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CHARACTERIZATION OF POROSITY IN SUPPORT OF MECHANICAL PROPERTY ANALYSIS[1]

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ABSTRACT

Previous laboratory investigations of tuff have shown that porosity has a dominant, general effect on mechanical properties. As a result, it is very important for the interpretation of mechanical property data that porosity is measured on each sample tested. Porosity alone, however, does not address all of the issues important to mechanical behavior. Variability in size and distribution of pore space produces significantly different mechanical properties. A nondestructive technique for characterizing the internal structure of the sample prior to testing is being developed and the results are being analyzed. The information obtained from this technique can help in both qualitative and quantitative interpretation of test results.

INTRODUCTION

The general applicability of laboratory data for engineering purposes is a prime concern for the design and licensing of a potential repository of high level nuclear waste at Yucca Mountain, Nevada. One specific example involves mechanical property results obtained from experiments in a rock mechanics laboratory for the Yucca Mountain Site Characterization Project (YMP). In order for the results of these experiments to be applicable to the repository scale, the data must be scaled to *in situ* size and conditions. The standard approach to this problem is for the mechanical behavior of the intact (i.e., non-fractured) rock and fractured rock to be evaluated in separate experiments. The results are then input to realistic constitutive models to predict rock mass response to certain sets of environmental conditions. In order to validate these models, the predicted results are compared to data obtained in large scale experiments that are performed *in*

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situ. This paper focuses on one aspect of these issues: evaluation of the scale dependence of the mechanical properties of intact rock and how porosity is a major factor in that effect.

Mechanical properties of intact rock vary with scale as a result of the inclusion of increasingly larger inhomogeneities (e.g., pores, vugs, and lithic fragments) with larger sample sizes. In previously reported work[1,2,3,4], significant differences in elastic moduli and fracture strengths of rocks have been observed at different measurement scales. These studies include testing of many types of rock, including welded tuff from Yucca Mountain[3]. Generally, the inclusion of larger "flaws" (i.e., porosity) will decrease the Young's modulus and strength properties of a rock[5] and lithic fragments (i.e., relatively strong inclusions) can stiffen and strengthen a rock[6]. Most laboratory data suggest that as the sample size increases the strength of the rock decreases, indicating the effect of porosity on sample strength is more pronounced than the effect of more competent inclusions.

LABORATORY EXPERIMENTS

Samples are routinely deformed in compression experiments in the laboratory. The mechanical properties measured in these experiments are normally elastic moduli and ultimate strength. In order to aid in the interpretation of the these data and to determine applicability for their use in predicting the *in situ* properties of tuff, an extensive effort has been undertaken to characterize each rock as thoroughly as possible prior to testing. Routinely, careful measurements are made of sample bulk densities (dry and saturated) and ultrasonic wave velocities (compressional and shear). In addition, a general description of the sample petrology is made, the sample is photographed, and a CT (computerized tomography) scan is taken of each sample.

Because of its significant effect on mechanical properties, porosity is being determined on all samples prepared for laboratory mechanical testing for the YMP. Generally, the porosity is calculated from pre-test measurements of the finished sample dimensions, the dry bulk weight, and the saturated bulk weight. Analyses of existing mechanical property experiments on tuffs from Yucca Mountain have shown that the values of Young's moduli and strengths have a large scatter; however, they are systematically dependent on functional porosity[5]. (NOTE: Functional porosity is defined as actual pore space plus the volume of montmorillonite - a common mineral in Yucca Mountain tuffs with effectively no shear strength.) In addition, a study on welded tuff from the potential repository horizon has shown that intact strength varies in a predictable manner with sample size[3]. These studies indicate that total porosity is only one aspect of the effect of the pore space on mechanical behavior.

The distribution of the porosity is also a very important issue. For example, consider three hypothetical samples with the same total porosity of 20%. These three samples may mechanically behave very differently. Consider the first sample with the majority of porosity concentrated in microcracks (fractures that occur across a grain or along a grain boundary) oriented subparallel to the sample axis. This sample would have a relatively low Young's modulus, a high Poisson's ratio, a low strength, and a very nonlinear stress-strain relationship. The second sample could have the majority of porosity concentrated in a single, large cavity within the sample. This sample would have a moderate (initial) Young's modulus, a moderate Poisson's ratio, a low strength, and a nonlinear stress-strain relationship. The porosity in the third sample could be very small, oblate spheroid pores distributed homogeneously throughout the sample, resulting in a relatively high Young's modulus, a moderate Poisson's ratio, a high strength, and a linear stress-strain relationship.

The tuffs of Yucca Mountain do not have the petrofabric characteristics of the first hypothetical rock; however, there are tuffs similar to the other two examples described above. Four sizes of porosity are present in the Topopah Spring Member tuff from Yucca Mountain[7]. These pores range from lithophysal cavities (a few millimeters to several centimeters), small pores (under 0.2 mm) in vapor-phase-altered zones, 1-5 μm intergranular pores in vapor-phase-altered zones, and submicroscopic intergranular pores in the devitrified matrix. The vapor-phase-altered zones are low density (high porosity) regions of welded tuff matrix that have been altered by gases released during or very soon after deposition of the volcanic ash. The lithophysal cavities are also related to trapped gases. Both features vary in size, but are often a centimeter or more across. As a result, it is important for the researcher to know if one or more of these features occur within a sample being tested.

Surficial descriptions and photographs of the sample exterior yield a great deal of information, but some of the test samples contain completely enclosed weak zones or pores. In order to obtain as much information as possible from a limited set of samples, the internal structure of each sample is being characterized using CT scans and ultrasonic velocities. By taking the CT scans of the pre-test samples, a direct visualization of each specimen's unique pore geometry and distribution is available. These qualitative results and the related quantitative measurements from the images help in the interpretation of the mechanical property results and allow for prediction of larger scale rock response to *in situ* stress and environmental conditions.

Additional diagnostic information may be obtained from compressional and shear wave velocities, which vary due to microcrack density, pore geometry, and density. Taking careful measurements of these properties in the pre-test rock helps in such areas as the (1) interpretation of the mechanical property results from static tests (e.g., the comparison of the dynamic and the static moduli), (2) prediction of *in situ* static moduli following the measurement of rock mass velocity characteristics, and (3) characterization of mechanical anisotropy.

RESULTS

The previous work on porosity effects[5] was performed on samples with nominal diameter of 25 mm that were tested under fully saturated conditions at room pressure and temperature using a constant, nominal axial strain rate of $10^{-5}s^{-1}$. The study determined the following empirical relationship between Young's modulus and functional porosity:

$$E = 85.5e^{-6.96n},$$

where E is Young's modulus in GPa and n is functional porosity in volume fraction. The same study also determined the following empirical relationship between strength and functional porosity:

$$\sigma_u = 4.04n^{-1.85},$$

where σ_u is ultimate strength in MPa. Plots of these relationships are presented in Figures 1 and 2, respectively.

Figure 1. Young's modulus versus functional porosity.

Figure 2. Ultimate strength versus functional porosity.

A related study[3] of the effect of sample size indicated that ultimate strengths of the welded tuff from the potential repository horizon (within the Topopah Spring Member) decrease systematically with an increase in sample size. The samples tested in this study were 25, 51, 83, 127, and 229 mm (nominal diameter), all with a length to diameter ratio of approximately 2:1. This study involving room temperature and pressure experiments at a nominal axial strain rate of $10^{-5}s^{-1}$ produced the following strength-size relationship:

$$\sigma_u = 5.63D^{-0.846} + 69.5,$$

where σ_u is the ultimate sample strength in MPa and D is the sample diameter in m. A plot of this relationship is presented in Figure 3.

Figure 3. Ultimate strength versus sample diameter.

In recent work, a series of six saturated samples have been tested under room temperature and pressure conditions. The samples were deformed at a nominal axial strain rate of 10^{-9} s^{-1}. Porosity (ϕ), strength (σ_u), and static Young's modulus (E_s) data were collected for each sample. In addition, a dynamic Young's modulus (E_d) was calculated from density, p-wave velocity, and s-wave velocities measured on saturated samples. Table 1 lists the data for these samples.

TABLE 1. Results From Laboratory Experiments

Sample ID	ϕ %	σ_u MPa	E_s GPa	E_d GPa
BB-10AE-24Z-SNL	10.4	108.5	38.1	44.3
BB-10AE-11Y-SNL	9.0	97.4	34.1	41.5
BB-10AE-6Y-SNL	10.8	92.9	38.8	45.3
BB-10AE-11Z-SNL	10.0	87.2	33.6	42.9
BB-10AE-5x-SNL	12.0	81.2	32.4	44.7
BB-10AE-49W-SNL	11.7	45.3	26.1	38.5

Also, one CT scan through a central, two-dimensional slice of each sample was taken. Initially, the scans were used exclusively as a qualitative indication of the density contrasts in the sample. Figures 4a and 4b are two examples of the CT scans, Figure 4a is sample 24Z and Figure 4b is 49W.

Figure 4. (a) CT scan of sample BB-10AE-24Z-SNL. (b) CT scan of sample BB-10AE-49W-SNL. The white areas represent pores. The shades of gray illustrate differences in material density, with darker shades depicting increasing density. For example. many of the light gray zones are vapor-phase-altered zones.

Recently, a study was initiated to analyze the CT scans for quantitative measures of porosity that may aid in the interpretation of the resulting mechanical property data. In this analysis, detailed point counts (approximately 100 points per sample) of the relatively solid material and visual pores were performed on the CT scans of the six specimens in the low strain rate study. It can be shown statistically that with 100 points in the analysis, the counts are roughly equivalent to volume percent (and in this case, the counts indicate approximate porosity of the sample). The visible pores counted represent the population of larger pores as described in an earlier study[7] and above. Furthermore, counts also indicate zones of very low density, earlier referred to as vapor-phase-altered zones, which includes the second and third types of porosity. So, while these two types of pores are not counted directly and the submicroscopic pores (the fourth type) are not counted at all, the large pores and the large, low density zones are counted. These features are the 'flaws' discussed above, that tend to dominate mechanical properties (e.g., sample failure), by creating instabilities. The results of the point counts are illustrated in Figures 5 and 6. Figure 5 is a plot of ultimate strength versus pore counts. These data indicate a general trend of decreasing strength with an increase in pore counts. This trend is consistent with earlier results[5] and with general instability theory. Figure 6 shows plots of static and dynamic Young's moduli versus pore counts. These trends also generally agree with earlier work, with modulus generally decreasing with porosity, this trend is more distinct for the static data.

Figure 5. Ultimate strength versus pore counts.

Figure 6. Young's modulus versus pore counts.

CONCLUSIONS

Several studies have shown that porosity has a significant effect on mechanical properties. In addition to standard measurements of sample porosity, other techniques are being developed to obtain a more detailed characterization of the pore volume and distribution of a test sample.

Computerized tomography (CT) scans are an important pre-test characterization tool for qualitative evaluation of the mechanical 'quality' of a sample. Initial results of a recent quantitative, point count study of the scans has produced general results similar to previous studies analyzing the effect of porosity on mechanical properties. This technique offers great promise for this type of analysis and future work will expand on the study described in this report. For example, an additional study will be performed on the aspect ratio of pores and the size distribution of the porosity. Also, as the project proceeds, this type of detailed study will be extended to incorporate larger specimens. Analysis techniques such as these will be extremely useful in establishing scaling laws for specimens tested in the laboratory.

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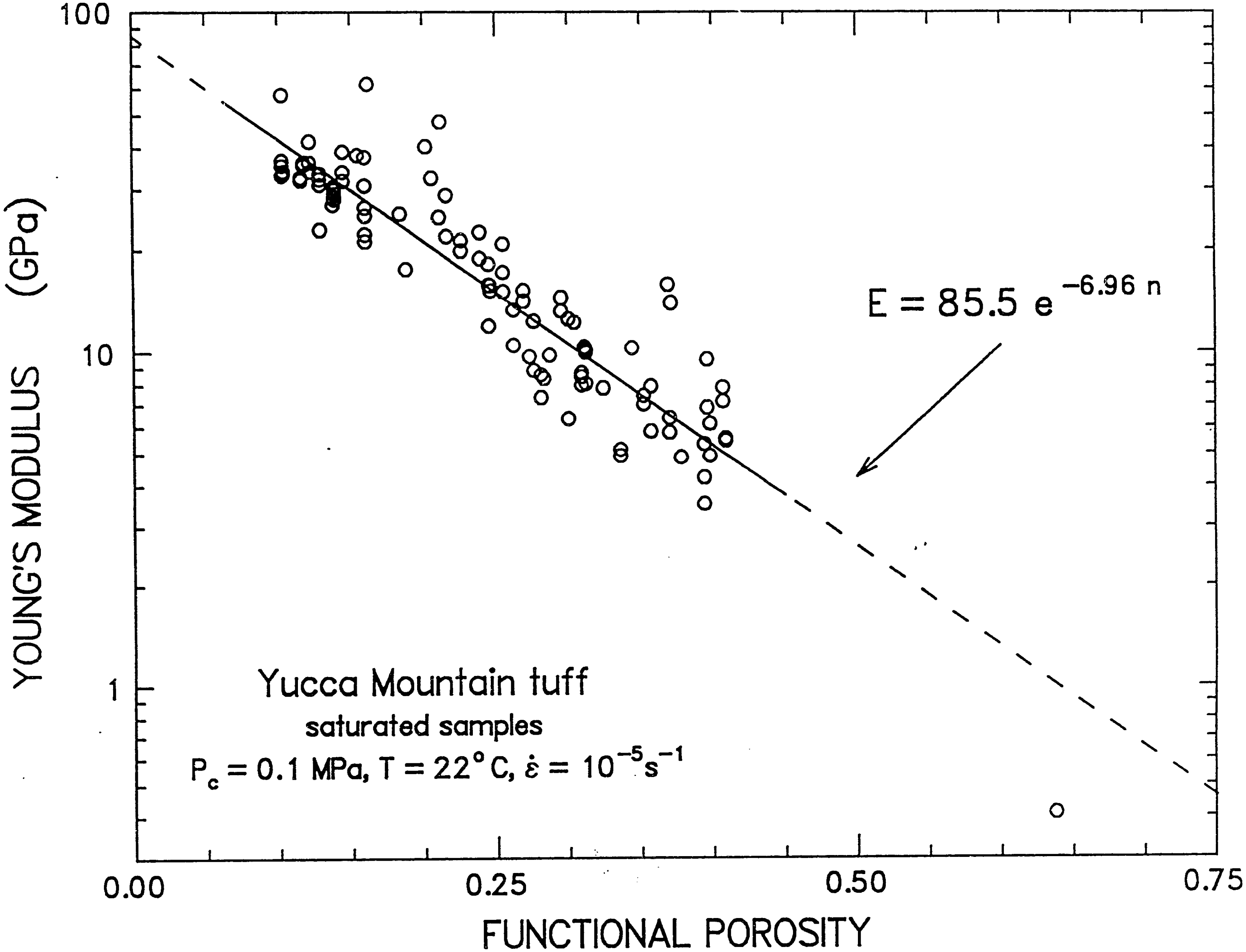
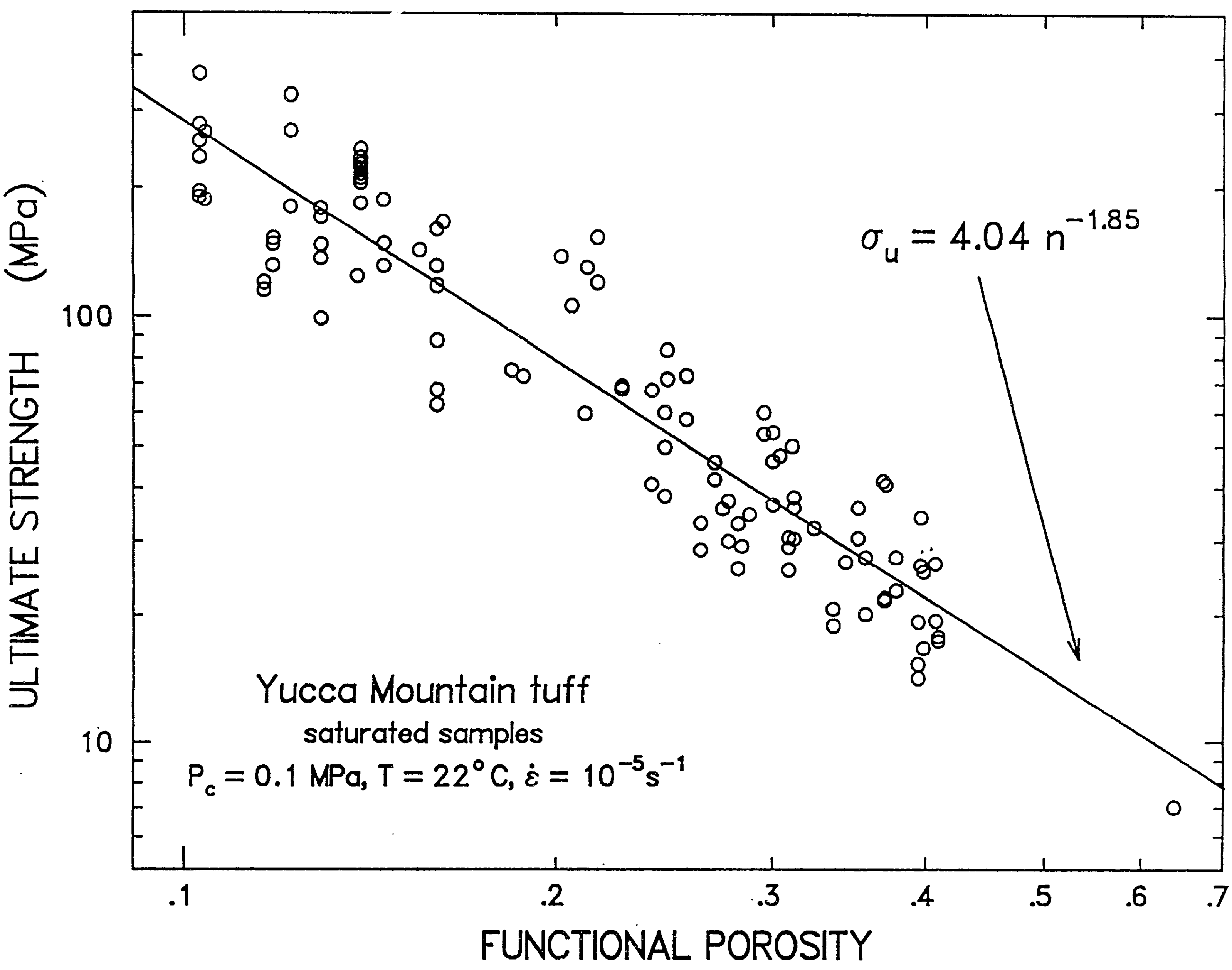
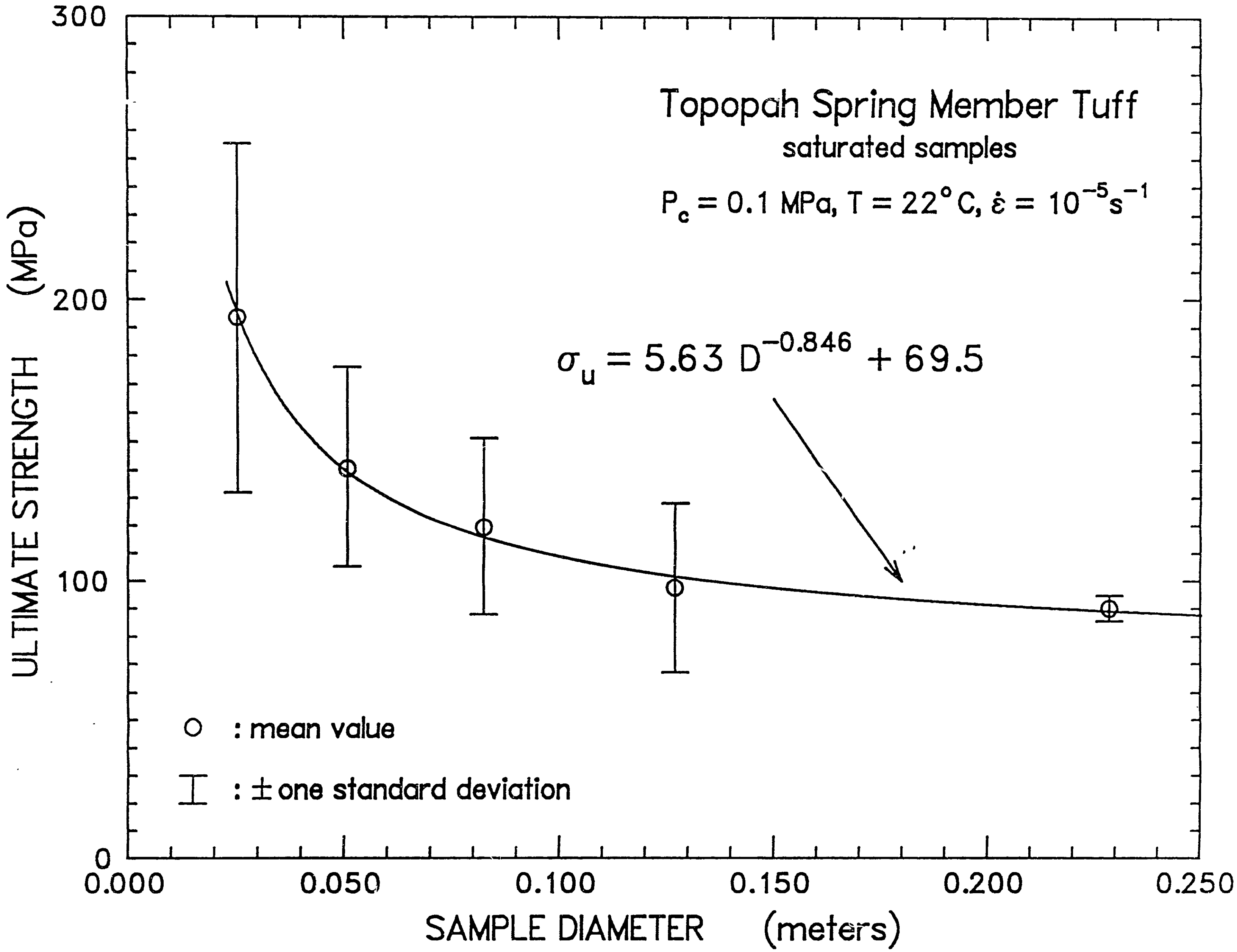

100
10
1
0.00
0.25
0.50
0.75
YOUNG'S MODULUS (GPa)
FUNCTIONAL POROSITY
$E = 85.5\ e^{-6.96\ n}$
Yucca Mountain tuff
saturated samples
$P_c = 0.1$ MPa, $T = 22°$ C, $\dot{\varepsilon} = 10^{-5} s^{-1}$



ULTIMATE STRENGTH (MPa)
100
10
.1
.2
.3
.4
.5
.6
.7
FUNCTIONAL POROSITY
$\sigma_u = 4.04\ n^{-1.85}$
Yucca Mountain tuff
saturated samples
$P_c = 0.1$ MPa, $T = 22°C$, $\dot{\varepsilon} = 10^{-5}s^{-1}$


Topopah Spring Member Tuff
saturated samples
$P_c = 0.1$ MPa, $T = 22°C$, $\dot{\varepsilon} = 10^{-5} s^{-1}$
$\sigma_u = 5.63\ D^{-0.846} + 69.5$
: mean value
: ± one standard deviation
ULTIMATE STRENGTH (MPa)
300
200
100
0
0.000
0.050
0.100
0.150
0.200
0.250
SAMPLE DIAMETER (meters)

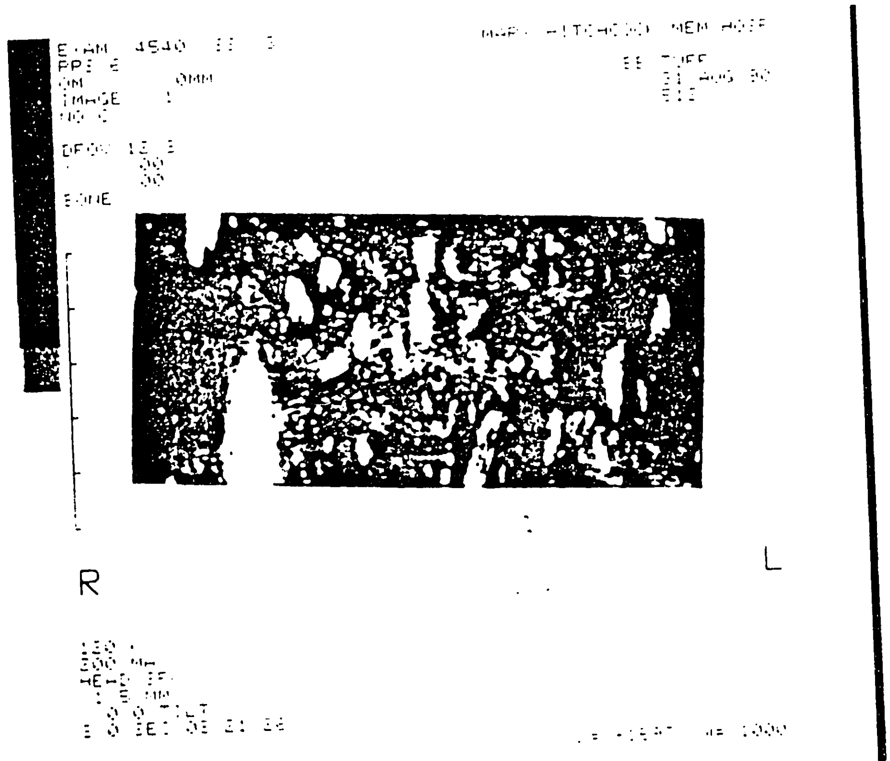


FIGURE 4

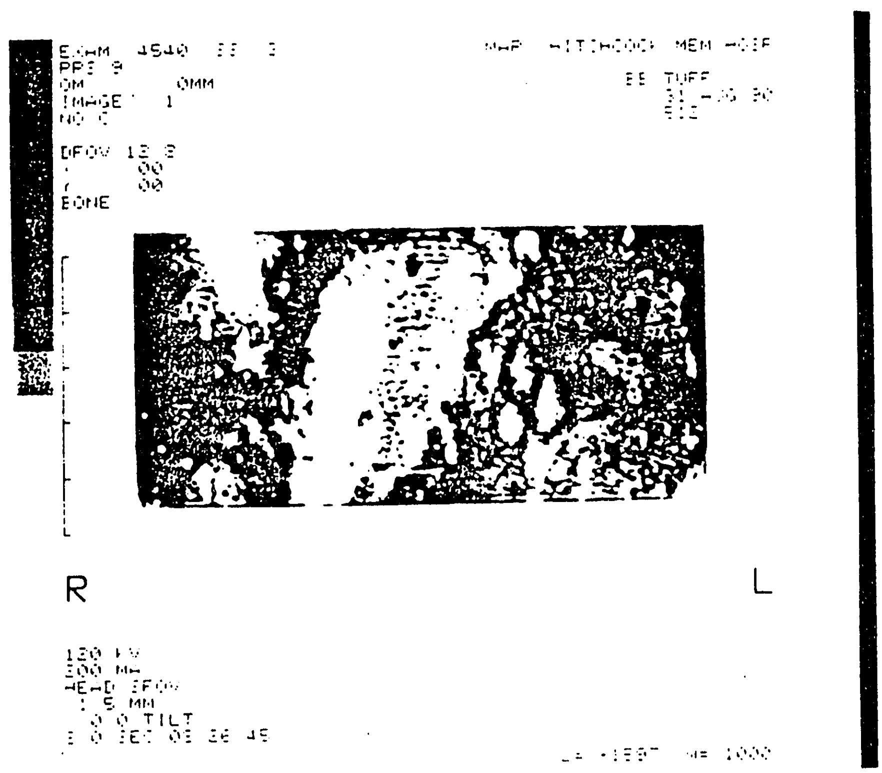
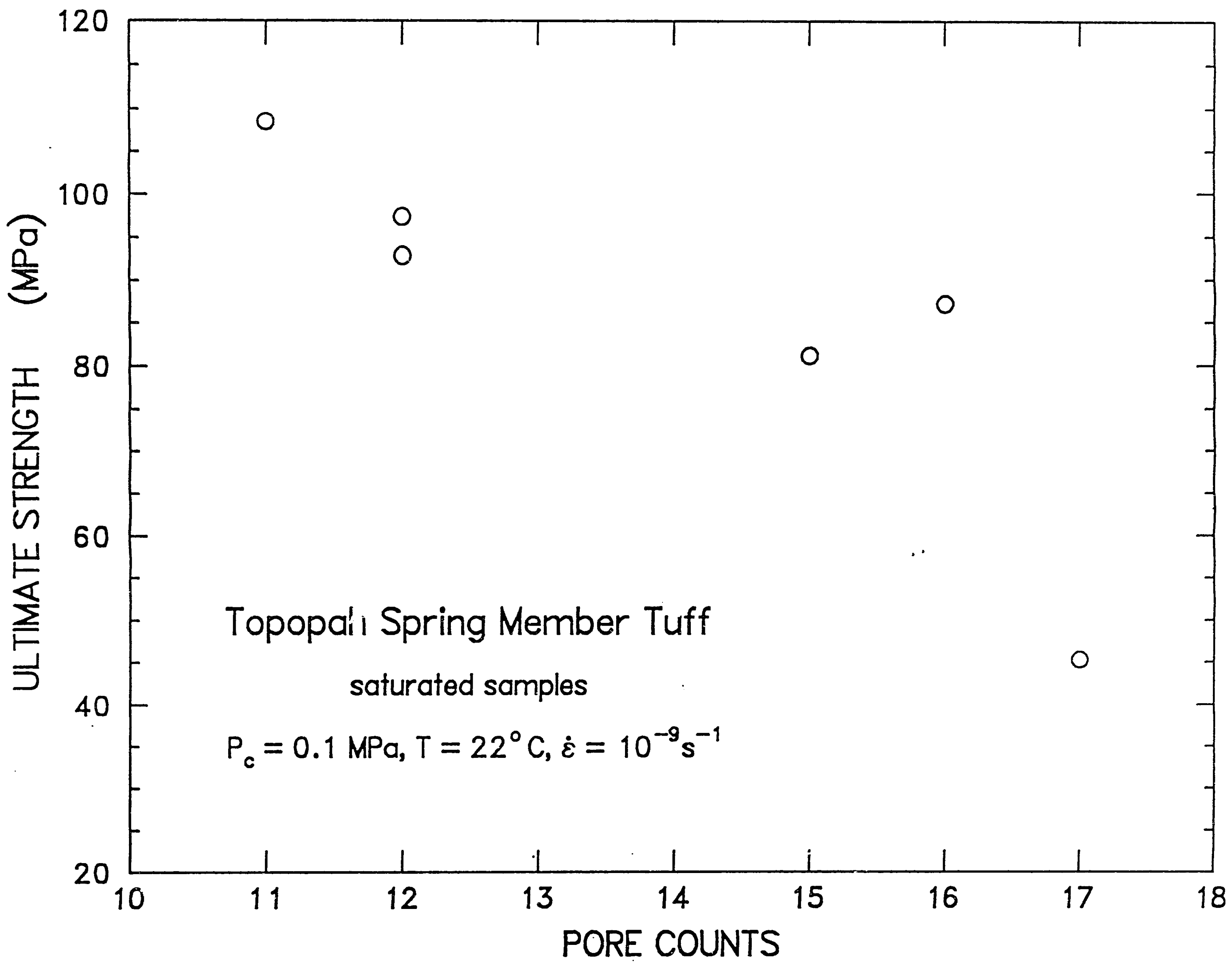
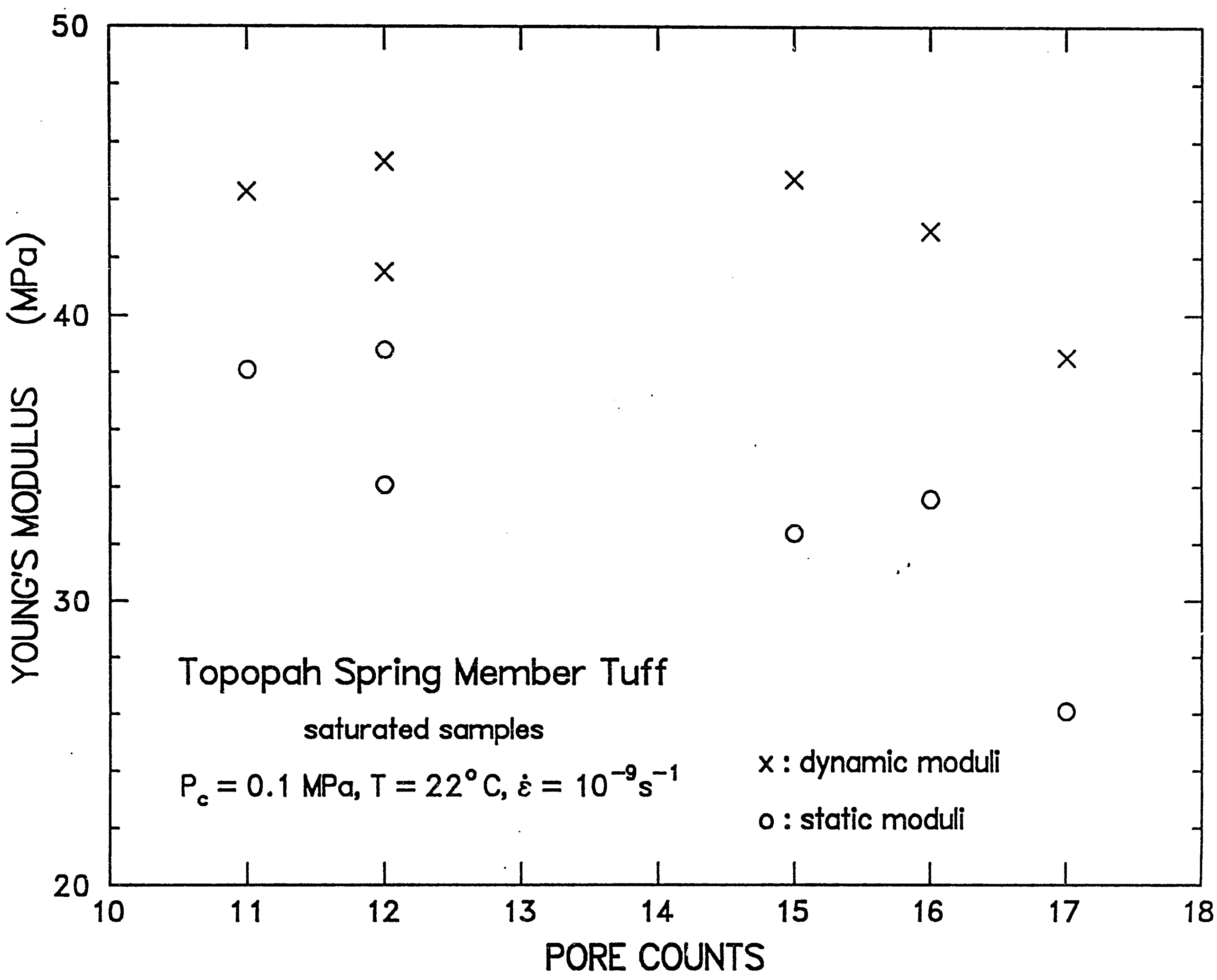


FIGURE 5


120
100
80
60
40
20
10
11
12
13
14
15
16
17
18
ULTIMATE STRENGTH (MPa)
PORE COUNTS
Topopah Spring Member Tuff
saturated samples
$P_c = 0.1$ MPa, $T = 22°C$, $\dot{\varepsilon} = 10^{-9} s^{-1}$



YOUNG'S MODULUS (MPa)
50
40
30
20
10
11
12
13
14
15
16
17
18
PORE COUNTS
Topopah Spring Member Tuff
saturated samples
$P_c = 0.1$ MPa, $T = 22^\circ C$, $\dot{\varepsilon} = 10^{-9} s^{-1}$
x : dynamic moduli
o : static moduli

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