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LABORATORY DETERMINED SUCTION POTENTIAL OF TOPOPAH SPRING TUFF AT HIGH TEMPERATURES

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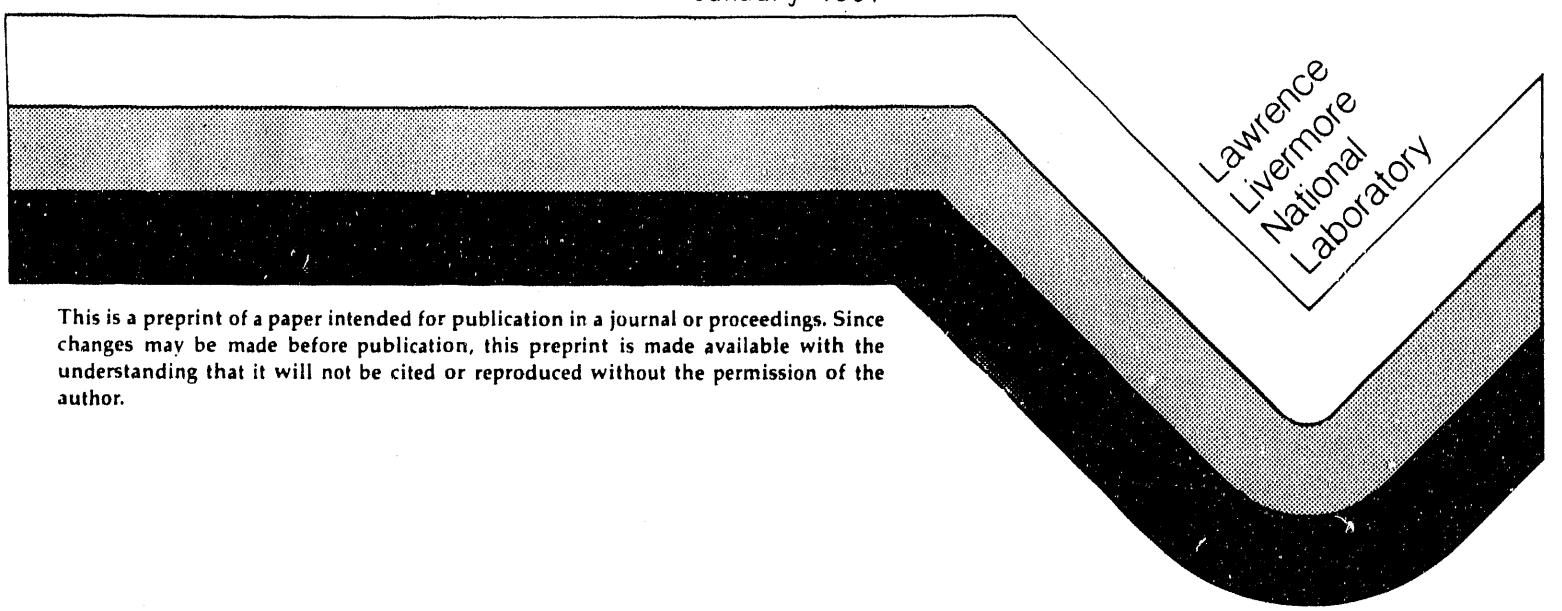

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ABSTRACT

The purpose of this work is to experimentally determine the capillary suction potential of Topopah Spring tuff from Yucca Mountain, Nye County, Nevada. This data can be used to help characterize the unsaturated hydraulic properties of the densely welded tuff at this site.

INTRODUCTION

The Yucca Mountain Project of the U. S. DOE is studying the suitability of the tuffaceous rocks at Yucca Mountain at the Nevada Test Site for the possible construction of a high level nuclear waste repository. The proposed repository will be located in the unsaturated zone of the Topopah Spring member of the Paintbrush Tuff unit at Yucca Mountain. Transport of water within the near field of a nuclear waste package is strongly influenced by the suction potential of the repository rocks. One of the tasks of the Yucca Mountain Project at Lawrence Livermore National Laboratory (LLNL) is to study the waste package environment hydrology. Therefore, we have determined, in the laboratory, the suction potential of several samples of the same rock type as that in the proposed repository horizon.

These data will be used in the models of the hydrological processes in the waste package environment. Current model calculations use the drying curves of Klavetter and Peters (1987). However, they did not study the hysteresis between the drying and wetting curves nor the effects of temperature on the suction potential. In the repository, the rockmass around the waste packages will become dry due to the thermal load of the waste but will then rewet during the long cooldown as the thermal output of the waste packages declines. Much of this process will occur at temperatures above 20°C. The goal of our work is to determine the importance of temperature and the wetting-drying hysteresis on the measured suction potential of densely welded tuff.

The water potential of a porous medium is a sum of its matric and osmotic potential. Similarly, the matric and osmotic suction of a rock are often referred to as the total suction potential of the rock. This combined potential for retention of water can be estimated directly from the vapor pressure of the water in the material. This is because the vapor pressure of the water is lowered in a predictable way by interaction with the solid matrix and by solutes. The combined potential can be related to the relative vapor pressure, expressed by ζ/ζ_o, where z is the pore water vapor pressure and z_o is the vapor pressure of bulk water at the same temperature.

If the water is relatively free of solutes (this is a good approximation for the pore water we used in the test) we may assume that the total water potential is primarily due to the matric potential. The matric potential p is related to the relative vapor pressure by

$$p = (\rho RT/M) \ln (\zeta/\zeta_o) \quad (1)$$

where ρ is the density of water, R is the gas constant (on a mole basis), T is the Kelvin temperature, and M is the molecular weight of water (e.g., Marshall and Holmes, 1981).

As well as the explicit temperature dependence of equation 1, it is generally acknowledged that suction potential has an implicit temperature dependence because surface tension depends on temperature. The capillary pressure decreases with temperature for a given water content because the surface tension in each capillary decreases with temperature. If the meniscus that forms at the air-water interface in the pore is hemispherical and has a radius of curvature r then

$$p = 2\gamma/r \quad (2)$$

where γ is the surface tension of pure water (Marshall and Holmes, 1981). Equation 2 describes the potential for an individual pore. Therefore, this expression represents a macroscopic sample if a pore radius can be chosen that is characteristic of the sample. Then the matric potential is sometimes estimated to be directly proportional to the temperature dependency of surface tension

$$p_2 = p_1 \gamma(T_2)/\gamma(T_1) \quad (3)$$

where the subscripts represent the values at two temperatures.

Peters *et al.* (1984) and Klavetter and Peters (1987) measured suction potential of both welded and nonwelded tuff from Yucca Mountain. They used a thermocouple psychrometer to measure the relative humidity in equilibrium with the samples at each saturation value. Samples were initially saturated and then dried in stages in a microwave oven. Mercury intrusion was used to determine pore size distribution of the rocks and theoretical models were used to calculate the suction potentials. Psychrometic data were compared with the calculated values. All these data were taken at room temperature.

EXPERIMENTAL PROCEDURE

Nine different samples of densely welded tuff were studied from the Topopah Springs Member of the Paint Brush Tuff unit at Yucca Mountain located at the Nevada Test Site, Nye County, Nevada (see Table 1). Samples 1-3 were machined from drill core from borehole USW H-1 located in Yucca Mountain near the 366 m depth. However, sample 1 was from a different piece of that core than samples 2 and 3. Samples 4-9 were machined from the same piece of outcrop material from Fran Ridge at Yucca Mountain. The petrology and geochemistry of densely welded tuff from the Topopah Spring Unit are reported in detail by Knauss (1984) and Bish *et al.* (1981). Bish and Vaniman (1985) report the mineralogical composition of a core from borehole USW H-6 in this unit. Three samples from 333 to 350 m depth ranged in composition from 16 to 21% quartz, 9 to 15% cristobalite and 66 to 70% alkali feldspar. They reported only traces of smectite and mica and no clinoptilolite or analcime in these samples.

Each of the 9 samples was machined to a right circular cylinder. Under drying conditions, 3 were studied at 20°C and 6 at 70°C. Under wetting all 9 samples were studied at 20°C and 3 were studied at 70°C. At the beginning of the experiment all samples were intact with no visible fractures or breaks although by the end of the study 5 samples had developed cracks or had broken into pieces. Sample dry weights ranged from 8 to 114 grams and both drill core and outcrop samples were used. Table 1 summarizes the relevant data on the samples.

The samples were dried in a vacuum oven at 35°C until their weight stopped changing. (The samples were warm when weighed but errors due to convection were small for samples of several grams.) At this point they were considered dry. The saturated weight was obtained after the samples had come to steady state weight in J-13 water (the J-13 well penetrates a saturated zone of the Topopah Spring Member about 8 km horizontal distance from the repository site) under a pressure of about 0.7 MPa. Sample porosities were calculated using these saturated and dry weights.

Measurements were made with the samples initially dry, to obtain data during wetting, and also when samples were initially saturated, to obtain drying data. The procedure consisted of placing the samples together in a chamber of known constant humidity and temperature and allowing them to absorb water or dehydrate by vapor transport through diffusion until they were in equilibrium with the controlled atmosphere in the chamber. When the pore vapor pressure reached equilibrium with the environment vapor pressure, wetting or drying ceased. When equilibrium was reached at one level of humidity and the samples weighed, the humidity was changed to another value and a new equilibrium achieved. This equilibrium was detected by weighing each sample. We assumed equilibrium when the weight change was within the precision of measurement. This precision was about 0.002% of the mass of the water at saturated conditions. Fifteen to 30 days was required at each humidity value to reach equilibrium. The entire experiment was 18 months in duration.

TABLE 1

Sample	Origin	Dry weight, g	Bulk den, g/cc	Porosity, %
1	H-1 core	114.296	2.32	8.40
2	H-1 core	17.5741	2.34	7.40
3	H-1 core	8.5790	2.29	7.59
4	Fran Ridge	11.6012	2.30	8.64
5	Fran Ridge	11.6124	2.31	8.55
6	Fran Ridge	11.6407	2.31	8.17
7	Fran Ridge	11.5970	2.30	8.35
8	Fran Ridge	11.5445	2.29	8.29
9	Fran Ridge	11.5546	2.30	8.38

RESULTS AND DISCUSSION

Drying at 20°C—Figure 1 shows the results for samples 1-3 at room temperature when the samples were initially totally saturated. Within experimental error, data for samples 2 and 3 are the same. These samples were machined from the same piece of core and so similar behavior might be expected due to smaller rock variability.

Wetting at 20°C—Figure 2 shows the results from samples 1-9 at room temperature when the samples were initially dry. Again, samples 2 and 3 are experimentally identical while sample 1 has a larger capillary suction. In fact, sample 1 shows a larger suction than samples 2 and 3 for both drying and wetting. One explanation for this is a variation in suction properties due to intrinsic rock variability since sample 1 was machined from a different piece of core than samples 2 and 3. Another possibility is that sample 1 did not equilibrate with the environment in the chamber because of its smaller surface to volume ratio (it was the largest sample). If this is the explanation then sample 1 would have shown a higher measured suction for drying and a lower suction for wetting. This is not the case so that we believe the higher suction for sample 1 is real and due to rock variability.

There is a clear and measurable hysteresis between the drying and wetting curves for each of samples 1–3, although the hysteresis is smaller for samples 2 and 3. The outcrop samples (4–9) all show similar capillary characteristics, which are between the values of the core samples. The outcrop samples were not studied for drying conditions at room temperature.

Drying at 70°C—Figure 3 shows the results of samples 1, 2, 4, 5, 6 and 8 at 70°C with the samples initially saturated. Core samples 1–3 again have the bounding values of suction with the outcrop samples grouped at intermediate values.

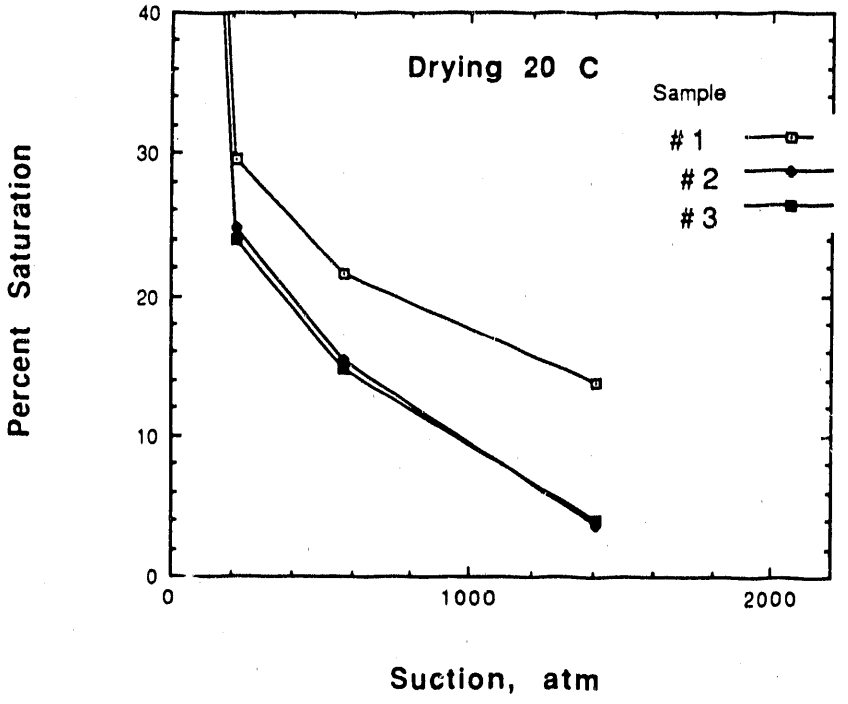

Figure 1. Percent saturation as a function of suction potential measured at 20°C for 3 samples of Topopah Spring tuff. Samples were initially saturated so that these data are the capillary suction for drying. All samples were from USW H-1 core.

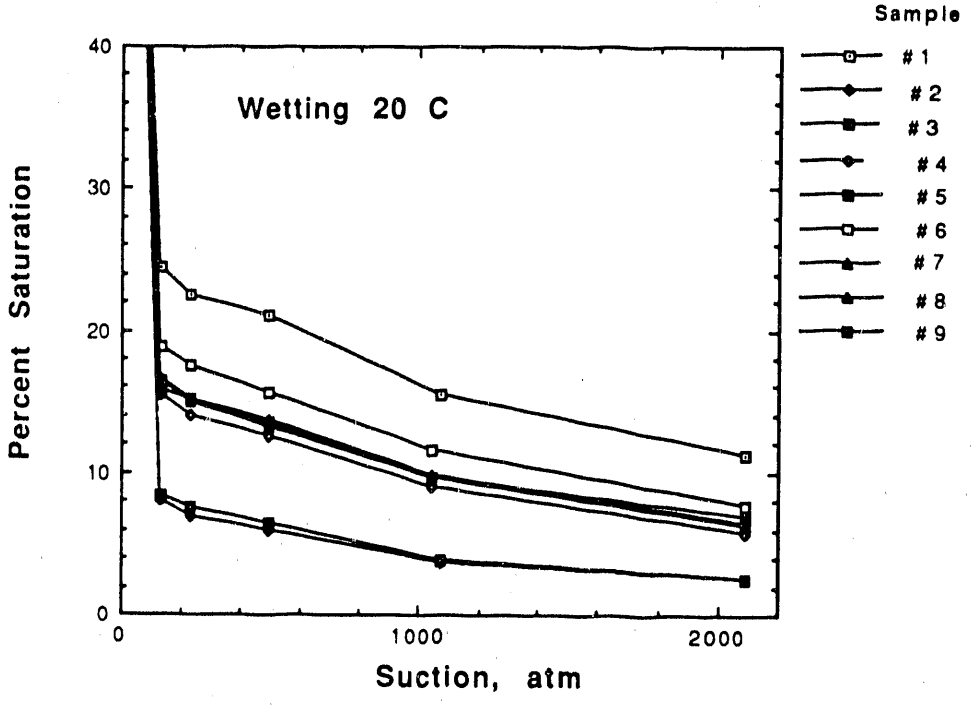

Figure 2. Percent saturation as a function of suction potential measured at 20°C for 9 samples of Topopah Spring tuff. Samples were initially dry so that these data are the capillary suction for wetting. Samples 1-3 were from USW H-1 core and samples 4-9 were for Fran Ridge outcrop.

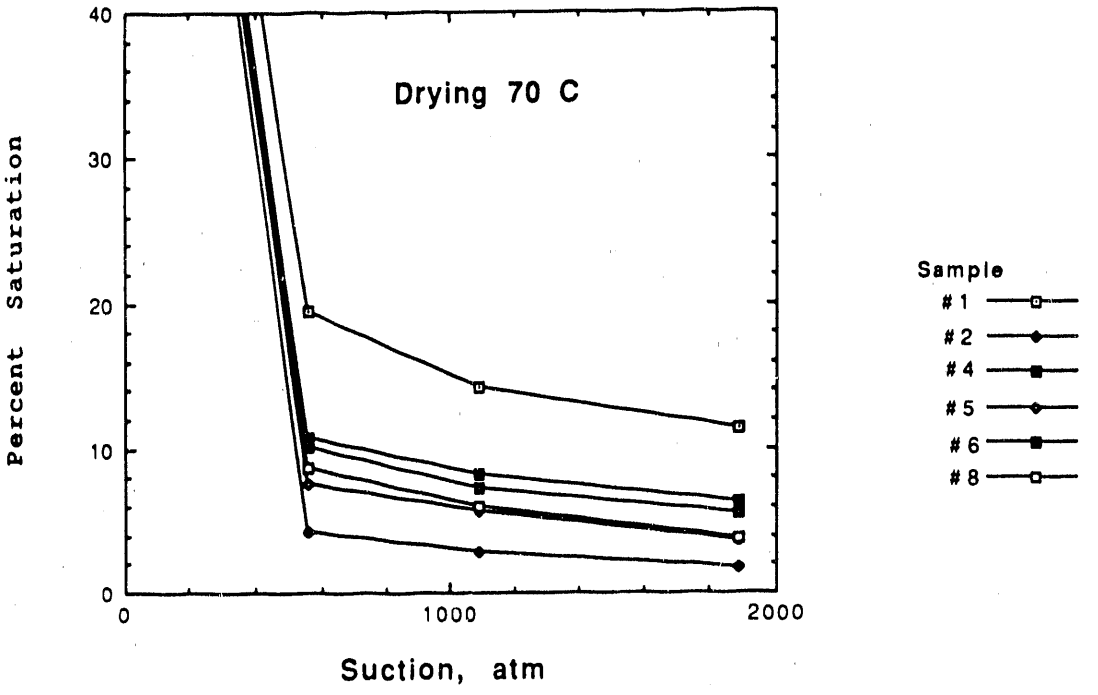

Figure 3. Percent saturation as a function of suction potential measured at 70°C for 6 samples of Topopah Spring tuff. Samples were initially saturated so that these data are the capillary suction for drying. Sample 1 and 2 are from USW H-1 core and the others are from Fran Ridge outcrop.

It is possible to compare data only for the core samples at the two temperatures. At a suction of about 1400 atm, saturation at room temperature is just a few per cent above that measured at 70°C. At about 600 atm the difference is about the same for sample 1. However, at this pressure sample 2 has about 10% higher suction at room temperature than at 70°C. Unfortunately, data at 200 atm and 70°C was not taken. These data could have confirmed this trend of increasingly higher suctions at lower temperature as compared to the higher temperature. Equation 3 predicts that the ratio of suctions at 70°C and 20°C is equal to the ratio of the surface tensions at these temperatures. From the accepted values of surface tension (International Formulation Committee, 1967) this ratio is about 0.88.

Wetting 70°C—Figure 4 shows the results of samples 3, 7 and 9 at 70°C when the sample initial conditions were dry. The outcrop samples show very similar behavior while the core sample shows consistently lower saturations.

At 70°C the same samples were not measured during both drying and wetting, so that it is difficult to evaluate the magnitude of hysteresis at this temperature. However, the data suggests that the capillary properties of samples 2 and 3 are similar. If this is true, a comparison of 2 under drying (Figure 3) and 3 under wetting (Figure 4) shows no measurable hysteresis. The same comparison of samples 4, 5, 6 and 8 with samples 7 and 9 leads to the same conclusion. Therefore, the data is suggestive of no measurable hysteresis at 70°C.

It is possible to compare the wetting data at the two temperatures for core sample 3 and outcrop samples 7 and 9. Just as for the drying results at the two temperatures, the capillary suction is systematically lower at 70°C. For sample 3 at 4% saturation the ratio of suctions at 20 and 70°C is about 0.44. For both samples 7 and 9 the same ratio at 10% saturation is about 0.33. Equation 3 would predict this ratio to be 0.88 which is a significantly smaller temperature effect than that measured for these three samples.

Comparison with Other Published Measurements--Klavetter and Peters (1987) report thermocouple psychrometry and mercury intrusion measurements used to calculate the capillary suction of tuffs from Yucca mountain. Borehole and outcrop samples were studied from several welded and non welded formations. All their measurements were made at room temperature. Since these experimental procedures were different from ours, we briefly summarize them here before comparing results of the two studies.

Thermocouple psychrometry began with the samples saturated with water and the vapor pressure measured at several values of water content as the sample was dried. Therefore, these data describe drying conditions for a wetting fluid (water). Mercury intrusion began with the samples dry and the volume of mercury penetrating the sample recorded as it is forced under pressure in the pores. From the cumulative pore volume distribution as a function of intrusion pressure that can be derived, the mercury saturation as a function of intrusion pressure may be calculated. From this, the water saturation as a function of capillary pressure may be estimated. Therefore, the mercury intrusion results are for intrusion of a nonwetting fluid (mercury). Klavetter and Peters use the mercury intrusion results to compare to the psychrometry data, especially at

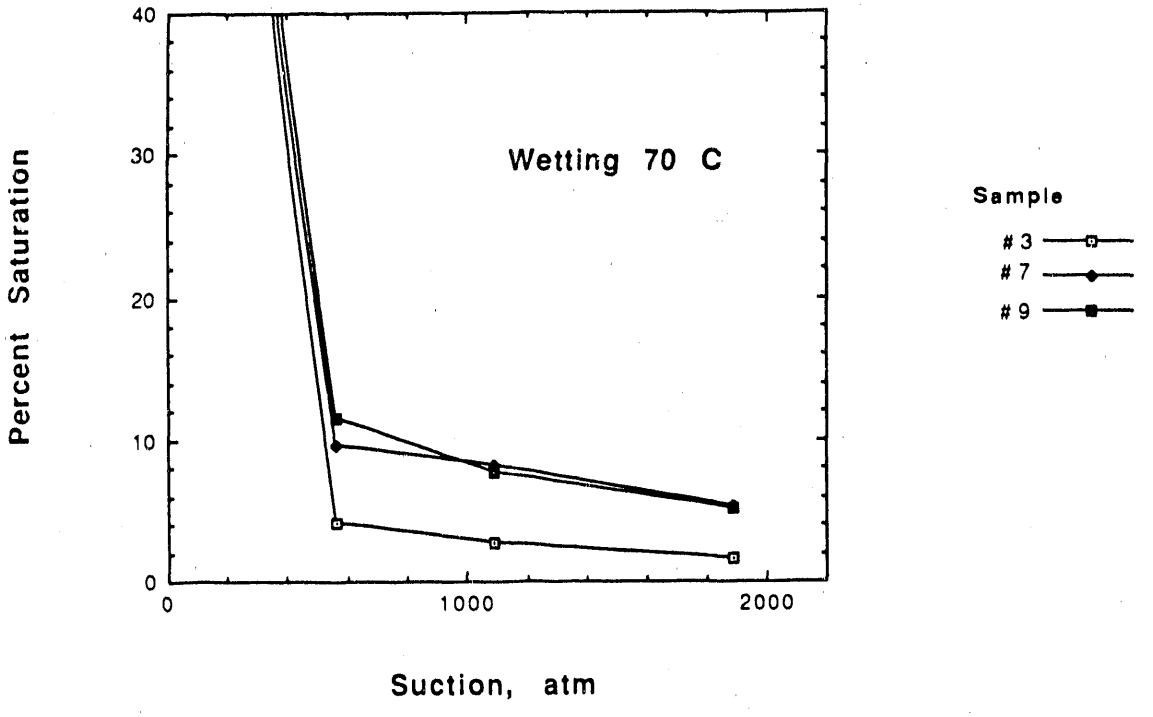

Figure 4. Percentage saturation as a function of suction potential measured at 70°C for 3 samples of Topopah Spring tuff. Samples were initially dry so that these data are the capillary suction for wetting. Sample 3 is from USW H-1 core and 13 and 15 are from Fran Ridge outcrop.

the low suction values where the psychrometer results are most uncertain. However, it is uncertain how the mercury intrusion results relate quantitatively to water capillarity.

Note that both our results and those of Klavetter and Peters show a wide variability in measured suction pressures at a given saturation. For example, the Klavetter and Peters data reflects a sample variability that is about one order of magnitude in suction potential over much of the range of measured psychrometer data and 2 to 3 orders of magnitude in the mercury intrusion determined suction, over an equally wide range of saturations. Our data shows approximately a factor of three difference in suction between samples 1 and 3 at 15% saturation (Fig. 1).

This variability in capillary suction between samples of the same lithological and hydrological unit may be a consequence of rockmass inhomogeneity. Note that the samples measured by Klavetter and Peters (1987) were all from USW G-1, USW GU-3 and USW G-4; sampled at depths representative of the densely welded Topopah Springs unit. Our samples were from borehole H-1 at a depth corresponding to the densely welded Topopah Spring unit and outcrop material at Fran Ridge. Nevertheless, the results from the two studies are consistent. The room temperature drying curves of Figure 1 are within the spread of corresponding psychrometer results of Klavetter and Peters (1987, Fig. 4, p. 31).

SUMMARY

Matric suction potential was measured on 9 samples of densely welded tuff from the Topopah Springs unit (core and outcrop samples), at 20°C and 70°C and for both wetting and drying conditions. Core and outcrop samples show similar behavior but different values of suction at a given saturation level. Considerable variability was measured between all samples, implying a heterogeneity of suction properties in the Topopah Springs unit.

At 20°C there was a measurable hysteresis between drying and wetting curves. Data was not available to study this hysteresis at 70°C but indirect evidence suggests a lack of measurable hysteresis at this higher temperature. As expected, lower suctions were measured at the higher temperature.

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