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Relevance of Partial Saturation to the Mechanical Behavior of Tuffs*

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ABSTRACT: In this paper, equivalent confining pressures are estimated for samples of tuff using an expression that relates capillary pressure and effective confining pressure to the saturation state of the pores. These confining pressures are compared to the pressures calculated from strain measurements during drying; the calculations use elasticity theory.

It is found that stresses and strains are caused by capillary forces in certain partially saturated rocks. This phenomenon has a direct impact on experiments that rely on strain measurements to calculate a rock property. Specific problem areas are the performance of unconfined mechanical tests, calculation of elastic parameters from laboratory data on unjacketed samples, and determination of in situ stress by any method involving stress relaxation.

1 INTRODUCTION

For many years, the rock mechanics community has been aware of the potential effects of water on the compressive strength of rock. Qualitatively, wet rocks are weaker than dry rocks. Paterson (1978) provides a summary of the literature pertaining to the topic; some of the more detailed papers include Colback and Wiid (1965), Chenevert (1969), and Michalopoulous and Triandafilidis (1976).

The explanations for the relative values of compressive strength include (1) a decrease in the surface free energy of the solid framework in the presence of water (Colback and Wiid, 1965; Swolfs, 1972); (2) enhanced mobility of dislocations in minerals (Griggs and Blacic, 1965; Griggs, 1967); and (3) an increase in the effective confining pressure caused by the capillary forces in the pores of a partially saturated (i.e., air-dried) rock (Chenevert, 1969; Rao et al., 1987).

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Data are available from a number of tuffaceous samples which support the last of the possible explanations mentioned above. In the following sections, these data are described; the description includes both the experimental observations and some associated hypotheses concerning the physics of the process. More importantly, two separate lines of experimental evidence lead to similar, quantitative estimates of the capillary forces in the pores of partially saturated samples.

Although the data to be discussed in subsequent sections are interesting, similar observations have been made in other rock types in the past. The goal of this paper is to use the quantitative estimates of pore pressures as a spur to outline the implications for routine measurements of mechanical properties in the laboratory and in the field.

2 DESCRIPTION OF DATA

During the more than eight years that samples from Yucca Mountain have been tested, several sets of data were collected by different investigators to determine different rock properties. First, the length changes of a number of saturated samples were examined using a dilatometer while they were equilibrating with ambient laboratory conditions. The combination of this first data set with a second data set of elastic properties (e.g., Young's moduli, Poisson's ratios) obtained on a different set of samples during uniaxial compression tests allowed the calculation of equivalent pressures which would have caused the same strains if the dilatometer samples had been subjected to hydrostatic compression. Finally, hydrologic properties were measured on a third set of samples; these properties have been used in several equations from the hydrologic literature to estimate pore pressures as a function of the saturation of the pores.

2.1 Dilatometric Data

The first set of data (see Table 1) is a collection of strain measurements that were made on eleven small (2.54 x 0.32 x 0.32 cm) samples of four types of tuff (two welded devitrified, one welded vitric, two nonwelded vitric, and six nonwelded zeolitic). Each sample was saturated and then placed in a dual-pushrod dilatometer and allowed to equilibrate with the laboratory environment (i.e., ambient temperature and relative humidity). The measure of equilibration was achievement of stable length within the resolution of the dilatometer (approximately 4×10^{-5} in.). Without exception, the samples contracted and reached stable lengths in 5 to 40 hr. The strains experienced by the samples ranged from 0.0001 to 0.0023.

2.2 Elastic Properties

The contraction of the samples must be caused by forces exerted on the samples. In order to relate the sample contractions to the causative forces, the relationship between applied stresses and the resulting strains must be known. It has been determined from many compression experiments that, in general, the tuffs at Yucca Mountain are linearly elastic materials for most of the range of stresses below the failure stress. Consequently, elastic theory is used to relate the sample contractions to the causative forces. The second data set, consisting of values for Young's moduli (E) and Poisson's ratios (ν) for the tuffs of interest, is given in Table 1, together with the data from the dilatometer measurements.

Table 1. Observed Strains, Elastic Properties, and Calculated Equivalent Confining Pressures for Dilatometric Properties

Sample ID[a]	Tuff Type[b]	Time to Stable Length (hr)	Observed Strain[c]	Young's Modulus[d] (GPa)	Poisson's Ratio[d]	Equivalent Confining Pressure[d] (MPa)
G1-504.1	wd	35	0.00010	19.9 ± 3.0	0.17 ± 0.04	3.0 ± 1.6
G1-1151.1	wd	12	0.00016	32.7 ± 4.6	0.22 ± 0.03	9.3 ± 3.3
G1-1288.9	wv	15	0.00010	23.7 ± 2.5[e]	0.15 ± 0.05[e]	3.4 ± 1.7
G1-1342	wv	30	0.00020	15.8 ± 2.0[e]	0.17 ± 0.05[e]	4.8 ± 1.5
G1-1362.4	nwv	5	0.00016	15.8 ± 2.0[e]	0.17 ± 0.05[e]	3.8 ± 1.4
G1-1395.8	nwz	>20[f]	0.00228[f]	6.0 ± 1.8	0.23 ± 0.05	>25.3[f] ± 8.9
G1-1470.2	nwz	30	0.00168	6.0 ± 1.8	0.23 ± 0.05	18.7 ± 6.6
G1-1470.7	nwz	15	0.00174	6.0 ± 1.8	0.23 ± 0.05	19.3 ± 6.8
G1-1744	nwz	40	0.00144	11.5 ± 4.0	0.16 ± 0.05[e]	24.4 ± 9.2
G1-1763.7	nwz	>7[f]	0.00104[f]	11.5 ± 4.0	0.16 ± 0.05[e]	>17.6[f] ± 6.7
G1-1799.8	nwz	30	0.00182	11.5 ± 4.0	0.16 ± 0.05[e]	30.8 ±11.7

a. All samples are from Corehole USW G-1; the number in the sample ID is the sampling depth in feet.
b. wd = welded devitrified; wv = welded vitric; nwv = nonwelded vitric; nwz = nonwelded zeolitized.
c. Standard deviations are not available for strain. An equivalent, in the form of experiment uncertainty, is estimated to be approximately 4.8×10^{-5}.
d. Numbers given are the mean value and one standard deviation [(n-1) degrees of freedom] for samples from this tuff type.
e. Data available for one experiment only; value for standard deviation assumed based on expert judgement.
f. No upper limit is available because temperature was increased before a stable length was achieved.

2.3 Estimated Stresses

It is assumed that length changes in the contracting samples occur by elastic deformation of an isotropic homogeneous material. Thus, the two elastic properties (E and ν) and the observed axial strains (ε_a) are used to estimate the equivalent confining pressure (P_c) to which each dilatometric sample would need to be subjected to obtain the observed axial strain:

$$P_c = \varepsilon_a \left(\frac{E}{1-2\nu} \right) \quad . \qquad (1)$$

In addition, the uncertainty (U) in the calculated value of P_c can be estimated using the following equation (derived from Equation 1 using the approach of Abernethy et al., 1985):

$$U_{P_c} = \left(\frac{1}{1 - 2\nu}\right)\left[\left(EU_{\varepsilon_a}\right)^2 + \left(\varepsilon_a U_E\right)^2 + \left(\frac{2\varepsilon_a EU_\nu}{1 - 2\nu}\right)^2\right]^{1/2} \quad . \tag{2}$$

The calculated values of P_c and U_{P_c} also are given in Table 1.

The uncertainties in P_c that are shown in Table 1 as standard deviations are relatively large, ranging from 31 to 53% of the calculated values. The size of these uncertainties is attributable to the variability of the materials, as reflected in the standard deviations for the two elastic parameters, and to the large relative uncertainty in the strain data.

2.4 Hydrologic Theory

In partially saturated rock, the pressure of water in the pores is negative and exerts a stress on the pore walls that is assumed to be equivalent to a hydrostatic confining pressure applied to the exterior of the rock. Capillary-bundle theory (e.g., Hillel, 1971) can be used to estimate the capillary pressure as a function of the pore-size distribution of the rock sample. In general, if two rock samples have the same saturation, the capillary pressure and the confining pressure resulting from capillary forces will be larger for the sample with smaller pores. One can relate the capillary pressure to the resulting confining pressure if the functional relationship between sample saturation and capillary pressure is known (e.g., McTigue et al., 1984).

The third set of data available for rock samples from Yucca Mountain consists of data relating sample saturation and capillary forces. These data were obtained by drying the sample and measuring the relative humidity of air in thermodynamic equilibrium with the sample. The capillary pressure in the sample may be determined using the relative-humidity value and the psychrometric equation (see Campbell, 1977)

$$\psi = -(R/M)T \ln (RH/100) \quad , \tag{3}$$

where ψ is the capillary pressure, R is the universal gas constant, M is the molecular weight of the water, T is the absolute temperature, and RH is the relative humidity (expressed in percent) of the air in equilibrium with the sample. The data were taken as the sample was being dried; data for a sample being saturated would show a general shift of the curve to capillary-force values closer to zero. These sample-drying data are appropriate for comparisons with the dilatometer data because the samples in the dilatometer also were being dried. The curve used to fit the saturation versus capillary-pressure data is based on a function suggested by van Genuchten (1980).

The relationship between capillary pressure and an equivalent confining pressure has been discussed by a variety of authors [see Narasimhan (1982) and Rao et al. (1987)]. In the paper by McTigue et al. (1984) the relationship between a change in capillary pressure and the resulting change in stress is given by the following equation:

$$d\sigma = (s - s_r)\, d\psi \qquad (4)$$

where s is the saturation and s_r is the residual saturation.

Thus, in order to find the change in effective confining pressure between some initial saturation (e.g., full saturation) and a given final state (e.g., the saturation associated with a sample in equilibrium with room air of a known relative humidity) the function relating saturation and capillary pressure is substituted into Equation 4, which is then integrated between the initial and final capillary pressures.

Calculation of the effective confining pressure resulting from the capillary pressure in a specific sample of unsaturated tuff requires knowledge of the relative humidity of the air during the time the samples were tested in the dilatometer as well as the water saturation curve of the dilatometer sample. Unfortunately, neither piece of information is available for the dilatometric samples discussed earlier.

The approach that has been taken for this work is to obtain saturation curves from data published for tuff which will maximize and minimize the confining pressure that is calculated in the manner described above. The values of capillary pressure that were selected as final states for the integration in Equation 4 correspond to relative humidities of 20, 40, 60, and 80%. The range of relative humidities is used because the laboratory humidity at the time of the dilatometer measurements is unknown, but is estimated to lie in this range with the most probable value(s) being less than 50%. Data for saturation curves were taken from Peters et al. (1984).

3 RESULTS

Figures 1a-1c compare equivalent confining pressures that were estimated using the two different techniques. The points plotted as a function of relative humidity are obtained from hydrologic data: the vertical brackets indicate the range of pressures calculated for each of the dilatometer samples using measured strains from the first data set and estimates of the elastic properties from the second data set (see Table 1).

The following concepts are important to one's understanding of Figure 1. The relative humidity of the laboratory during dilatometer measurements is unknown. Thus, only qualitative statements can be made about environmental conditions. Also, the values calculated from hydrologic theory using data from a number of rock samples should provide upper and lower bounds on pressures which are estimated by this technique.

Figures 1a and 1b show estimated confining pressures for welded devitrified and nonwelded zeolitized tuff, respectively. In both cases, pressures estimated from dilatometer and mechanical property data fall within the bounds obtained from hydrologic theory. Also, estimated confining pressures for these two rock types can be quite large, especially for the zeolitized tuff.

Figure 1c presents data for samples of vitric tuff. Qualitatively, because densely welded tuff has lower porosity, smaller average pore diameters, and lower permeability, welded tuff should experience larger equivalent confining pressures than would nonwelded vitric tuff under the same conditions. Nonwelded vitric tuff is expected to experience equiva-

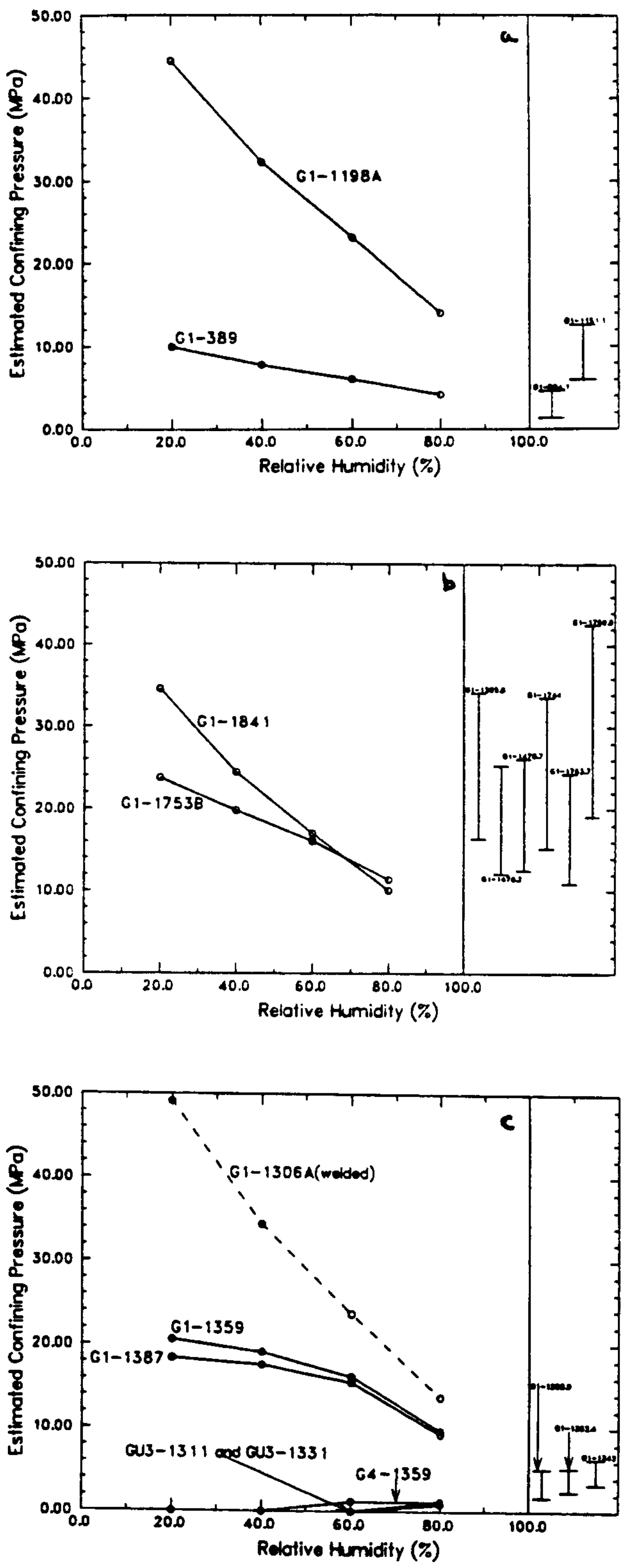

Figure 1. Estimated Confining Pressures in Tuff as Estimated by Two Independent Techniques. Hydrologic Estimates are in the Left Portion of Each Plot. Dilatometer-Mechanical Estimates are in the Right Portion. 1a - Welded, Devitrified Tuff. 1b - Nonwelded, Zeolitized Tuff. 1c - Vitric Tuff.

lent confining pressures similar to those shown for the two lower sets of points shown as a function of relative humidity in Figure 1c. It is inferred that the three vitric dilatometer samples all represent non-welded or partially welded material, and that the two middle curves in Figure 1c were obtained for moderately welded vitric tuff.

4 DISCUSSION

The preceding section presented calculations of equivalent confining pressures estimated by two independent methods. The good agreement of equivalent confining pressure values (Figure 1) determined by these two methods implies that significant capillary forces may exist for conditions of low relative humidity. Implications of the potential effects of capillary forces on standard rock mechanics tests are discussed briefly in the following sections.

4.1 Mechanical Property Testing

The relative effects of partial saturation on the compressive strength of rocks have been previously observed. However, what apparently has not been considered is the number of pitfalls awaiting one who is unaware of the potential effects of reequilibration of samples during testing. For example, performing a valid unconfined compression test using an unjacketed saturated sample may be impossible for materials with hydrologic properties similar to those of the zeolitized tuffs discussed earlier. If the laboratory air is sufficiently dry that the sample loses a substantial portion of its water, such tests actually may be equivalent to tests performed under confining pressures of 30 MPa or more because of capillary forces resulting from sample drying. For the zeolitized samples, such confining pressures would increase the compressive strength of the sample by more than 15% of the unconfined value and would change the deformation behavior from linear-elastic toward nonlinear or ductile behavior. In addition, samples would be subjected to a continually increasing confining pressure from test initiation through sample failure or sample moisture equilibration, whichever came first. The rate of this pressure increase would not be steady, but would probably be exponentially decreasing during a test. Thus, interpretation of the resulting stress-strain data would be quite difficult.

The scenario discussed in the preceding paragraph would be more likely at lower strain rates (or stress rates). Tests conducted at strain rates of 10^{-6} s^{-1} or less will experience stresses resulting from capillary effects unless a laboratory has relative humidities greater than 70 to 80%. In creep tests, strains caused by capillary forces could obscure the transitions in creep behavior.

Finally, because of strain induced by capillary forces, erroneous estimates of elastic parameters (e.g., Young's modulus and Poisson's ratio) could be made. The stress-strain behavior during a 10^{-7} s^{-1} test has been calculated in two ways for each of two materials. First, the strictly linear response was calculated using an average value for Young's modulus. Second, the effect of capillary-force-induced strain was added using the measured strains (as a function of time) for two of the dilatometer samples. The apparent Young's moduli calculated for the second case were lower than the average measured values by 8% for the welded devitrified material and by 24% for the nonwelded zeolitized material.

So far, the discussion has focused on rocks that began a test in an initially saturated state. Similar problems will occur for rocks that begin a test dry, especially for rocks that have been dried in an oven or in a vacuum. Such rocks also will tend to equilibrate with the laboratory air, although evidence suggests that the rate of equilibration is slower. Nevertheless, the reequilibration process will lead to equivalent confining pressures in these samples as well.

The magnitude of the effects of capillary forces will vary depending on the hydrologic properties of the rock, the relative humidity and temperature of the testing laboratory, the duration of an individual test, and the geometry (especially the surface area) of the sample. The first three of these factors have already been discussed. The fourth factor addresses whether the sample is jacketed during testing. National and international testing procedures (e.g., ASTM or ISRM) suggest that samples be jacketed for all triaxial tests and for uniaxial creep tests on soft rock. Procedures for uniaxial compression and tensile strength tests do not address the need to jacket test samples.

If a sample is jacketed, the exposure to the laboratory environment usually is, at most, through an open vent where pore pressure normally would be monitored. This opening is a trivial amount of surface area relative to the total area of a sample; therefore, jacketed samples should undergo little if any reequilibration with the relative humidity of a laboratory.

4.2 In Situ Stress Determination

Many techniques for the determination of in situ stress are based on the measurement of sample strains resulting from stress relaxation and the calculation of relevant stresses using a number of methods. These techniques are subject to the same potential problems as are the laboratory tests. Samples collected from in situ states will change dimensions if the air to which they are exposed has a relative humidity different from the humidity value in equilibrium with the in situ saturation state of the sample. The amount of dimension change will depend on the hydrologic properties and the length of time over which the strain measurements are made. For comparison, the dilatometer samples contracted 0.1-2.3 millistrain when equilibrating with laboratory air. During strain measurements for determining in situ stress, strains are of the same magnitude (e.g., Teufel, 1981). Thus, the potential exists for strains induced by capillary forces to complicate or completely obscure the strains expected from stress relaxation.

Conversely, if the in situ stress can be measured accurately, the interpretation of the data may require modification from the usual approach. Normally, three components of in situ stress are considered: gravitational, tectonic, and residual. If a rock is partially saturated in situ, then the capillary forces should be considered as a fourth component. The capillary forces would be an effective hydrostatic stress which contribute to all three principal stresses equally. According to the calculations earlier in the paper, this effective hydrostatic stress could comprise a significant portion of the overall in situ stresses.

5 SUMMARY AND CONCLUSIONS

Equivalent confining pressures caused by capillary forces in tuff have been calculated using two methods--analysis of strains induced by capillary forces and estimation using hydrologic theory. The equivalent pressures calculated by the two methods are in substantial agreement. All rock samples will experience equivalent confining pressures if they are allowed to equilibrate with air of less than 100% relative humidity. The magnitude of the equivalent confining pressures will be greater for lower relative humidities, samples with smaller pores and lower porosity, longer test times, and larger ratios of surface area to volume.

In the laboratory, unconfined tests (both tensile and compressive) are subject to the potential problems associated with reequilibration. These problems include the effects of an equivalent confining pressure on the boundary conditions assumed for a test (i.e., that a test is being conducted under a uniaxial state of stress) and potential errors in the interpretation of strain data obtained during the test. Elastic parameters may be in error because of additional strains caused by the capillary forces. Creep behavior may be complicated or obscured by the capillary-force-induced strains. If the equivalent confining pressure is of sufficient magnitude, the deformation mode may change from elastic-brittle to a more ductile response.

A similar understanding is important when strains are used to determine the in situ stress state. The strains induced by capillary forces could be as large as those that result from stress relaxation. Such relative magnitudes may invalidate in situ stresses calculated from the strain data.

The major conclusion of this paper takes the form of a recommendation. In order to ensure that samples do not undergo strains as a result of equilibration with the testing environment, two options exist. It is strongly recommended that any sample on which strains are to be measured should be

- isolated from the ambient relative humidity by means of a jacket or other coating material, or

- tested in a known environment with which the sample is already in equilibrium.

The latter option usually will be impractical for fully saturated or oven-dried samples in a laboratory or for field measurements of in situ stress. Thus, jacketing of samples immediately after achievement of the desired saturation state of the sample would be the preferred option. This approach should be added to those widely accepted testing procedures which do not currently include such a provision.

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