Variation of Permeability with Temperature in Fractured Topopah Spring Tuff Samples

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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. Our previous studies showed that the water permeability of fractured Topopah Springs tuff samples decreased by more than three orders of magnitude when the sample’s temperature (in the case of a sample under a thermal gradient, the temperature in the hot zone) increased to 150°C at a constant confining pressure of 5 MPa. When the fractured tuff samples were returned to room temperature the water permeability did not recover. We attributed the permeability decrease to smoothing of the asperities on the fracture surfaces, which was caused by the dissolution and redeposition of silica minerals as water flowed through the sample. Water permeability of an intact tuff sample did not change significantly under similar experimental conditions.

In this study, a fractured Topopah Springs tuff sample was used to determine the variation of nitrogen (N₂) permeability with increasing temperature at a constant confining pressure of 5 MPa under the following conditions: dry sample, sample saturated with standing water, and steam flowing through the sample. The N₂ permeability of a dry fractured tuff sample was independent of temperature. The water permeability measured at room temperature before and after the sample was heated to 150°C with standing water did not change either. On the other hand, flowing steam
through the sample at 127°C for about one week decreased the N₂ permeability by more than one order of magnitude. Apparently flowing steam and flowing water have a similar effect on smoothing the asperities of the fracture surfaces.

Introduction

Host rock may be one of the barriers to the transport of radioactive nuclides from leaking waste containers buried in deep geological repositories. The Yucca Mountain Project (YMP) at Lawrence Livermore National Laboratory (LLNL) sponsored a study of the hydrological properties of Topopah Spring tuff, a geological horizon at Yucca Mountain, Nevada, for which the suitability of a nuclear-waste repository is being investigated. The study addressed the permeability of intact and fractured tuff samples to either water, steam or dry nitrogen (N₂), 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 can increase its permeability by more than three orders of magnitude; therefore, understanding the hydrological properties of fractured rock are very important for the containment 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, understanding the hydrological properties of the tuff at high temperatures is also essential to understanding the hydrological transport of a repository.

Studies have shown that the water permeability of rocks greatly depends on temperature. Morrow et al. attributed the decrease in the permeability of intact crystalline rock samples to the dissolution and deposition of silica in the grain-boundary cracks of the rocks. Daily and Lin reported that the temperature effect on the water permeabil-
ity of Berea Sandstone was greater for a fractured sample than for an intact sample.\textsuperscript{2} Also, the water permeability of an intact Topopah Spring tuff sample was independent of temperature and dehydration and rehydration cycles.\textsuperscript{3,5} On the other hand, the water permeability of a fractured tuff sample depended greatly on temperature and time.\textsuperscript{3,4,6} Similar results were obtained from a sample under a thermal gradient.\textsuperscript{7}

In the previous investigations, the water permeability was measured when water was flowing through the samples at high temperatures. In this study, to determine the role of water in the variation of permeability at high temperature, we measured the \( N_2 \) permeability in a fractured Topopah Springs tuff sample under the same pressure and temperature conditions as in the previous experiments. We also investigated the effect of standing water and flowing steam on the permeability of the tuff sample. This paper is a summary of laboratory experiments designed to understand the effect of temperature on the permeability of the tuff samples. We include the results of experiments on one intact and seven fractured Topopah Spring tuff samples. Three types of fracture surfaces were studied: a naturally sealed and re-opened fracture, an induced tensile fracture, and a saw-cut.

**Sample Preparation and Experimental Procedures**

We studied rock from the Topopah Spring Member of the Paintbrush Tuff. Bish and Vaniman reported the mineralogical composition of a Topopah Spring tuff core sample taken from the USW H-6 hole as alkali feldspar (66 - 70\%), quartz (16 - 20\%), and cristobalite (9 - 15\%), plus trace amounts of smectite and mica.\textsuperscript{9} Samples used in this study were obtained from holes USW H-6, USW G-1, and from the outcrop at Fran Ridge, Yucca Mountain. Samples were machined into right-circular cylinders (Table 1).
All of the fractured samples contained longitudinal fracture almost parallel to the sample's axis. The natural fractures, which were all healed, were 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 and saw-cut fractures were induced in originally intact samples. The saw-cut surfaces were roughened by sanding them with 120-grit sand paper, and cleaned by blowing air at them.

Table 1. Sample Information

<table>
<thead>
<tr>
<th>#</th>
<th>Diameter x Length(cm)</th>
<th>Fracture</th>
<th>Source</th>
<th>Fluid</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.54 x 10.36</td>
<td>Intact</td>
<td>Fran Ridge</td>
<td>J-13 water, flowing</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2.54 x 9.25</td>
<td>Natural</td>
<td>Fran Ridge</td>
<td>J-13 water, flowing</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>2.54 x 7.62</td>
<td>Natural</td>
<td>USW G-1</td>
<td>J-13 water, flowing</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>8.23 x 10.10</td>
<td>Natural</td>
<td>USW H-6</td>
<td>J-13 water, flowing</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>3.49 x 4.53</td>
<td>Natural</td>
<td>USW H-6</td>
<td>J-13 water, flowing</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>2.54 x 7.05</td>
<td>Tensile</td>
<td>USW H-6</td>
<td>J-13 water, flowing</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>2.54 x 9.64</td>
<td>Saw-cut</td>
<td>Fran Ridge</td>
<td>J-13 water, flowing</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>8.23 x 7.78</td>
<td>Natural</td>
<td>USWH-6</td>
<td>N₂</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>8.23 x 7.78</td>
<td>Natural</td>
<td>USWH-6</td>
<td>J-13 water, standing</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>8.23 x 7.78</td>
<td>Natural</td>
<td>USWH-6</td>
<td>N₂, flowing steam</td>
<td>8</td>
</tr>
</tbody>
</table>

The samples were jacketed in a Viton jacket. The detailed jacket assembly is described in Lin and Daily and shown in Figure 1. Each sample, except Sample 8, 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. Sample 8 was not designed to study water movement in the sample.

The experimental apparatus consisted of three subsystems: confining pressure,
pore pressure, and computerized electronics. For a detailed description of the apparatus, refer to Daily and Lin.\textsuperscript{2} A 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 that were maintained by external heating of the pressure vessel. The thermal gradient sample (Sample 5) was heated by a resistance heater that was 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 with valves and monitored with pressure transducers. The pore fluid was water from Well J-13 (located to the east of Yucca Mountain, where the Topopah Spring tuff lies below the water table), steam, or dry N\textsubscript{2}. The pore-fluid pressure gradient was assumed to be linear over the sample length and was measured with one differential and two absolute pressure transducers (one at each end of a sample) and with a Heise pressure gage located at the upstream end of the sample.

We began each experiment with a saturated sample. A conventional steady-state flow method was used to measure the permeability. The pore-fluid pressure was usually maintained at 0.1-0.5 MPa; the maximum pore-fluid pressure applied to a sample was 2.0 MPa. We kept the pore-fluid pressure difference minimal to minimize turbulent flow. The pore pressure differences ranged from 0.001 to 0.6 MPa. For Samples 1 through 8, after the initial permeability measurement at room temperature, the temperature was increased in steps to a maximum temperature of about 150°C and either the water or N\textsubscript{2} permeability was measured at each temperature step. The maximum temperature at the hot end of the thermal gradient sample was about 150°C.

The duration of these experiments ranged from about three months to more than five months. Sample 8 was used again as Sample 9 (Table 1); in this case, the water permeability was measured at room temperature. Then, the valves on both ends of the sample were closed to trap the water in the sample. The temperature was increased and maintained at 150°C for about one week. The water permeability was measured
again when the sample temperature had decreased to room temperature.

Sample 8 was then used as Sample 10 (Table 1). The sample was dried at a temperature of about 150°C for a few weeks. The \( N_2 \) permeability was measured when the sample was at 127°C. Then steam was flowed through the sample while the temperature was maintained at 127°C for about one week. The sample was then dried and the \( N_2 \) permeability was measured again.

Results and Discussion

The results of the experiments on Samples 1 through 7 have been reported\(^3\)\(^\text{AA7} \); we summarize those results here. The water permeability of an intact Topopah Springs tuff sample was independent of temperature, time, dehydration, and rehydration. The water permeability of the fractured samples decreased by more than three orders of magnitude when the sample's temperature increased to 150°C at a constant confining pressure of 5 MPa. For Sample 3, which was always saturated with J-13 water, results indicate that dehydration was not necessary to cause the permeability decrease. All of the fractured samples showed that the first major decrease of permeability occurred when the sample temperature was increased to above 90°C while the samples were saturated with water. After that initial decrease of permeability, the permeability gradually decreased as a function of time, regardless of other experimental conditions such as temperature and dehydration. At the end of each experiment, when the sample temperature had decreased to room temperature, the permeability did not return to its original room temperature value. This indicates that the decrease of permeability was not reversible with temperature.

Similar results were obtained for the sample under a thermal gradient (Sample 5).\(^7 \) 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 conditions.

Samples 6 and 7 (Table 1) contained a tensile and a saw-cut fracture, respectively. The fracture surfaces of these two samples did not have the silica coating of the natural fracture samples. The decrease of the water permeability with increasing temperature in these two samples was similar to that of the samples with a natural fracture. Apparently, the silica-mineral coating on the surface of the natural fracture did not play a significant role in the effect of temperature on permeability. However, the fracture surface roughness might have had some effect on the permeability. The decrease of permeability of the tensile fracture sample occurred earlier in the heating history when the sample temperature was below 150°C. The saw-cut sample decreased most in permeability when the sample temperature was at 150°C. The tensile fracture's permeability seemed to behave more like that of the re-opened natural fracture.

The N₂ permeability was quite different from the water permeability. As shown in Figure 2, under the same experimental conditions, the N₂ permeability of a sample with a natural fracture (Sample 8) does not change with temperature nor time. Also shown in Fig. 2 is the temperature history of this experiment. The permeability remains at a mean value of about 40 millidarcy. The up-stream pore-pressure of these permeability measurements ranged from 0.145 to 0.27 MPa; the flow rate of N₂ in these measurements ranged from 0.01 to 5 cm³/s. The scattering of the permeability values shown in Fig. 2 is partially due to the differences in the up-stream pore pressure. For the purpose of this study, we can conclude that the N₂ permeability of the fractured tuff sample is independent of temperature.

The results of the N₂ permeability measurements show that water in the fractured sample is necessary to cause the permeability to decrease with increasing temperature.
Based on the chemical composition of the water that flowed through the sample, and on the scanning electron microscope images of the fracture surfaces before and after the experiments, we concluded that dissolution and redeposition of silica minerals on the fracture surfaces by flowing water is the main cause of the decrease of permeability. Apparently the dissolution and redeposition of silica minerals on the fracture surfaces smooths the asperities of the fracture surfaces. When the sample is under a confining pressure of 5 MPa, smoothing of the asperities of the fracture surfaces decreases the effective aperture of the fracture, which, in turn, decreases permeability.

To test the effect of standing water in a sample on permeability, the same sample used in the N₂ permeability measurements was re-saturated with J-13 water at room temperature, as described for Sample 9 in the "Sample Preparation and Experimental Procedures" section. Figure 3 shows the water permeability of the fractured tuff sample and the temperature history during the experiment. As mentioned before, the sample was saturated with water during the entire duration of the experiment. Water permeability was measured only when the sample was at room temperature, and no water flowed through the sample at high temperatures. Fig. 3 shows that the water permeability at room temperature remained unchanged before and after heating the sample to 150°C. This result indicates that flowing water in a fractured sample at high temperatures is required to cause the decrease in permeability, as previously observed.

The same fractured tuff sample was used again to test the effect of flowing steam on the permeability. Figure 4 shows the N₂ permeability as a function of time. Also shown in Fig. 4 is the up-stream pore pressure applied to the sample during the experiment. The up-stream pore pressure plot illustrates the experimental conditions. Around the 10300 hour the N₂ permeability was measured in the dry sample with an up-stream pore pressure of about 0.05 MPa. The sample was then saturated with steam by applying water at pressures of no more than 0.1 MPa at a temperature of about 127°C, as shown by the line representing temperature in Fig. 4. The steam was
then allowed to flow through the sample for about four days. The sample was then
dried, as indicated by the virtually zero up-stream pore pressure between 10600 and
10820 hours. The sample was re-saturated with N\textsubscript{2} and the N\textsubscript{2} permeability was measured at about the same up-stream pore pressures. The permeability values at the
10300 hour of Fig. 4 are about one quarter of those measured at the 2000 hour (Fig.
2). Several factors may contribute to the decrease of permeability: long-term creep of
the contact points on the fracture surfaces (the sample was under a confining pressure
of 5 MPa all the time), residual moisture in the sample after the standing-water experi-
ment, etc. But the gradual decrease in permeability is not as significant as that associ-
ated with the steam flow, as will be discussed in next paragraph.

Figure 4 shows that the N\textsubscript{2} permeability measured at the same up-stream pore
pressure decreased by more than one order of magnitude after the flowing of steam
through the sample. The effect of flowing steam on the permeability of a fractured
sample is consistent with that of flowing water at high temperature. A sample of the
steam that flowed through the sample was not taken, so the chemical process related to
the mechanism of decreasing permeability is unknown. However, it is possible that
steam may have the same function of smoothing the asperities of the fracture surfaces
as liquid water.

As mentioned before, our sample was under a constant confining pressure of 5
MPa during the experiments. 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 normal stress across the fracture,
smoothing of fracture surfaces might not cause a decrease in permeability. In this
case, fracture healing might be achieved by deposition and filling of the fracture.
Conclusion

We have shown that water permeability can decrease when water flows through fractured rock at temperatures above 90°C and under a certain confining pressure. The decrease of permeability might be due to the dissolution and redeposition of minerals, such as silica, on the fracture surfaces. The fracture surface roughness might have some effect on this process. This process can occur on a natural fracture coated with silica mineral as well as on a fresh (such as induced tensile or saw-cut) fracture.

Our experimental results also show that heating either a dry sample or a sample with standing water, under a constant confining pressure, does not cause the decrease in permeability. On the other hand, flowing steam and flowing water through a fractured tuff sample seem to have a similar effect on permeability.

If laboratory-observed fracture healing can occur in the near field of a nuclear-waste repository, an envelope of low permeability might be created around the waste package. That envelope would prevent future infiltration of water into the vicinity of a waste container. It would also alter the hydrological properties of the near-field region from a fracture-dominated medium to a medium with characteristics more like that of a porous, low-permeability medium. Further investigations are needed to determine the variation of permeability in a partially saturated fractured rock at various normal stresses across the fracture.

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REFERENCES


Gas Permeability of Tpt at 0.2 MPa Pore Pressure

Perm (md)

T (C)

Permeability (lz-J) and Temperature (C)

Time (HR)

Fig. 2
Data from "water perm of Tpt, standing"
Data from "gas-perm-steam, pup=0.5"