N-S direction, than the block in the vicinity of the stress meters. This difference indicates that the foliation and quartz lenses in the block were not satisfactorily represented by the core. A more detailed knowledge of the inhomogeneity of the deformation modulus within this foliated lenticular body of rock would be required for improved results to be obtained from these gages.

2.6 Joint Permeability

The location of the joint permeability test is indicated in Figure 1. The rough mineralized joint was first flow tested before the flatjack slots were drilled, then after drilling, and finally during successive stages of loading and unloading. The results of one of the ambient tests are shown in Figure 9. In this test, flat-jack loading was equal and biaxial, and the joint was therefore under the influence of pure normal stress, with no shear component at this stage. A result which was common to previous ambient temperature block tests, was the difficulty of closing the natural joint beyond some limiting aperture. In this case it appeared that the conducting aperture of 30 microns could not easily be reduced by

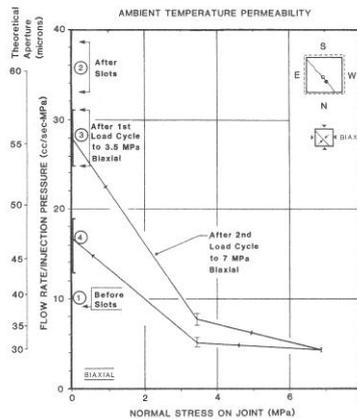


Fig. 9 Effect of normal stress on the flowrate and on the theoretical smooth wall aperture (e).

the influence of stress alone. This theoretical smooth wall aperture is derived from the well known "cubic" flow law for parallel plates:

$$q = \frac{de^3}{12\mu} \cdot \frac{dP}{dy} \quad (4)$$

where: $\frac{dP}{dy}$ = pressure gradient
 μ = absolute viscosity (1.2×10^{-5} gm.sec/cm² at 12°C)
 d = width of flow path
 q = flow rate

A second ambient biaxial test (points 9, 10 and 11 in Figure 10) showed a similar minimum aperture of 30 μ m at a maximum normal stress of 6.9 MPa. However, when the block temperature was raised to 55°C following 22 days heating at 500 watts/heater, and to 74°C following a further 13 days at 700 watts/heater, the conducting aperture was found to reduce considerably, despite controlled boundary stresses.

In summary, the test joint exhibited a four-fold reduction in permeability when loaded from 0 to 6.9 MPa under ambient conditions, and a thirty-fold reduction when temperature was also increased to 74°C. Increased temperature alone, with no change in the normal stress, reduced permeability ten-fold.

This remarkable reduction of flow aperture 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 anisotropic thermal expansion. 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 reestablished 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 10).

2.7 Shear Displacement Constraints

Two of the ambient temperature tests involved uniaxial loading, which was achieved by activating the N-S flat-jacks and E-W flat-jacks separately. Figure 11 indicates that the N-S loading develops clockwise shear along the diagonal test joint, and shear reversal when activating the E-W flat-jacks.

Careful shear strength estimates which are described later, indicated that the maximum applied shear and normal stress components would be sufficient to shear the joint in the absence of the stiff intact base of the block. A specific limitation of the flat-jack-loaded in situ block test is indicated by the small magnitudes of shear displacement and the artificially high shear stiffness. Only 0.25 mm of shear displacement was recorded, and reversal through the origin did not occur.

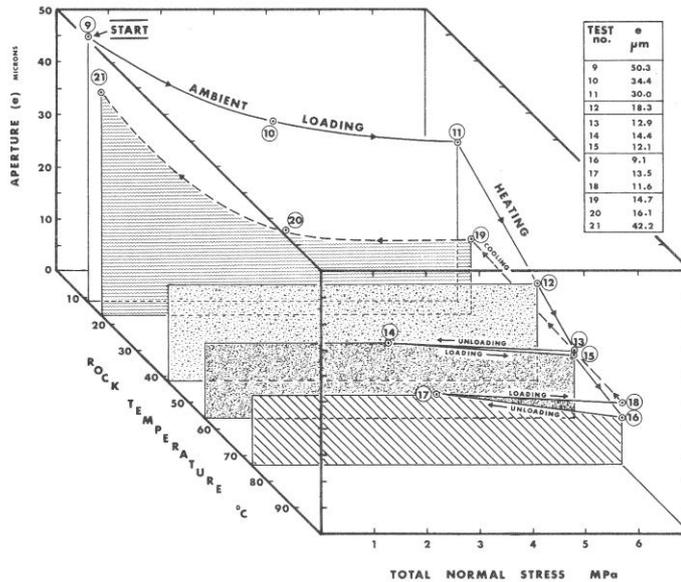


Fig. 10 Biaxial loading at elevated temperatures facilitates hydrothermomechanical coupling, causing dramatic reductions in flow aperture.

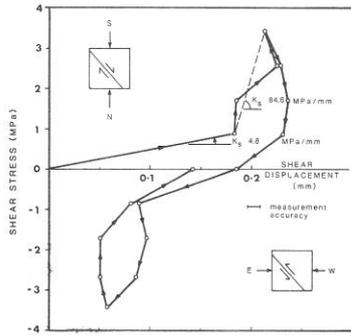


Fig. 11 Shear displacement and reversal measured along the diagonal, permeability test joint, during the N-S and E-W uniaxial tests that were conducted at ambient temperature.

Despite the limited shear displacements, there was an indication of "aperture strain", and the beginnings of dilation, as seen in the flowrate-stress data shown in Figure 12. Once again conducting apertures were only reduced to marginally less than 30 μm . The reduced aperture achieved during the E-W test is probably a function of slightly improved joint "seating" caused by asperity damage during the reversal.

A significant finding from these tests was the lack of equality between measured changes of joint aperture and calculated changes of flow aperture. The former always exceeded the latter by a factor of 2 to 7. This effect is presumably due to roughness and tortuosity, and is consistent with other data reported in the literature (Barton, 1981).

2.8 Laboratory Cube Test

Limited shear displacements are difficult to avoid in an in situ block test, unless extreme measures are taken to "disconnect" the block from the underlying rock mass, using wire sawing or hydraulic fracturing

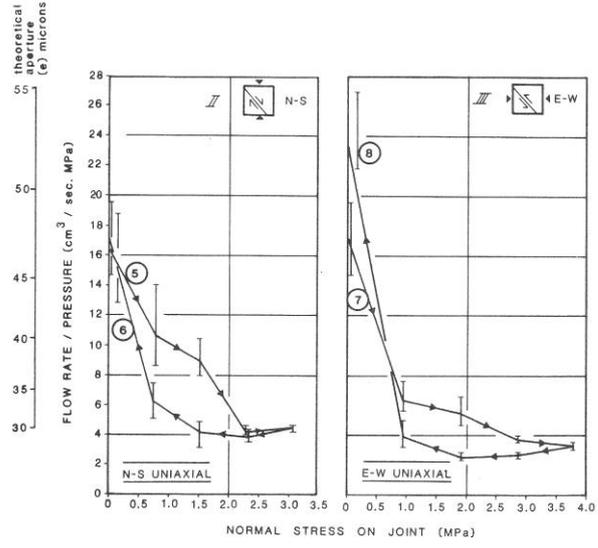


Fig. 12 Effect of proportional shear and normal stress on flow rate and theoretical smooth wall aperture, under ambient temperature.

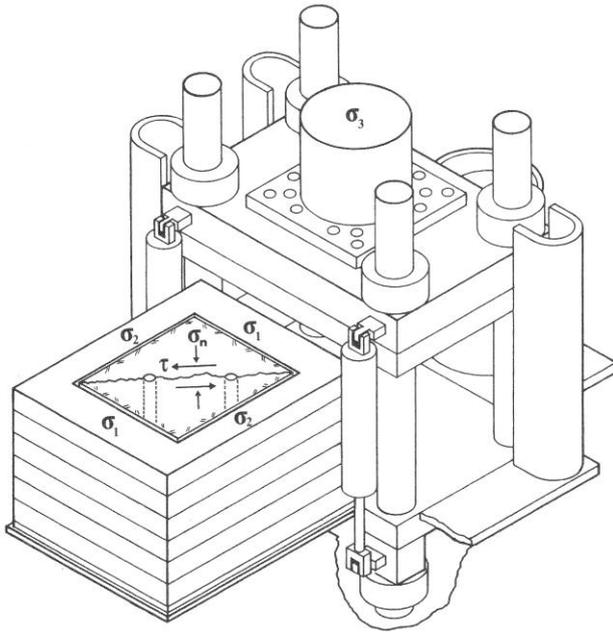


Fig. 13 Laboratory cube test facility for investigating hydrothermomechanical coupling phenomena in jointed 1 m³ blocks of rock.

of the base. Terra Tek's 1 m³ cube machine depicted in Figure 13 is not subject to these shear displacement limitations and is capable of applying elevated temperature, polyaxial loading up to 35 MPa (5000 psi). Sample acquisition is facilitated by pre-bolting the joint to be tested, and wire sawing the sample using the five-side release method described by Londe (1972).

3 SHEAR STRENGTH CHARACTERIZATION

The heated block test described in the preceding pages provides quite reliable characterization of the following stress and temperature dependent parameters on a large scale:

1. intact and jointed rock modulus
2. joint normal stiffness
3. joint permeability and conducting aperture
4. coefficient of thermal expansion

5. thermal conductivity and diffusivity
6. dynamic Young's modulus (cross-hole)

With the possible exception of the dynamic modulus each of the above parameters represents important direct input for comprehensive modeling of near-field repository response to thermal loading. Additional data is required to quantify the following parameters:

7. joint wall strength
8. joint roughness
9. joint shear strength
10. joint shear stiffness
11. shear-dilation-permeability coupling

Tunneling and mining experience, physical joint models and numerical models demonstrate the possibility of significant shear displacement along joints that are exposed by excavation in anisotropic stress regimes. The potential migration of groundwater across a repository will be

strongly influenced by the zones of reduced permeability caused by joint closure, and by the zones of increased permeability caused by shear displacements. Data is required so that a coupled model of thermal-mechanical-hydraulic behavior can be formulated and quantified.

3.1 Quantitative Joint Characterization

A simple, though quite complete method of characterizing the shear behavior of rock joints has been developed in recent years. It consists of three components: ϕ_b , JRC and JCS. A basic or residual friction angle (ϕ_b or ϕ_r) for flat non-dilatant surfaces in fresh or weathered rock, respectively, forms the limiting value of shear strength. To this is added a roughness component (i). This is normal stress dependent and varies with the magnitude of the joint wall compressive strength (JCS), and with the joint roughness coefficient (JRC). The latter varies from about 0 to 20 for smooth to very rough surfaces respectively. The peak drained angle of friction (ϕ') at any given effective normal stress (σ'_n) is expressed as follows:

$$\phi' = \phi_r + i = \text{JRC} \log(\text{JCS}/\sigma'_n) + \phi_r \quad (5)$$

Example

$$\phi_r = 25^\circ, \text{JRC} = 10, \text{JCS} = 100 \text{ MPa},$$

$$\sigma'_n = 1 \text{ MPa}$$

$$\text{equation 5 gives } \phi' = 45^\circ$$

The compression strength of the joint walls (JCS) has increased influence on the shear strength as the joint roughness increases. Values of JCS and its variation with weathering are measured with the Schmidt (L) hammer. Experimental details are given by Barton and Choubey (1977). The residual friction angle (ϕ_b) of weathered joints is very difficult to determine experimentally due to the large displacements required, particularly if only small joint samples are available. A simple empirical approach has been developed as shown below.

$$\phi_r = (\phi_b - 20) + 20 r_1/r_2 \quad (6)$$

where:

ϕ_b = basic (minimum) friction angle of flat unweathered rock surfaces (obtained from tilt tests on sawn blocks, or from triple core tilt tests - see Figure 14)

r_1 = Schmidt rebound on saturated, weathered joint walls

r_2 = Schmidt rebound on dry unweathered rock surfaces (i.e., saw cuts, fresh fracture surfaces, etc.)

Example:

$$\phi_b = 30^\circ, r_1 = 30, r_2 = 40$$

$$\text{equation 6 gives: } \phi_r = 25^\circ$$

The value of JRC can be back-calculated directly from a tilt test on jointed core, as depicted in Figures 14 and 15. The shear strength equation is rearranged to give:

$$\text{JRC} = \frac{\alpha^\circ - \phi_r}{\log(\text{JCS}/\sigma'_{no})} \quad (7)$$

where

$$\alpha^\circ = \text{tilt angle when sliding occurs} (\alpha^\circ = \arctan \tau/\sigma'_{no} = \phi')$$

$$\sigma'_{no} = \text{effective normal stress acting across joint when sliding occurs}$$

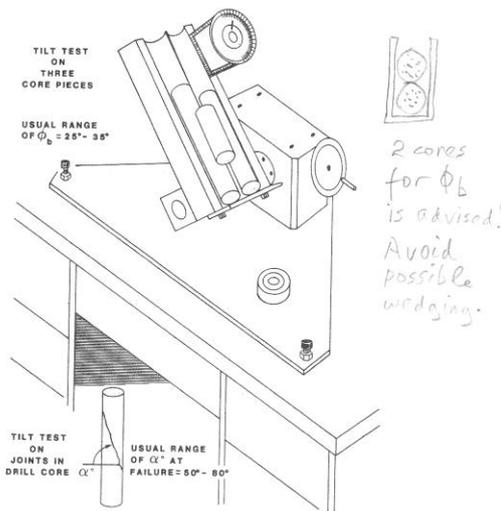


Fig. 14 Tilt tests of axially jointed core provided estimates of the full-scale shear strength of joints, after correction for scale effects.

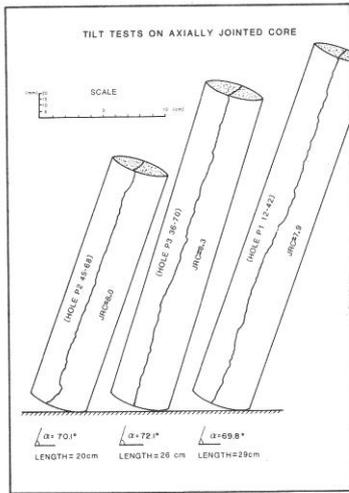


Fig. 15 Tilt tests performed on jointed cores obtained from the permeability test holes in the heated block. Measured roughness profiles are shown, drawn at the mean angles of tilt measured when sliding occurred.

Example: $\alpha = 75^\circ$, $\phi_r = 25^\circ$, JCS = 100

MPa, $\sigma_{no}' = 0.001$ MPa

equation 7 gives:

JRC = $(75^\circ - 25^\circ)/5 = 10$ (i.e., moderately rough, undulating)

The values of JRC, JCS, and ϕ_r can be used to generate peak shear strength envelopes over the required range of stress. The following table of values shows how the value of ϕ' varies inversely with the log of effective normal stress. This is a fundamental result for rock joints, rock-fill, gravel, etc. (Barton and Kjaernsli, 1981).

Example: JRC = 10, JCS = 100 MPa,
 $\phi_r = 25^\circ$

The table below indicates the following relation between stress level and friction angle:

Type of Test	σ_n' MPa	ϕ' °
Approx. lab tilt test	0.001	75°
Approx. field tilt test	0.01	65°
	0.1	55°
Approx. design loading	1.0	45°
	10.0	35°

*Note: ϕ' varies by JRC degrees (°) for each ten-fold change in stress, in this case, 10°.

3.2 Scale Effects

Large-scale shear tests of joints in quartz diorite (Pratt, et al. 1974) and a comprehensive series of tests performed by Bandis (1980) have indicated that larger shear displacements are required to mobilize peak strength as the length of joint sample is increased. This means that larger but less steeply inclined asperities tend to control peak strength as the length of sample is increased.

Tests by Bandis (1980) indicate that during a shear test, the block size will determine both the distribution, number and size of contact areas. While this level of detail can obviously not be modeled numerically, its effect on joint behavior must be taken into account. The following possible size-dependent properties have to be considered:

1. shear displacement to mobilize peak strength (δ peak)
2. joint roughness coefficient (JRC)
3. joint wall compression strength (JCS)
4. shear stiffness (K_s)
5. dilation during shear (d_n)

A method of estimating (or measuring) the size-dependency of these parameters is needed, before a satisfactory constitutive law of behavior can be developed.

Figure 16 shows schematically but quite realistically how the shear strength, stiffness, peak displacement and dilation are changed by increasing block size, for the case of non-planar joints. However, there is strong evidence to suggest that these scale effects do not extend beyond the natural block size in a jointed rock mass (Bandis, et al. 1981). Large scale tilt and pull tests on natural blocks as depicted in Figure 17 are therefore recommended for obtaining scale free values of the joint roughness coefficient (JRC).

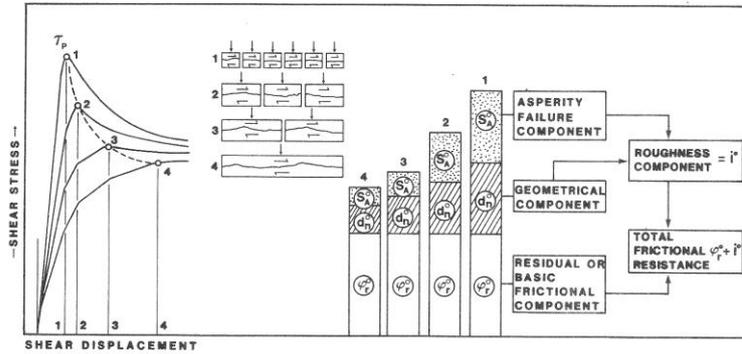


Fig. 16 Size dependence of shear strength components, after Bandis, et al. 1981.

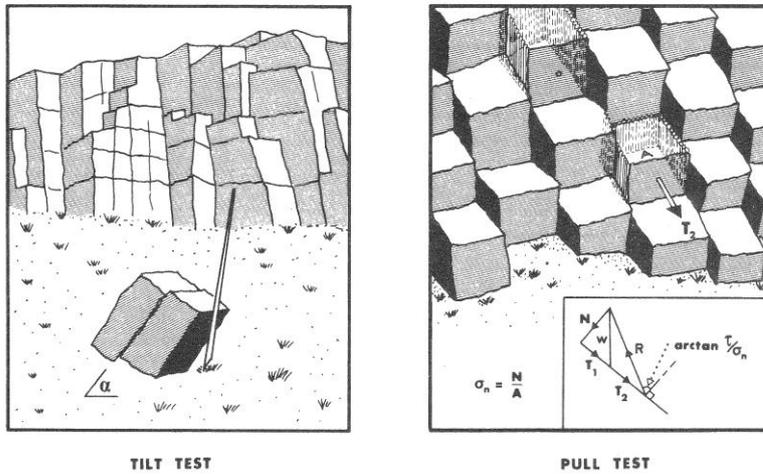


Fig. 17 Self-weight tilt and pull tests are used to quantify the joint roughness component of shear strength at full-scale.

3.3 Strength-Displacement-Size Coupling

Frequently it will not be possible to extract or test natural scale blocks, and smaller scale tests such as tilt tests on jointed core or shear box tests have to be relied upon. Recent work reported by Bandis, et al. (1981) and Barton (1981) has provided a method for predicting how

the values of JCS and JRC obtained from small scale tests reduce with increasing block size. Numerous shear box tests indicate that the values of these parameters reduce most strongly in the case of rough undulating joints having high values of JRC on a laboratory scale. Values of $\delta(\text{peak})$ are found to increase with in-

creasing block size, the increase being most marked for the case of rough joints.

The table inset in Figure 18 gives examples of the quantitative changes of JRC, JCS and $\delta(\text{peak})$ that occur with increasing block size, for a rough joint that exhibits a JRC value of 15 on a laboratory size (10 cm long) sample. Scale dependent values such as these are used to generate complete stress-displacement and dilation-displacement curves for any given block size. Validations with experimental data indicate an excellent degree of fit (Barton, 1981).

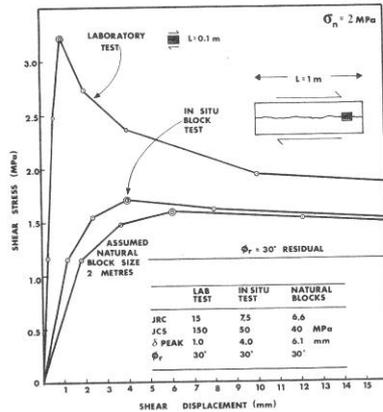


Fig. 18 A constitutive model relating stress, displacement, dilation and block size has recently been developed (Barton, 1981).

3.4 Permeability-Displacement Coupling

Normal stress and shear stress perturbations may cause changes in the undisturbed aperture of a joint, which would be superimposed on the initial aperture and cause corresponding changes in permeability. The undisturbed conducting aperture may be estimated from carefully controlled borehole pump-in tests, using accurately located, closely spaced packers, or using the statistical method proposed by Snow (1968). This method provides estimates of the mean theoretical smooth wall conducting aperture (e) (equation 4) and estimates of the mean spacing (S) of water conducting joints, assuming the rock mass

can be idealized as a cubic network of water conducting joints.

In the case of the heated block test described earlier, the value of (e) and its variation with normal stress and temperature can be studied directly. The problem lies in generating similar data at the bottom of a 1000 meter deep borehole, and including the coupling between shear displacement and permeability. This data will usually be required before access is made available for actually extracting blocks, for tests such as depicted in Figure 13.

Recent constitutive modeling and experimental data indicates that the parameters JRC and JCS determine the magnitudes of both normal closure and the dilation induced by shear. In the case of normal closure, laboratory scale values of JRC and JCS determine behavior, as shown by Bandis (1980) and Barton (1981). Only when shearing occurs do the lower, size-dependent values of JRC and JCS dominate behavior.

Comparison of the predicted aperture and permeability reductions with measurements obtained in the heated block experiment show good agreement. However, the limited shear displacement (0.25 mm) achieved in the heated block test was insufficient to test the predictive capabilities of the JRC-JCS shear-flow model. The only coupled shear-flow data known to the authors is Maini's data, which was reported by Maini and Hocking (1977).

This test was performed under extremely low normal stress, generated by the self-weight of a block of slate of 160 cm² area. The joint was a planar cleavage parting. The flow rate was monitored as shear displacement was increased in steps to about 6 mm. The initial conducting aperture was found to increase significantly, resulting in two orders of magnitude increase in permeability. This experimental result and our prediction are compared in Figures 19 and 20. The method shows promising agreement. Closeness of fit could possibly have been improved if Schmidt hammer and tilt tests had been performed. The values of JRC and JCS shown in Figure 19 are best estimates only, representing realistic values for smooth, almost planar cleavage surfaces in a moderate strength slate.

4 CONCLUSIONS

1. Heated in situ tests of jointed rock using flat-jacks to load several m³ of rock can provide the majority of the

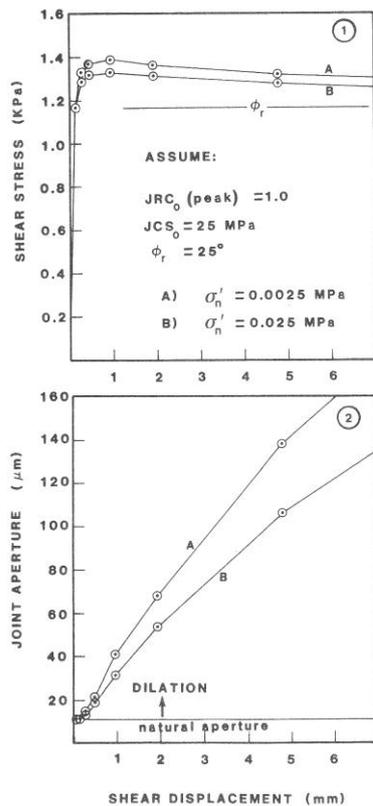


Fig. 19 An example of stress-displacement and dilation-displacement modeling (graphs 1 and 2).

hydrothermomechanical input data needed for rock mass characterization of potential nuclear waste repositories.

2. The potentially low stiffness and high permeability of joints under conditions of shear can be measured in a large cube testing machine capable of applying polyaxial mechanical loading, and thermal loading to jointed blocks of up to 1 m³ volume. Access to the repository horizon, or to an equivalent rock mass, is assumed in both the above block tests.

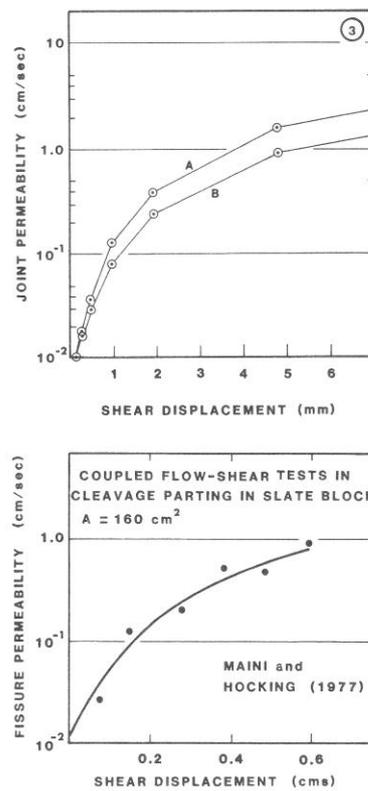


Fig. 20 Comparison of permeability-displacement modeling (graph 3) with the results of a coupled flow-shear test reported by Maini and Hocking (1977).

3. Useful data can also be obtained prior to site access, using jointed pieces of drill core. Tilt tests and Schmidt hammer tests to quantify the roughness (JRC) and wall strength (JCS) of the joints can provide the necessary data for preliminary constitutive modeling. These parameters determine the magnitudes of joint deformability and shear strength, and the critically important coupling between permeability, normal closure, shear, dilation and size effects.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

- Bandis, S., 1980. "Experimental Studies of Scale Effects on Shear Strength, and Deformation of Rock Joints," Ph.D. Thesis, University of Leeds, Dept of Earth Sciences.
- Bandis, S., A.C. Lumsden and N. Barton, 1981. "Experimental Studies of Scale Effects on the Shear Behavior of Rock Joints," *Int. J. Rock Mech. Min. Sci. and Geomech. Abstr.*, Vol. 18, pp. 1-21.
- Barton, N. and V. Choubey, 1977. "The Shear Strength of Rock Joints in Theory and Practice," *Rock Mechanics*, Vol. 10, pp. 1-54.
- Barton, N. and B. Kjaernsli, 1981. "Shear Strength of Rockfill," *Journal of the Geotechnical Engineering Division, American Society of Civil Engineers*, Vol. 107, No. GT7, Proc. Paper 16374, July, pp. 873-891.
- Barton, N., 1981, "Modeling Rock Joint Behavior From In Situ Block Tests: Implications for Nuclear Waste Repository Design," Office of Nuclear Waste Isolation, Columbus, Ohio, 96 p.
- Chan, T., M. Hood and M. Board, 1980. "Rock Properties and Their Effect on Thermally Induced Displacements and Stress," Proc. American Society of Mechanical Engineers, Energy Sources Technology Conf., New Orleans.
- Hardin, E.L., N. Barton, R. Lingle, M.P. Board and M.D. Voegelé, 1981. "A Heated Flatjack Test Series to Measure the Thermomechanical and Transport Properties of In Situ Rock Masses," Office of Nuclear Waste Isolation, Columbus, Ohio, 193 p.
- Londe, P., 1972. "The Mechanics of Rock Slopes and Foundations," Imperial College London, Rock Mechanics Research Report No. 17, April 1972, 89 p.
- Maini, T. and G. Hocking, 1977. "An Examination of the Feasibility of Hydrologic Isolation of a High Level Waste Repository in Crystalline Rock," *Geologic Disposal of High-Level Radioactive Waste Session, Annual Meeting of the Geological Society of America*, held in Seattle, Washington.
- Poulos, H.G. and E.H. Davis, 1973. "Elastic Solutions for Soil and Rock Mechanics," John Wiley and Sons, New York.
- Pratt, H.R., A.D. Black and W.F. Brace, 1974. "Friction and Deformation of Jointed Quartz Diorite," *Proceedings of the 3rd International Congress on Rock Mechanics*, held in Denver, CO, Vol. 2A, pp. 306-310.
- Snow, D.T., 1968. "Rock Fracture Spacings, Openings, and Porosities," *Proceedings, American Society of Civil Engineers*, Vol. 96, No. SM 1, pp. 73-91.