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COUPLED HYDRO-THERMAL CRACKING IN GRANITE FRACTURES AND APPLICATION TO RADIOACTIVE WASTE REPOSITORY

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SYNOPSIS

Deep underground repository in granite and crystalline rocks is normally reserved for the disposal of radioactive wastes. The heat generated by the radioactive waste during their natural decay may alter the geologic and the hydraulic properties of the surrounding rock masses. Hydraulic flow tests were conducted on heated granite samples containing natural and artificially induced fractures by injecting cold water through, as part of the studies on the hydro-thermo-mechanical properties of fractures in granite. Scanning electron microscope observations show that thermally induced, interconnected intragranular cracks was produced in the granite during tests. These thermal cracks may form a network which could in theory provide new pathways for fluid flow. However, the study also indicate that the introduction of these potentially additional flow paths has little effect on overall hydraulic behaviour, since fluid flow is concentrated in the fractures. In contrast, major changes in fracture hydraulic properties are influenced by hydro-thermo-mechanical alteration. The test results showed that in general, the overall hydraulic permeability decreases as temperature increased. Thermal cracking alone is unlikely to effect the hydraulic and thermal performance of nuclear radioactive waste repository in granitic rocks.

INTRODUCTION

Recent development in large scale research of nuclear waste repository design requires to study hydraulic and thermal performance of the surrounding rock masses under the presence of groundwater circulation (Milnes, 1985). It has been concerned that the radioactive waste may heat up the rock, with the presence of groundwater, to produce thermal cracking and to expand major fracture aperture, so that additional leakage of radioactive waste would occur through the fractures by groundwater circulation.

For granite and many crystalline rocks, the hydrogeological properties are controlled by fluid flow within a highly impermeable but fractures medium since flow is concentrated in the fractures. The aperture of fractures is therefore, a major parameter influencing the hydraulic conductivity of granite rock mass. Because of the roughness of fractures surfaces, it is unrealistic to assume that fractures have smooth parallel walls. Studies on fracture hydraulic properties have been conducted both in the laboratories (e.g., Detournay 1980; Raven & Gale 1985; Zhao 1987) and on the field (e.g., Witherspoon et al, 1981; Cook 1983; Makurat et al, 1990). Fully-coupled hydro-thermo-mechanical joint behaviour tests were conducted on a rough joint in gneiss by Hardin et al (1982). The test joint exhibited a significant reduction in hydraulic conductivity when temperature was increased.

For many locations, the current understanding of flow through crystalline rocks is adequate to predict with sufficient confidence the physical and hydrogeological behaviour of these rocks. However, there is still a lack of proper understanding of the hydrogeological properties of the rock masses at elevated temperature after the nuclear waste is emplaced. It therefore, requires both further laboratory as well as field investigations to provide sufficient confidence for modelling and engineering.

TEMPERATURE ELEVATION AND THERMAL CRACKING

For wastes containing large amounts of long lived radionuclide, it is generally admitted that the degree of long-term isolation associated with geological disposal is required. In the nuclear power generation, these types of waste are essentially high level waste from reprocessing operations, alpha-bearing waste and encapsulated spent-fuel elements if declared as waste.

Both vitrified high-level waste and spent nuclear fuel are a source of heat from radioactive decay but one which decreases naturally with time. Typical rates of heat generation and their evolution over time for these two forms of radioactive waste are given in Table 1. The thermal power decreases relatively rapidly by a factor of 50 or more in a hundred years. The contribution of the major fission becomes insignificant after 250 years.

The thermal power due to radioactive decay of the waste generates a time-dependent temperature rise. The heat transfer is mainly by conduction in the repository host rocks, convection through groundwater movement is negligible (Heremans et al 1980). The temperature evolution around heat-generating wastes is characterized by a rapid temperature rise after emplacement of the waste. The average local temperature elevation could be over 30°C (CEC 1983). For high level waste from reprocessing the maximum local and repository temperatures will occur within 50 to 100 years. For spent fuel disposal, the maximum repository temperatures can be maintained for about 1000 years or longer (Bocola 1983).

Table 1 Thermal power of waste as a function of time in watts per metric tone of heavy metal in the original fuel element (From Bocola 1983).

Time from reactor discharge (Years)	High-level waste	Spent fuel
10	1120	1290
100	134	284
1,000	6.8	49.4
10,000	0.6	13.5
100,000	0.1	1.0

It has long been recognized that cracking can result from thermo-elastic stress gradients set up in rapidly heated or cooled rock (e.g. Richter and Simmons, 1974). The development of cracking porosity can modify significantly the rock's mechanical and transport properties including deformability, strength, thermal conductivity and permeability (e.g., Richter and Simmons, 1974; Heuze, 1983; Vaughan et al, 1986). In a scanning electron microscope study of thermal cracking in the Westerly granite, Vaughan et al (1986) compared crack distributions in the fresh material with those in samples subjected to hydro-thermal fluid flow at 300°C. They found the distribution of cracks in the tested samples to be not completely homogeneous. Grain boundaries surrounding quartz grains were usually cracked open or had been filled following cracking. Grain boundaries between feldspars, on the other hand, cracked open only rarely. The fluid pathways were connected more effectively in the regions containing quartz grains suggested that the geometrical distribution of quartz is important in determining the matrix permeability of granitic rocks. Homand-Etienne and Houpert (1989) examined the Senones and the Remiremont granites samples thermally cracked at temperatures ranging from 20°C to 600°C under scanning electron microscope. They concluded that the intracrystalline cracks are always longer than the intercrystalline ones, and crack widths increase with temperature. They also reported that the shape of cracks is not consistent with an elliptical model, rather similar to a network of tubes, having rough surfaces and sharp crack tips.

LABORATORY TESTS ON FRACTURE HYDRO-THERMAL PROPERTIES

An experimental study of the influence of temperature on the hydro-thermo-mechanical behaviour of natural joints and artificially induced fresh extension fractures in the Carnmenellis granite from Cornwall, SW England, has been carried out using a hydro-thermo-mechanical testing facility.

The Carnmenellis granite is a coarse to medium grained (2-5 mm) biotite-muscovite granite with potassium feldspar phenocrysts. The phenocrysts are up to 200 mm long and randomly oriented in a predominantly coarse groundmass of plagioclase feldspars, quartz, biotite, muscovite and tourmaline. The granite contains about 30% quartz, 30% alkali feldspar, 20% plagioclase, 10% muscovite, 6% biotite and 4% other minerals. The intact granite has an average uniaxial compressive strength of 135 MPa at room temperature and a permeability of 10^{-11} m^2 determined by the water diffusion method (Pearson 1980).

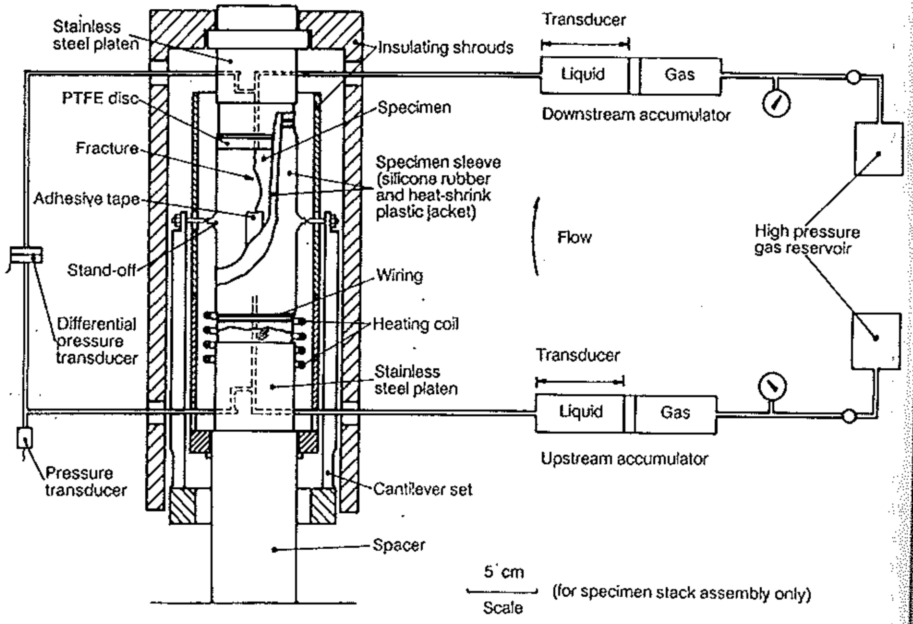

Fig. 1 Schematic arrangement of the fracture hydro-thermo-mechanical test stake assembly.

Samples of natural joints were taken from unused core obtained from a 102 mm diameter horizonatal borehole drilled in the Carnmenellis granite. Visual inspection of the samples showed the joint surfaces to be clean and fairly well matched with little sign of previous shearing.

Artificially induced extension fractures were prepared by loading and splitting the intact Carnmenellis granite core across is diameter between two sharp edged steel cutters. The fractures were typically fresh extension fractures. The fracture surfaces were generally rough, with high degrees of unevenness over their lengths. The two faces of each fracture were matched precisely.

Prepared specimens were 51 mm in diameter and 102 mm in length with fractures oriented axially. Fracture permeability tests using water initially at room temperature were carried out at a range of effective stresses and specimen temperatures. The tests were conducted in a triaxial cell allowing for permeability tests at elevated temperatures. During the experiments, measurements of flow rate, differential hydraulic pressure, effective normal stress, fracture normal displacement and temperature were taken for each test. Details of specimen set-up and test procedures were given by Zhao (1987, 1992). Fig. 1 gives a schematic arrangement of the test stake assembly.

FRACTURE HYDRAULIC PROPERTY AND TEMPERATURE EFFECT

The testing facility provided measurements on the fracture permeability at various effective normal stresses and sample temperatures. For each applied effective normal stress, the flow rate (Q) was measured against the hydraulic head gradient (i) for laminar flow. The hydraulic data obtained in the tests showed that the parallel plates flow law provides good prediction of the laboratory measurements. Hence, hydraulic aperture (e) of the fracture can be obtained from the parallel plates flow law :

$$\frac{Q}{i} = \frac{wg}{12\upsilon} e^3 \tag{1}$$

where w is the width of the fracture; g is the acceleration due to gravity and υ is the kinematic viscosity of the fluid flow.

The fracture permeability k_f (units L^2) is a property dependent on the geometry of the fracture. For the purposes of comparison, especially where temperature effects the properties of the permeating fluid, the quantity permeability is to be preferred to the hydraulic conductivity (units LT^{-1}). For laminar flow between parallel plates, k_f is given as

$$k_f = e^2/12 \tag{2}$$

The calculated values of k_f are plotted against effective normal stress in Fig. 2. The fracture permeability shows asymptotic reduction with increasing of effective normal stress, and as the effective normal stress increases, the flow rate approaches zero while the fracture deformation approaches the maximum possible closure. The data fit well with the predictions of the models. In Fig. 2, the experimental data are compared with an simplified Walsh's hydraulic model (Walsh 1981; Zhao & Brown 1992). The model suggested a logarithmic relation between the fracture permeability and the effective normal stress, i.e.,

$$\frac{k_f}{k_o} = 1\text{-}BLn\left(\frac{\sigma'}{\sigma_o}\right) \tag{3}$$

where k_o is the fracture permeability at initial (zero) effective normal stress σ'_o and B is a parameter dependent on surface properties of the fracture and the environmental conditions.

The results indicate that at the same range of effective stress applied, the permeability of artificially induced extension fractures is much smaller than the permeability of natural joints. The latter had been subjected to alteration and mismatching due to mechanical and chemical weathering.

Hydraulic aperture changes with the testing temperature. Unified changes of initial apertures, defined as change of initial aperture due the temperature divided by

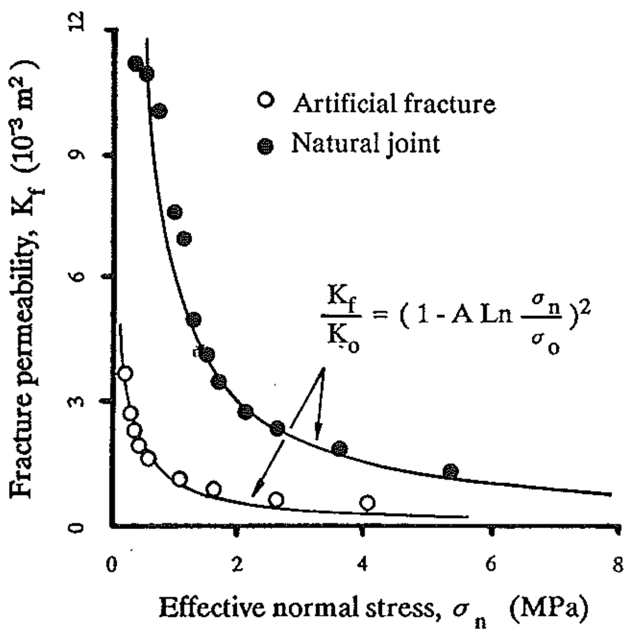

Fig. 2 Change of fracture permeability under effective normal stress.

initial apertures at initial (room) temperature, are shown in Fig. 3, where e_o is the initial hydraulic apertures at room temperature under zero effective stress; and e_t is the hydraulic aperture at elevated temperatures under zero effective stress.

The results show that raising the test temperature reduces the fracture hydraulic aperture and fracture permeability, as e_t decreases with increasing temperature. From the plot on Fig. 3, it appears that the change of the initial hydraulic apertures with change in testing temperature lies within the limites defined by :

$$0.0033\,\Delta T \le (e_o - e_t)/e_o \le 0.0072 \cdot \Delta T \qquad (4)$$

SCANNING ELECTRON MICROSCOPE (SEM) OBSERVATIONS

Thin sections for examination under the scanning electron microscope (SEM) were prepared only from a fresh sample and from a sample containing induced extension fracture that had been subjected to permeability test at temperature of 100°C. The section planes were normal to the planes of the fluid conducting extension fracture.

Standard SEM thin sections containing fractures and cracks were cut and hand or machine lapped to thickness of about 30 µm and a flatness of ± 1.0 µm using 600 grit silicon carbide. The thin sections were examined in the SEM equipped with an energy dispersive X-ray detector in the Department of Geology, Imperial College, London.

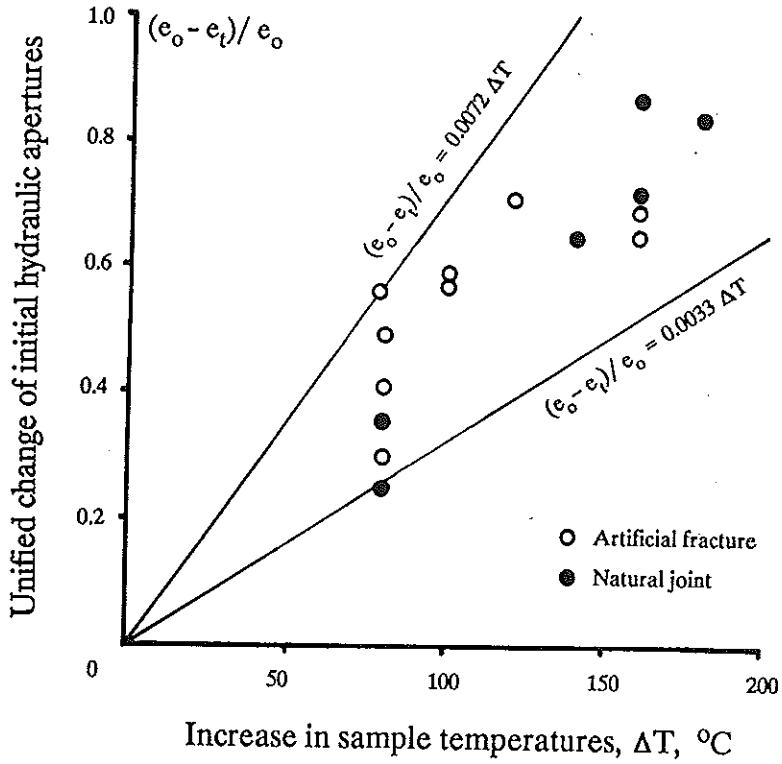

Fig. 3 Change of hydraulic aperture of fractures with temperature.

Fresh sample

The fresh sample of granite was examined in order to help distinguish between features that were initially present in the rock and those that were formed as a result of the hydro-thermo-mechanical experiment. From these observations qualitatively comparisons of the fresh material may be made with granites studied by others (e.g., Lo and Wai, 1983; Fonseka et al, 1985; Vaughan et al, 1986). As shown in Fig. 4, the fresh rock material is composed of compact crystalline grains. On the whole, the joint surface and rock material are very dense and contain low numbers of cracks and pores.

However, a small number of grain boundaries between quartz grains and between grains of different compositions are cracked (Figs. 4a and b). Pores are

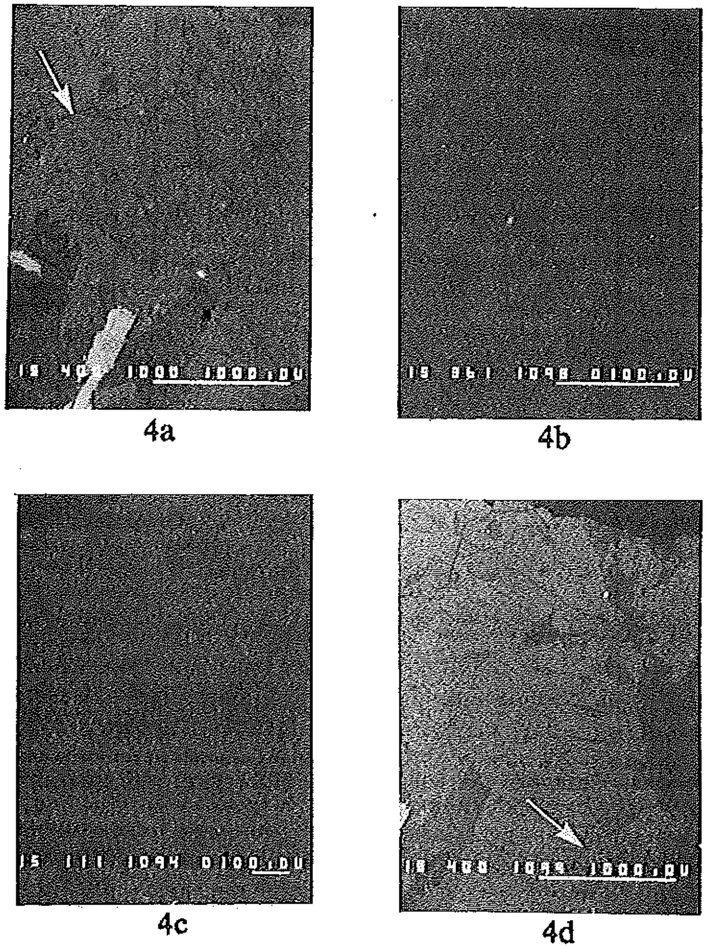

Fig. 4 SEM micrographs of a fresh granite sample.

present most abundantly in feldspars, and least commonly in quartz. In places intragranular cracks run through the pores (Fig. 4c). A few transgranular cracks which meet two grain boundaries are presented in the original material (Fig. 4d). Such cracks are present in some of the smaller grains, especially those of quartz. Intergranular cracks which pass from one grain into another are very scarce.

Tested samples

It is clear that the crack density in the tested sample is much greater than those in the fresh samples (Fig. 5). In addition to intragranular cracks and grain boundary crack propagation and widening, intergranular cracks passing through grain boundaries are also introduced (Fig. 5a). The SEM micrograph reveals that the quartz grains in the altered sample contain the highest densities of intragranular cracks (Fig. 5b). As quartz grains tend to occur in clusters, the intragranular cracks are intimately associated with grain boundary cracks (Figs. 5b). Large intragranular cracks in the feldspars are generally similar to those in quartz, although they are somewhat less numerous and have widths of as much as a few micrometers (Fig. 5c).

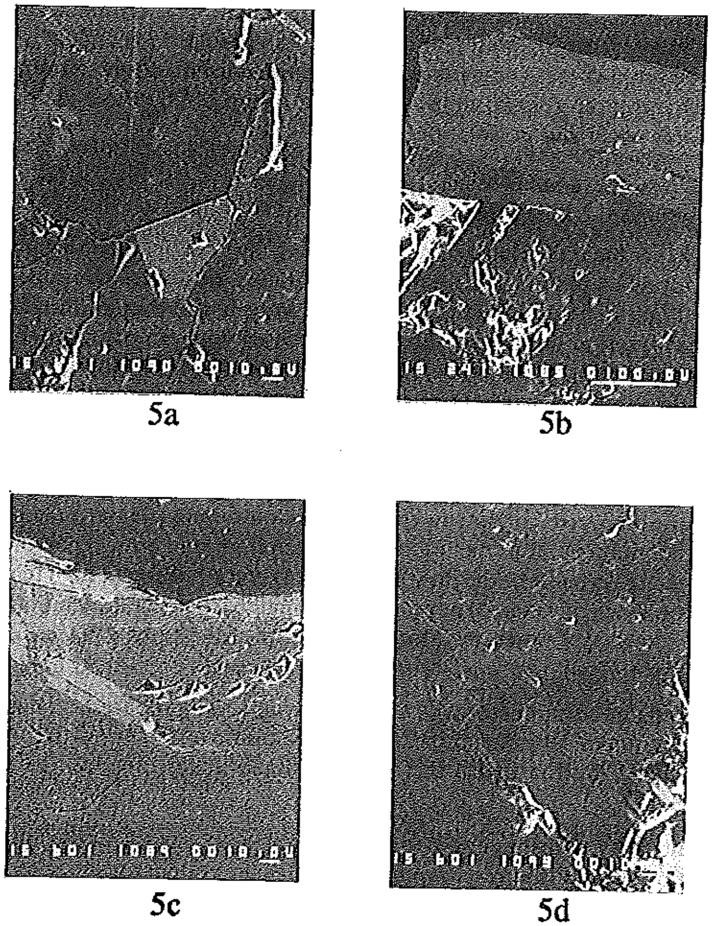

Fig. 5 SEM micrographs of a fractured granite sample subjected to flow tests at sample temperatures to 100°C.

The altered sample contains arrays of intersecting, transgranular cracks which form networks by meeting cracked grain boundaries. Such transgranular cracks are especially prevalent in quartz. Most of the grain boundaries between feldspar in the fresh sample material were closed and remained closed during the heating and flow experiments. The grain boundaries between quartz and feldspars and those between quartz and the minor minerals in the tested samples are frequently cracked forming grain boundary cracks (Fig. 5a). The grain boundaries between quartz grains are often cracked in the altered sample and interconnected with intragranular cracks, which sometimes form a network (Fig. 5a). In this respect, the results are similar to those obtained by Vaughan et al (1986) for the Westerly granite.

At the presence of water and at high temperature, chemical reaction is generated at rapid speed. Some mineral has been dissolved and therefore, large pore spaces have appeared. While some pores being connected by thermal cracks, there are also pores occurring in isolation (Fig. 5d).

DISCUSSION

The experimental results show that raising the test temperature reduces the fracture hydraulic aperture and fracture permeability. However, laboratory observation carried out on granite fractures during the same hydro-thermo-mechanical tests showed that fracture mechanical aperture increases with temperature (Zhao 1987; Zhao & Brown 1992). It should be noted that the equivalent hydraulic aperture of a fracture differs from the mechanical aperture; it is not the mean of the distance apart of the overall fracture walls, but rather depends on the critical narrow places in the fracture. The fracture hydraulic aperture (and permeability) may be reduced due to elevated temperature by : 1) non-homogeneous thermal expansion, reduces the aperture of some critical narrow places; 2) non-homogeneous precipitation of different material present in the fracture; 3) precipitation in critical narrow places in the fracture; blocks some of the flow pathways; 4) crack healing at high temperatures and in the presence of water; 5) appearance of small particles cracked at high temperatures and presence of water and block the fracture at the narrow places (Zhao 1987; Zhao & Brown 1992).

Scanning electron microscope observations made on the fresh granite material and granite samples subjected to heating and water flow tests show that new cracks were introduced by the hydro-thermo-mechanical action imposed in the experiments.

It is not easy to distinguish between cracking associated with the initial heating up of the sample and that resulting from the injection of cold water into the heated rock. The grainite samples were heated before the flow tests at rates of not more than 1°C per minute. Studies carried out by others (e.g. Richter and Simmons, 1974; Lo and Wai, 1982) indicate that significant thermal cracking should not occur at this rate. Therefore, the thermal cracking produced in the experiments is attributed largely to the injection of cold water into the fractures in the heated granite. The mechanisms by which such cracking occurs have been discussed by Richter and Simmons (1974) among others.

The network of intragranular cracks produced in the experiments appears to provide the interconnected porosity required to make the rock material more permeable. The intragranular cracks in quartz grains frequently intersect each other and the cracked grain boundaries. The feldspars exhibit a somewhat lower density of large, intragranular cracks and almost no cracks along grain boundaries with other feldspars. Thus, during the experiment those regions containing quartz should be substantially more permeable due to the difference in crack distribution. If the quartz forms continuous pathways through the rock, then the permeability is likely to be greater than if it occurs only in isolated clusters. This confirms the conclusion of Vaughan et al (1986) that the geometrical distribution of the major phases could be an important factor in determining the permeabilities of granitic rocks.

In addition to the cracks, pores with roughly equal dimensions are present. In quartz and K-feldspar, these pores appear to be concentrated along and associated with cracks (Fig. 5). These observations show that the cracks and pores may provide new possible fluid flow paths additional to the joint.

However, since the flow is concentrated in the joints, the introduction of the additional fluid flow paths formed by this crack network is likely to have little effect on the overall joint hydraulic behaviour. Simple calculations show an additional flow path with an aperture of 5 μm and same length as an original joint having an aperture of 50 μm, will increase the total flow rate by only about 0.1%.

The plot presented in Fig. 3 shows that the initial hydraulic apertures of both natural joints and extension fractures reduce with increasing sample temperature despite the development of potential additional flow paths by thermal cracking. From the results available it is not possible to isolate the effect of thermal cracking on joint permeadility. However, it can be inferred that it is not large compare with other effects of temperature on joint behaviour.

Fully-coupled hydro-thermo-mechanical joint behaviour tests were conducted on a rough joint in gneiss by Hardin et al (1982). The test joint exhibited a four-fold reduction in hydraulic conductivity 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 normal stress, reduced the hydraulic conductivity ten-fold.

The flow tests were of short-term nature and so do not provide data on long-term behaviour. Several studies have demonstrated that the permeability of granite decreases substantially with time during experiments in which a heated aqueous fluid is passed through the rock under an applied temperature gradient (Moore et al, 1984; Vaughan et al, 1986). Vaughan et al (1986) found that about half the intergranular cracks formed in the rock contain Si-rich or Ca-rich fillings at the end of two week experiment. They proposed that the processes involved in producing the observed 25 fold reduction in rock permeability could be dissolution and homogeneous and non-homogeneous precipitation of quartz and other minerals, precipitation at critical narrow locations in the cracks, and crack healing. The experiment conducted by Zhao (1987) also reveals that despite the increases in measured joint mechanical aperture, the overall joint hydraulic aperture and permeability decrease with increases in temperature. These observations provide further evidence to suggest that thermal cracking is unlikely to provide new long-term circulation paths which will enhance the hydraulic permeability of the host granitic rock masses of radioactive waste repositories.

CONCLUSIONS AND APPLICATION TO NUCLEAR WASTE DISPOSAL

It has been concerned that the radioactive waste in a deep granitic rock repository may heat up the rock, with the presence of groundwater, to produce thermal cracking and to expand major fracture aperture, so that additional leakage of radioactive waste would occur through the fractures by groundwater circulation. Hydraulic flow tests were conducted on heated granite samples containing natural and artificially induced fractures by injecting cold water through, as part of the studies on the hydro-thermo-mechanical properties of fractures in granite.

Observations made under the scanning electron microscope show that the granite material adjacent to joints was altered significantly during flow tests at elevated temperatures. The observations suggest that the cracks and pores initiated and expanded by hydro-thermal action may establish fluid pathways in addition to the pre-existing joint. This network of cracks and pores provides the interconnected porosity needed to make the rock more permeable. However, since flow is concentrated in the much wider joint, the introduction of these additional fluid flow pathways appears to have little effect on the overall joint hydraulic behaviour. Contrastingly, combined hydro-thermo-mechanical alteration under elevated temperature causes major changes in the joint permeability. Under the conditions of the experiment, increasing the sample temperature decreased the overall joint permeability despite the introduction of thermal cracking. The results suggest that thermal cracking will not have much influence on the long-term performance of radioactive waste repositories in granitic rocks. The major effects due to the elevation of temperature are thermal loading, thermal expansion and joint thermal healing. Together, they reduce the hydraulic permeability of the rock masses significantly.

Disposal of high level radioactive waste, spent fuel and alphe-bearing waste in the geologic environment can provide the most certain safe containment. The objective of underground disposal is to isolate radioactive wastes from man and his environment for a period of time such that any possible subsequent release of radionuclides from the repository will not result in undue radiation exposures. This is achieved by designing multi-component systems, the isolation capability of which is a function of the performance of the system as a whole. The components, such as the waste package and the engineered repository, together with the essential contribution of the geological setting, provide multiple barriers to radionuclide release and transport back to man's environment. Together, they combine to provide the requisite degree of isolation for the wastes.

After the emplacement of radioactive waste, the repository host rock masses will anticipate a rapid rise of temperature. This thermal effect appears to enhance the hydrogeological role of the rock masses as a barrier to the radioactive waste. However, it should be noted that the elevation of temperature will also produce thermal stresses. The design of the repository therfore should take into the account of thermo-mechanical properties of the rock masses to allow for the heat loading without damaging the structural competency of the repository or the host rock.

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