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**Laboratory Study of Fracture Healing
in Topopah Spring Tuff - Implications for Near Field Hydrology**

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Abstract

Fractures will play an important role in the near field hydrology of a nuclear waste package in a mined repository. Seven Topopah Spring tuff samples (one intact and six fractured) have been studied to determine water permeability in this rock under pressure and temperature conditions similar to those expected in the near field of a nuclear waste package. Six of the seven samples were studied under isothermal condition; the other was subjected to a thermal gradient. Four of the six fractured samples contained a reopened, healed, natural fracture; one of the other samples contained an induced tensile fracture and the other contained a saw-cut. The fracture surfaces were examined using scanning electron microscope (SEM) before and after the experiments and the water that flowed through the samples was sampled for chemical analysis. The experimental durations ranged from about 3 months to almost 6 months.

Water permeability of the fractured samples was found to decrease by more than three orders of magnitude when the sample temperature (in the case of the sample

under a thermal gradient, the temperature in the hot zone) increased to 150° C. The sharpest decrease in permeability occurred when the temperature was increased above 90° C. Permeability of the intact sample did not change significantly under the similar experimental conditions. At the end of each experiment, when the temperature returned to room conditions, the water permeability did not recover. The mechanical strength of one healed sample was about half that of the intact rock.

SEM studies of the fracture surfaces and water chemical analysis of the water that flowed through the samples suggested that both dissolution and deposition occurred on the fracture surfaces. Smoothing of fracture asperities due to dissolution and deposition was probably the main cause of the permeability decrease. Deposition of dissolved silica was probably the main cause of fracture healing.

Introduction

Host rock may be one of the barriers to the transport of radioactive nuclides from leaking waste containers disposed of in deep geological repositories. The Yucca Mountain Project (YMP) at Lawrence Livermore National Laboratory (LLNL) sponsors study of the hydrological properties of Topopah Spring Tuff, which composes the geological horizon of the proposed nuclear waste repository at Yucca Mountain, Nevada. In this task we studied the water permeability of both intact and fractured tuff samples, along with other hydrological properties, such as the characteristic curves of the rock, and the imbibition of water in the rock.

It is well known that major fractures in a rock mass have a predominant effect on its hydrological properties. The presence of a single major fracture in a rock sample may increase its permeability by more than three orders of magnitude [eg,1-3]. Therefore the hydrological properties of fractured rock may be very important for the con-

tainment of water borne radioactive wastes. The near field temperature in the rock after the emplacement of nuclear wastes could be greater than 200° C. Therefore, a knowledge of the hydrological properties of the tuff at high temperatures is also essential to an understanding the performance of a potential repository.

Studies have shown that water permeability in rocks can strongly depend on temperature[4-6]. Morrow et al. [4] attributed the decrease of permeability in intact crystalline rock samples to the dissolution and deposition of silica in the grain-boundary cracks of the rocks. Daily and Lin [6] reported that the temperature effect on the water permeability of Berea Sandstone was greater for a fractured sample than an intact sample. Lin and Daily [3] and Daily et al. [7] reported that the water permeability of *an intact* Topopah Spring tuff sample was independent of temperature and dehydration and rehydration cycles. On the other hand, the water permeability of a fractured tuff sample depended strongly on temperature and time. They attributed the decrease of permeability to fracture healing due to the elevated temperature and pressure, and to the presence of water. Similar results were obtained from a sample under a thermal gradient [8].

This paper reports laboratory experiments designed to understand the fracture healing process in Topopah Spring tuff samples. Included are results of experiments on six fractured and one intact Topopah Spring tuff samples. Three types of fracture surface have been studied: a re-opened naturally sealed fracture, an induced tensile fracture, and a saw-cut.

Sample Description and Preparation

The rock studied is from the Topopah Spring Member of the Paintbrush Tuff. The petrology and geochemistry of the densely welded tuff from the Topopah Spring Unit

are reported by Knauss [9] and Bish et al. [10]. Bish and Vaniman [11] report the mineralogical composition of a Topopah Spring tuff core sample from USW H-6 hole as alkali feldspar (66-70 %), quartz (16-20 %), and cristobalite (9-15 %), plus trace amounts of smectite and mica. Samples in these tests were obtained from holes USW H-6 or USW G-1 or from outcrop from Fran Ridge at Yucca Mountain. Samples were machined into right circular cylinders (Table 1).

All fractured samples contain longitudinal fracture almost parallel to the sample axis. The natural fractures were all healed. Each was re-opened by inserting a wedge into the fracture. The two halves of the fractured samples were then put together for the test. The tensile fracture and saw-cut were induced in originally intact samples. The saw-cut surfaces were roughened by sanding with 120-grit sand paper, and cleaned by blowing air at them.

Dry bulk density was determined by drying samples in a vacuum oven at 35° C until the weight remained unchanged for at least one day. Dry bulk density was calculated from the dry weight and sample volume. The samples were then saturated with water at a water pressure of about 0.7 MPa, until their weight remain constant for at least one day. The effective porosity of a sample is the difference between the dry bulk density and the saturated bulk density. The density and porosity of samples 1 to 3 were reported by Lin and Daily [3]; the density and porosity of sample 4 were reported by Daily et al. [7]; the density and porosity of sample 5 were reported by Lin and Daily [8].

Table 1. Sample Information

<i>Sample #</i>	<i>Diameter x Length(cm)</i>	<i>Fracture</i>	<i>Source</i>	<i>Reference</i>
1	2.54 x 10.36	Intact	Fran Ridge	[3]
2	2.54 x 9.25	Natural	Fran Ridge	[3]
3	2.54 x 7.62	Natural	USW G-1	[3]
4	8.23 x 10.10	Natural	USW H-6	[7]

5	3.49 x 4.53	Natural	USW H-6	[8]
6	2.54 x 7.05	Tensile	USW H-6	
7	2.54 x 9.64	Saw-cut	Fran Ridge	

The samples were jacketed in either Viton (2.54 and 3.5 cm diameter samples) or Teflon (8.9 cm diameter sample) jacket. The detailed jacket assembly is described in [3] and shown in Figure 1. Each sample was equipped with electrodes and ultrasonic transducers because the experiments were also designed to study the movement of water in the sample during dehydration and rehydration processes.

Experimental Apparatus

The experimental apparatus consists of three subsystems: confining pressure, the pore pressure, and computerized electronics. Details of this apparatus were discussed by Daily and Lin [6]. Hydrostatic confining pressure of 5.0 MPa was maintained with a silicon based oil on the jacketed sample. All of the samples except Sample 5 were studied under isothermal conditions. Isothermal conditions were maintained by external heating of the pressure vessel. The thermal gradient sample (#5, Table 1) was heated by a resistance heater attached to one end cap of the sample assembly. The pore fluid pressure and the pore fluid pressure gradient across the sample were controlled manually by valves and monitored by pressure transducers. The pore fluid was introduced into the sample through one end cap and removed through the other. Flow rate of the pore fluid was determined by measuring fluid volume exiting the sample in a given time interval when the flow rate was stable. The pore fluid used in our experiment was water from well J-13 located to the east of Yucca Mountain where the Topopah Spring tuff lies below the water table. The pore fluid pressure gradient was assumed to be linear over the sample length and was measured by one differential and

two absolute pressure transducers (one at each end of a sample) and a Heise pressure gauge at the upstream end of the sample. A commercial automatic conductance bridge was used to measure the resistance between electrode pairs on the sample. The electrical resistance was used to monitor the condition of water saturation in a sample [7]. An iron-constantan thermocouple inside the pressure vessel adjacent to a sample, measured sample temperature. The electronic system was used to monitor and maintain a constant confining pressure as well as record experimental data.

Experimental Procedures

Each experiment was started with a saturated sample. Water permeability was measured as a function of pore fluid pressure and pore fluid pressure gradient at room temperature. The pore fluid pressure was usually kept between 0.1 and 0.5 MPa; the maximum pore fluid pressure ever applied to a sample was 2.0 MPa. A minimum pore fluid pressure difference over a sample length to obtain a practically measurable flow rate was used, in order to minimize turbulent flow. The pore pressure difference ranged from 0.001 to 0.6 MPa. After the initial permeability measurement at room temperature, the temperature was increased in steps to a maximum temperature of about 150° C and water permeability was measured at each temperature step. The maximum temperature at the hot end of the thermal gradient sample was about 150° C [8].

The experimental procedures of samples 1 to 5 have been reported previously [3,7, and 8]. A small leak of the confining fluid into sample 5 was observed near the end of the experiment. The effect of the leak on the experimental result will be discussed later. Samples 6 and 7 were kept saturated through out the experiment. However, a few unexpected power failures during the experiment may have caused Sample 7 to lose its pore fluid for several hours each time. The experimental duration of these

two samples ranged from about 4 months to more than 5 months. The effect of these power failures on the experimental result will be discussed later.

The techniques of measuring water permeability and the method of data reduction were previously discussed in reference [7]. Water that flowed through a sample during the permeability measurements was collected and analyzed, using inductively coupled plasma analysis, to determine the concentration of elements. Where possible, fracture surfaces were examined using an scanning electron microscope before and after the experiments.

Results and Discussion

The water permeability of Samples 1 to 4 (Table 1) have been reported before [3,7]. The results are summarized as follows. The water permeability of the intact tuff sample is independent of temperature, time, and dehydration and rehydration [3]. On the other hand, the permeability of the fractured samples decreased by more than three orders of magnitude at the end of the experiments [3 and 7]. The results of Sample 3, which was always saturated with J-13 water, indicates that dehydration is not necessary to cause the fracture healing and the associated permeability decrease [3]. All of the fractured samples show that the first major decrease of permeability occurs when the sample temperature was increased to above 90° C, while the samples were saturated with water. After that initial decrease, the permeability gradually decreased with time, regardless of other experimental conditions, such as temperature and dehydration. At the end of each experiment, when the sample temperature decreased to the room temperature, the permeability did not recover to its original room temperature value. This indicates that the decrease of permeability is not reversible with temperature over the duration of the test. After the experiment, the two halves of Sample 2 were bonded together, having a tensile strength of about half of

that of the intact ruff sample [3]. The strength of bonding varies in the other samples [3 and 7].

Figure 2 shows the permeability of a fractured sample under a thermal gradient (Sample 5), as a function of time. Also shown in Fig. 2 is the hot zone temperature of the sample. Again, the permeability began to decrease when the hot end temperature was increased to above 90° C. The overall decrease of permeability of the thermal gradient sample is more than three orders of magnitude, consistent with the previous experiments at isothermal condition. The leak of the confining fluid into the sample at about 2700 Hour may have made the later permeability values not valid. But it does not affect the overall conclusion that can be drawn for this experiment.

Figures 3 and 4 show the permeability of the samples with a tensile fracture and a saw-cut respectively. The fracture surfaces of these two samples (Sample 6 and 7) do not have the silica coating, as in the natural fracture samples. The silica mineral coating on the surfaces of the natural fractures is not a necessary condition for the decrease of permeability, because it was absent from the tensile fracture and the saw-cut surfaces. However, the fracture surface roughness may have some effect on the permeability. Figure 3 and Figure 4 show that the decrease of permeability of the tensile fracture occurs when the temperature was below 150° C. On the other hand, the saw-cut has most of its permeability decrease when the sample temperature is at 150° C. The tensile fracture permeability seems to behave more like that of the re-opened natural fracture (See Figure 3 of [3]).

Figure 5 shows the silica concentration in the water, that flowed through the saw-cut sample during the test, as a function of time. Also shown in Fig. 5 are the temperature history (the thin solid line) of the test and the silica concentration in water that becomes equilibrium with amorphous silica (the dashed line) and cristobalite (the dotted line) at various temperatures (therefore, time in the figure). The sample was kept saturated with the water during the experiment. However, there were three unex-

pected power failures at 2040 Hour, 2528 Hour, and 2740 Hour, during which the pore water pressure was released, and the sample may have lost its pore water for several hours each time. After each power failure, fresh J-13 water was re-introduced into the sample and the pore pressure was brought to equilibrium for at least a few days before next water sample was collected. Therefore we do not think that the power failures have significant effect on the water chemistry.

At temperatures below about 100° C silica concentration is approximately that for water in equilibrium with cristobalite, while at higher temperatures the fluid is saturated with respect to amorphous silica. At 150° C the silica concentration was even greater than that expected for water in equilibrium with amorphous silica. As temperature drops the fluid remains approximately saturated with amorphous. It is interesting to note that most of the permeability decrease in the saw-cut sample occurred when temperature was above 125° C (Fig. 4). The silica concentrations in the water that flowed through the thermal gradient sample, when the hot zone temperature was at about 150° C, were very close to amorphous silica saturation [8]. This indicates that dissolution of silica has occurred on the fracture surfaces. The dissolution may begin at the contact points on the fracture, where stress concentration may increase the solubility of minerals. The dissolution of silica may also be affected by other conditions, such as surface roughness, concentration of other minerals, etc. The dissolution of silica at the contact points of a fracture will smooth the asperities of the fracture surfaces. Verma et al.[12] reported that silica may migrate within the matrix itself due to the silica solubility variation related to thermal gradients. This may have happened to our sample that was subjected to a thermal gradient (Sample 5 in Table 1), but changes in matrix permeability are not significant, because permeability was dominated by the fracture. All other samples were under isothermal condition, therefore the thermal gradient induced chemical potential gradient was not applicable.

Scanning electron microscope (SEM) images of the fracture surfaces before and

after the experiments show evidence for both dissolution and deposition. Some of the SEM images have been shown before [3 and 7]. Figure 6 shows the SEM images of the sample under a thermal gradient before (a) and after (b) the experiment. The spherical particles that were present on the fracture surface before the experiment are not present after the experiment. In addition, the post-experiment surface shows evidence of deposition (the cluster of fine spherical particules) and dissolution (the cavity). Apparently, when the water is saturated with silica, redeposition can occur depending on micron-scale variation of flow rate, temperature, water pH, and the concentration of other mineral species. This deposition of silica can further smooth the fracture surfaces, and can thus explain the bonding of the two halves of some of the samples after the experiment.

Smoothing the fracture surfaces under a constant confining pressure will cause a decrease in the aperture. If the cubic law is applicable to the fracture permeability, a small decrease in aperture width will result in a large reduction in measured permeability. Without confining pressure, smoothing of fracture surfaces will not cause a decrease in permeability. In this case, fracture healing may be achieved by deposition and filling of the fracture, of which, the discussion is beyond the scope of this paper.

We are conducting an experiment now to study the role of water in the fracture healing process, by measuring dry gas permeability in a naturally fractured Topopah Spring tuff sample, at the same conditions used for the water permeability measurements. This experiment will provide information on the importance of dissolution, transport, and deposition by water of minerals on the fracture surfaces.

Conclusion

We have shown that a fracture may heal and water permeability decrease, when

rock is saturated with water at temperatures above 90° C, under certain confining pressure. In some cases the healing resulted in bonding together of the two halves of a sample. The healing process may be due to the dissolution and redeposition of minerals, such as silica, on the fracture surface. The fracture surface roughness may have some effect on the healing process. The silica coating on the natural fracture surfaces is not necessary for the fracture healing.

If the laboratory observed fracture healing can occur in the near field of a waste package, an envelope of low permeability may be created around the waste package. That envelope would diminish future infiltration of water into the vicinity of a waste container. It would also alter the hydrological property of the near field region from a fracture-dominated regime to a regime with characteristics more like that of a porous, low permeability medium.

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Figure Captions

Figure 1. Sample assembly of a fractured sample. The assembly is the same for the intact sample except for the absence of a fracture and the stainless steel sleeve.

Figure 2. Water permeability and the hot end temperature of a fractured Topopah Spring tuff sample under a thermal gradient (Sample 5), as function of time. The hot zone temperature reached 90° C at about 360 Hour.

Figure 3. Water permeability and temperature of a Topopah Spring tuff sample with a tensile fracture (Sample 6) as function of time.

Figure 4. Water permeability and temperature of a Topopah Spring tuff sample with a saw-cut (Sample 7) as function of time.

Figure 5. Silica concentration in the water that flowed through a saw-cut Topopah Spring tuff sample (Sample 7) as function of time. The dashed line indicates the concentration of silica in an aqueous fluid saturated with respect to amorphous silica; the dotted line is the saturation concentration with respect to cristobalite. The thin solid line is the temperature history of the test.

Figure 6. SEM images of the fracture surfaces of a Topopah Spring tuff sample under a thermal gradient before the experiment (a) and after the experiment (b).

a)

b)

APPENDIX A

INFORMATION FROM THE REFERENCE INFORMATION BASE USED IN THIS REPORT

No

CANDIDATE INFORMATION FOR THE REFERENCE INFORMATION BASE

No

CANDIDATE INFORMATION FOR THE SITE & ENGINEERING PROPERTIES DATA BASE

No Yes [Signature] 9/1/89

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Date

Appendix A**Site & Engineering Properties Database**

<u>Sample #</u>	<u>Temperature (°C)</u>	<u>Time/Hour</u>	<u>Water Permeability (md)</u>
5	25	310	13
	92	360-700	3-8.4
	120	750-984	2.4-2.9
	150	984-1080	0.15-3.7
	150	2520-2664	0.003-0.015
6	25	100	250-450
	50	500-800	20-150
	98	850-950	1-1.6
	120	960-1650	0.065-0.8
	150	1800-2300	0.15-0.45
	102	2400-2550	0.007-0.52
	75	2700	0.17
	25	3100	0.08-0.2
7	25	200-650	30-40
	52	700-1150	17-50
	78	1250-1400	25-53
	98	1400-1800	3.7-20
	125	1850-2350	2-20
	141	2400-3350	2.5-0.00035
	90	3600-3650	0.0022-0.008
	75	3800	0.0006
	25	3900	0.0045