MECHANICAL AND BULK PROPERTIES OF INTACT ROCK COLLECTED IN THE LABORATORY IN SUPPORT OF THE YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT[1]

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ABSTRACT: A comprehensive laboratory investigation is determining the mechanical properties of tuffs for the Yucca Mountain Site Characterization Project (YMP). Most recently, experiments have been performed on tuff samples from a series of drill holes along the planned alignment of the Exploratory Study Facilities (ESF) north ramp. Unconfined compression and indirect tension experiments were performed and the results are being analyzed with the help of bulk property information. The results on samples from eight of the drill holes are presented. In general, the properties vary widely, but are highly dependent on the sample porosity. The developed relationships between mechanical properties and porosity are powerful tools in the effort to model the rock mass response of Yucca Mountain to the emplacement of the potential high-level radioactive waste repository.

1. INTRODUCTION

The applicability of laboratory data for engineering and modeling purposes is a prime concern for the design and licensing of a potential nuclear waste repository at Yucca Mountain, Nevada. One specific example involves mechanical property results obtained from experiments in a rock mechanics laboratory. In order for these data to be realistic, they 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, with the results then utilized in 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 situ*.

The study described here involves the testing of intact tuff samples in support of ramp and drift design for the ESF (Exploratory Studies Facility). The experiments have been performed on samples taken from a series of core holes designated as NRG (North Ramp Geology). A large number of data have been collected on bulk properties (average grain density, dry and saturated bulk densities, and porosity), elastic properties (dynamic and static Young's modulus and Poisson's ratio), and strength properties (unconfined and confined compression and indirect tension). Samples from eight of the drill holes were tested and the results are presented. The data exhibit the large

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scatter expected with tuff, a naturally inhomogeneous material. However, the data are internally consistent, with the mechanical properties being highly dependent on porosity, which varies from less than 0.10 to more than 0.50 (volume fraction). The functional forms of the property versus porosity trends are very similar to those observed in earlier studies on smaller Yucca Mountain tuff samples. The differences in the fitting parameters can be explained in terms of the sample size difference and, possibly, the clay content. These relationships between the mechanical properties and porosity are important because much more porosity information is gathered over the entire mountain, and these values will be used to confidently back-calculate the mechanical properties without having to perform additional (and more expensive) mechanical property experiments.

2. WORK

Raw cores were collected from each of the NRG drill holes, followed by the selection of appropriate samples of each rock unit (lithologic and thermal/mechanical stratigraphies) for the determination of mechanical and bulk properties. Each core piece was examined and a decision made on the appropriate uses for the available material (e.g., an unconfined compression sample, a Brazilian or indirect tension specimen, or both experiment types). A specimen from every core piece was taken for an average grain density measurement. To date, only larger diameter core with relatively homogeneous tuff has been used for testing the effect of pressure on moduli and strength. Each mechanical sample was then machined to the appropriate dimensions in preparation for testing. Following machining, the test samples were dried and then saturated, for the determination of the bulk densities and to prepare for testing under nominally saturated conditions.

A macroscopic description of all samples was performed in hand-specimen detail; however, the unconfined compression samples were also characterized by taking a CT (computerized tomography) X-ray scan of one slice through each specimen. In addition, the compressional (P-) and shear (S-) wave velocities were measured on the unconfined compression samples at both dry and saturated conditions. These techniques provide an analysis of the sample interior prior to testing and aid the post-test analysis of mechanical property results (Price, Martin, and Boyd, 1993).

The unconfined compression experiments were performed at the following standard set of conditions for baseline testing: a saturated sample with a diameter of approximately 50 mm and a length-to-diameter ratio of 2:1 is tested under room temperature, room pressure, and drained conditions at a constant axial strain rate of $10^{-5}s^{-1}$. The triaxial experiments were performed at pressures of 5 and 10 MPa, with the other conditions being similar to the unconfined experiments. The Brazilian experiments were performed using standard techniques on saturated samples.

As mentioned above, the collection of bulk properties data is very important in the interpretation of the mechanical data and will support YMP modeling efforts. As has been shown in earlier studies of tuff from Yucca Mountain, the elastic and strength properties of the tuffs are highly dependent on the material porosity (Price, 1983; Price and Bauer, 1985). For example, when plotted versus porosity, the Young's modulus data are relatively linear on a semi-log plot and the unconfined strengths are linear on a log-log plot (Price, 1983). Price and Bauer (1985) refined these fits by adding the volume of clay content for the determination of the sample's "functional porosity". Work has been initiated to measure the clay content in at least some of the samples tested in this study. In addition, preliminary analyses of the CT scans have produced promise that with a relatively small effort, the pore distribution information collected in the CT scans can be used to further improve the property versus porosity relationships (Price, Martin, and Boyd, 1993).

3. RESULTS

The Young's modulus data from the unconfined experiments have been analyzed as a function of porosity. The data have a relatively linear trend on a semi-log plot. The trend is approximately parallel to the functional form that was fit to earlier strength-functional porosity data from experiments on smaller samples (25.4 mm in diameter) tested under the same set of conditions (Price and Bauer, 1985). The data collected in this study yield a relationship as follows:

$$E = 74.3\ e^{-8.60\phi},$$

where E is the Young's modulus (GPa) and ϕ is the porosity (volume fraction). Figure 1 contains the new data on larger samples, the best fit to that data (solid line), and the fit to the earlier data on smaller samples (dashed line).

Poisson's ratio data have also been analyzed and there is little correlation with porosity. The Poisson's ratios are widely scattered between 0.0 and 0.5, with a mean value of approximately 0.2 (Figure 2). The lack of correlation with porosity indicates that Poisson's ratio may have a higher dependence on some other physical characteristic. For example, the distribution of the porosity may be a significant factor in the Poisson's ratio of a tuff sample. Future work on characterizing the porosity distribution will evaluate this hypothesis.

A similar comparison has been made between the two sets of data for the ultimate sample strengths from the unconfined experiments. These data have a relatively linear trend on a log-log plot of strength versus porosity. As with the Young's modulus data, the earlier study (Price and Bauer, 1985) produced a relationship approximately parallel to the following functional form determined from the data collected by this study:

$$\sigma_u = 0.95\phi^{-2.14},$$

where σ_u is the ultimate strength (MPa) and ϕ is the porosity (volume fraction). The data and two fits are plotted in Figure 3.

Figure 4 presents a plot of the compressional velocity of the unconfined samples in the dry condition versus the sample porosity. This graph illustrates the strong dependence of this dynamic property on the total sample porosity. Further study of the shear velocities and on the comparison of dynamic and static elastic moduli may be of help in putting some bounds on the seismic profiling work performed in the field. These analyses are continuing and the relationships are refined when appropriate.

Six sets of samples were tested at three confining pressures (0.1, 5 and 10 MPa) to determine the dependence of the elastic and strength properties on pressure. The samples were smaller diameter (about 25.4 mm) than the other unconfined experiments. The smaller-sized samples were necessary to have enough test specimens to isolate the effects of pressure by minimizing the lateral and vertical variability in the material properties. The remainder of the test conditions were the same as described for the unconfined experiments. An example set of the data from one piece of core is presented in Figure 5. Each of these sets of data are reduced to determine the parameters of the Coulomb criterion. Figure 6 presents the two Coulomb parameters for each of the six sets of data plotted against the average porosity of the tested samples.

The unconfined tensile strength results determined in indirect tension (Brazilian) tests have also been found to be distinctly related to porosity. The data collected in this study are best fit by the following equation:

$$T_0 = 20.2\, e^{-8.39\phi},$$

where T_0 is the unconfined tensile strength (MPa) and ϕ is the porosity (volume fraction). The data and fit are presented in Figure 7.

4. DISCUSSION

The difference in the two sets of fits on different-sized samples presented in the previous section are very small or can be explained in terms of the change in sample size and/or the lack of montmorillonite data for the latest set of samples.

The exponent (i.e., the slope in semilog space) of the fit to the new Young's modulus/porosity data is very similar to the slope for the smaller samples, indicating that the effect of porosity changes on mechanical behavior is the same for both sample sizes. In addition, the offset of the two fits is small. This result is not surprising, because no effect of sample size on this property was noted in an earlier study (Price, 1986) designed to investigate the effects of sample size on the mechanical properties of intact tuff.

The variability in Poisson's ratio has been very large in both sets of data. However, all of the data from the two sample sizes have clustered around a value of approximately 0.2, with the property apparently being independent of total porosity. Later study of the porosity distribution may shed some light on the scatter in this property.

The two fits of the unconfined compression strength data are approximately parallel; however, the fit of the larger samples is shifted downward from the earlier fit. This shift is relatively large, but can be explained in terms of the difference in sample size. The previous sample size study (Price, 1986) showed a significant decrease in strength of welded tuff samples by changing the sample diameter from 25.4 mm to 50.8 mm.

There are a few data points on the Young's modulus/porosity plot (Figure 1) and the strength/porosity plot (Figure 3) that fall relatively far below (or far to the left of) the best fits. These offsets tend to occur at the high porosity ends of the data. Generally, the samples of non-welded tuff have a higher probability of containing some montmorillonite. As the mineralogy data become available and the fits are made to functional porosity instead of simply pore volume, the data trend will probably become more distinct.

5. CONCLUSIONS

The mechanical and bulk property data discussed in this document are being collected in a detailed manner using standard laboratory procedures. The resultant data are wide ranging; however, all of the data are within expected bounds and the result of testing reasonably sized samples for characterizing the mechanical properties in the laboratory. The analyses of these data have supported the conclusion from earlier studies that porosity is the dominant factor in determining intact-rock, static and dynamic mechanical properties in the Yucca Mountain tuffs. The functional relationships between most of the mechanical properties and porosity will be valuable in the modeling of the potential repository at Yucca Mountain.

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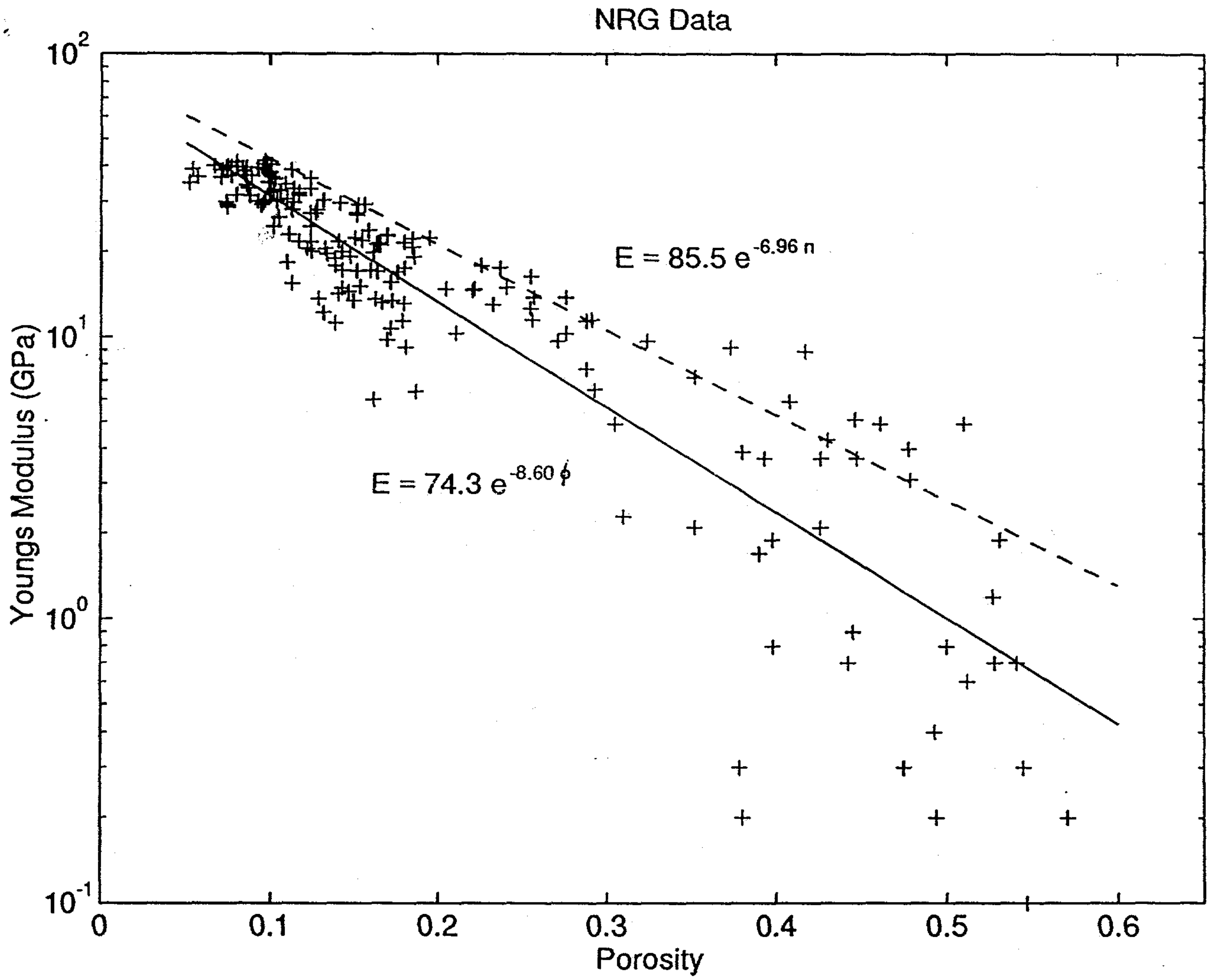


NRG Data
Youngs Modulus (GPa)
Porosity
E = 85.5 e^-6.96 n
E = 74.3 e^-8.60 φ
10^2
10^1
10^0
10^-1
0
0.1
0.2
0.3
0.4
0.5
0.6

FIGURE 1

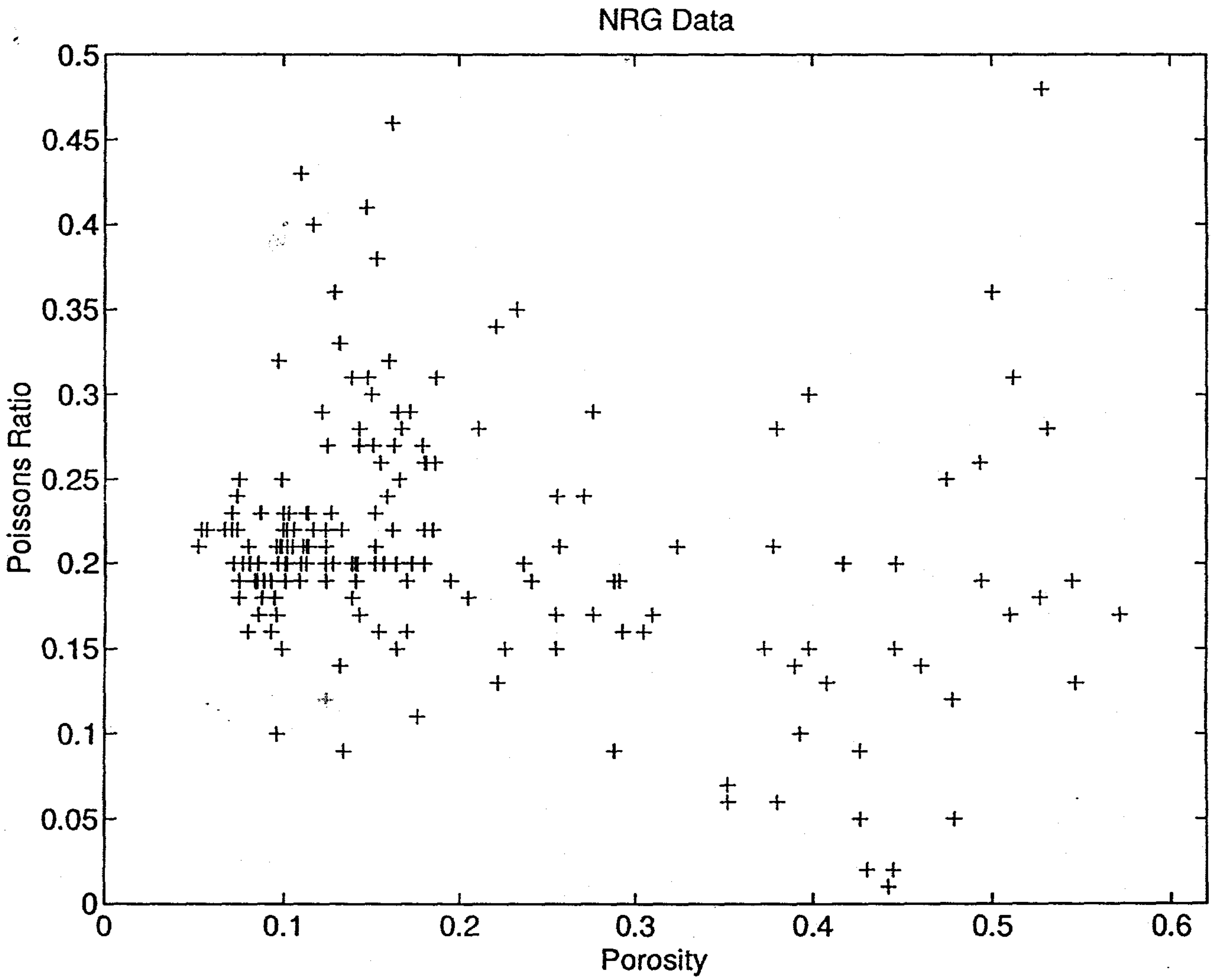
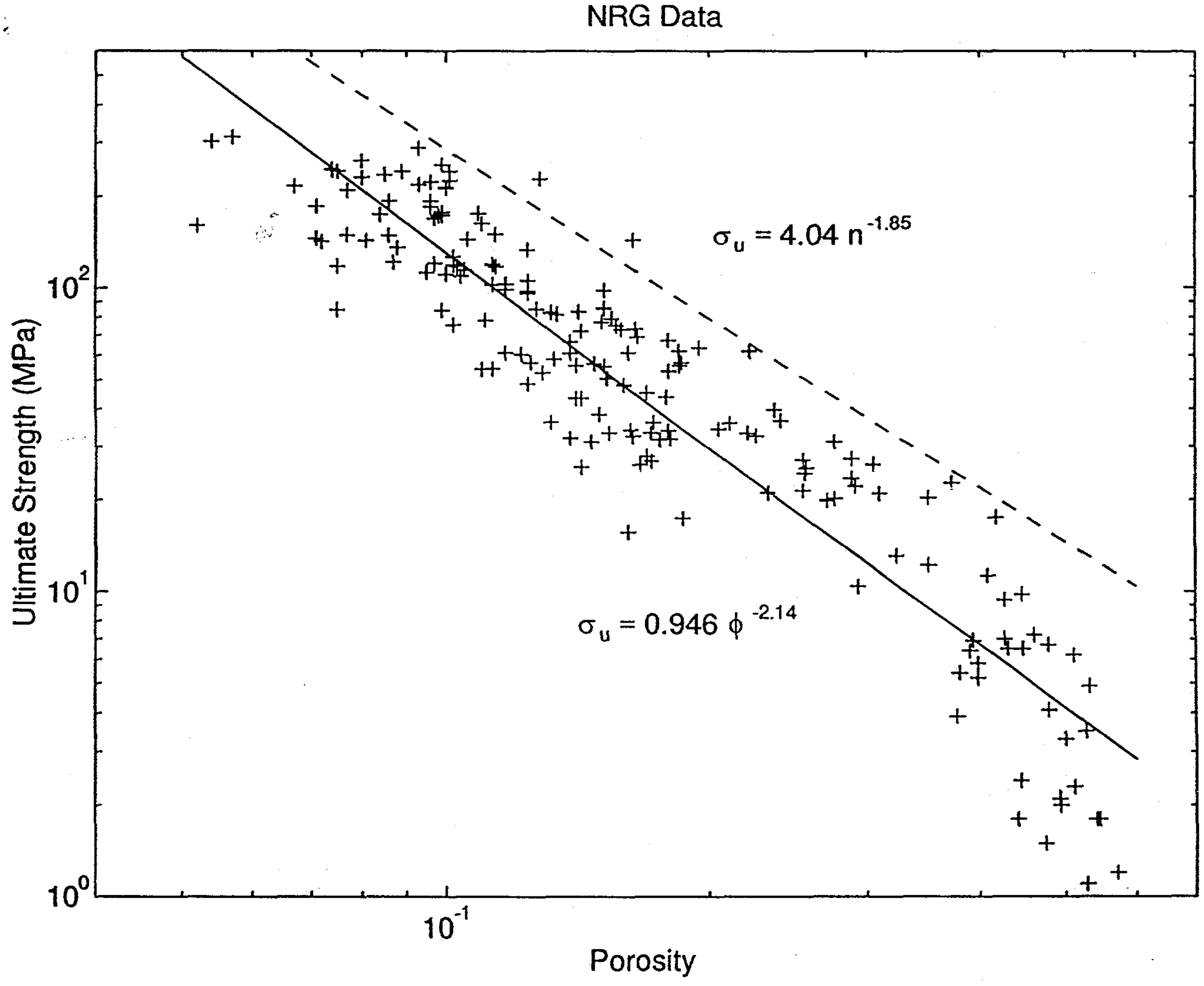

NRG Data
Poissons Ratio
Porosity
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.1
0.2
0.3
0.4
0.5
0.6

FIGURE 2



NRG Data
Ultimate Strength (MPa)
Porosity
σu = 4.04 n-1.85
σu = 0.946 ϕ -2.14
10^2
10^1
10^0
10^-1

FIGURE 3

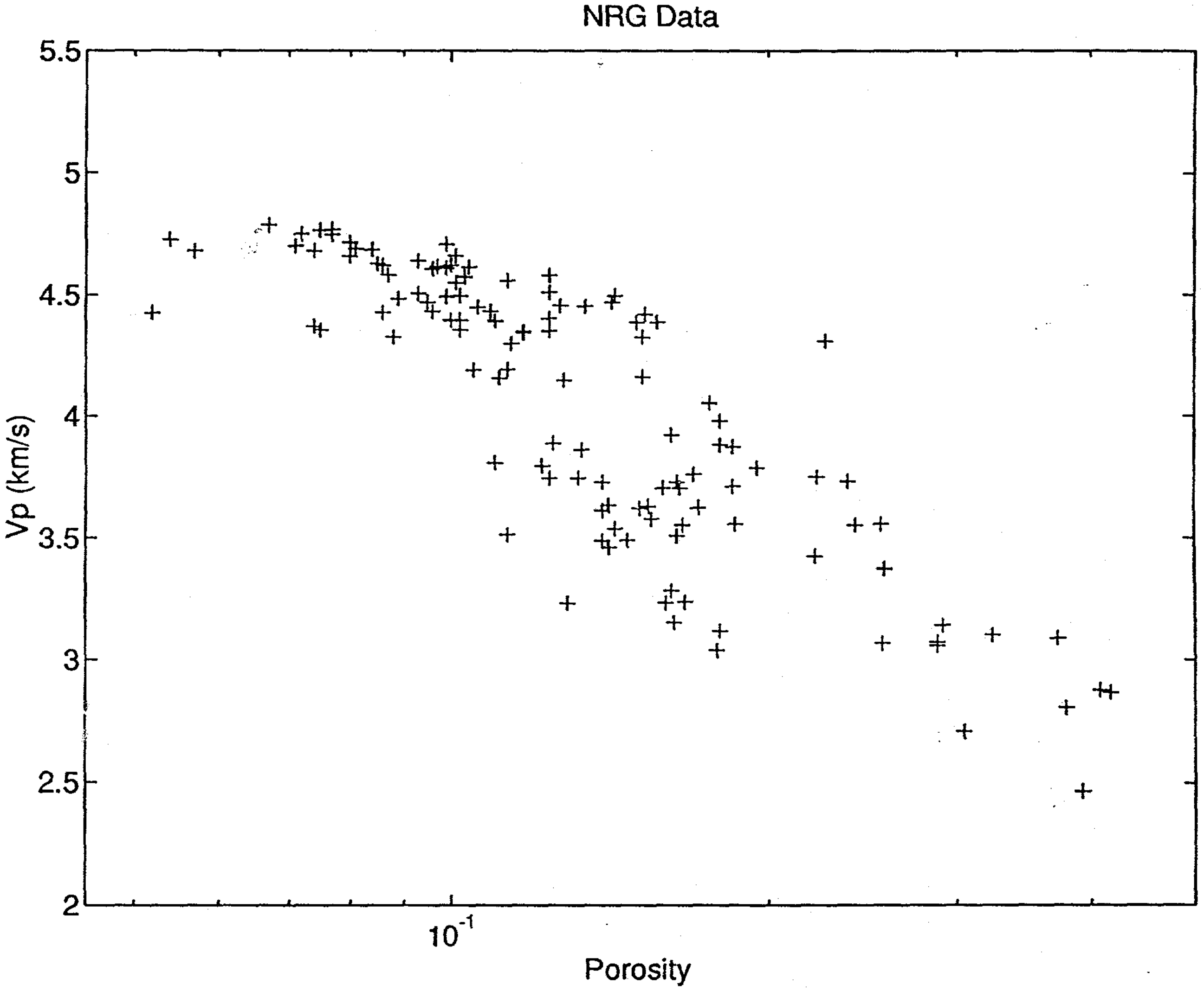


FIGURE 4

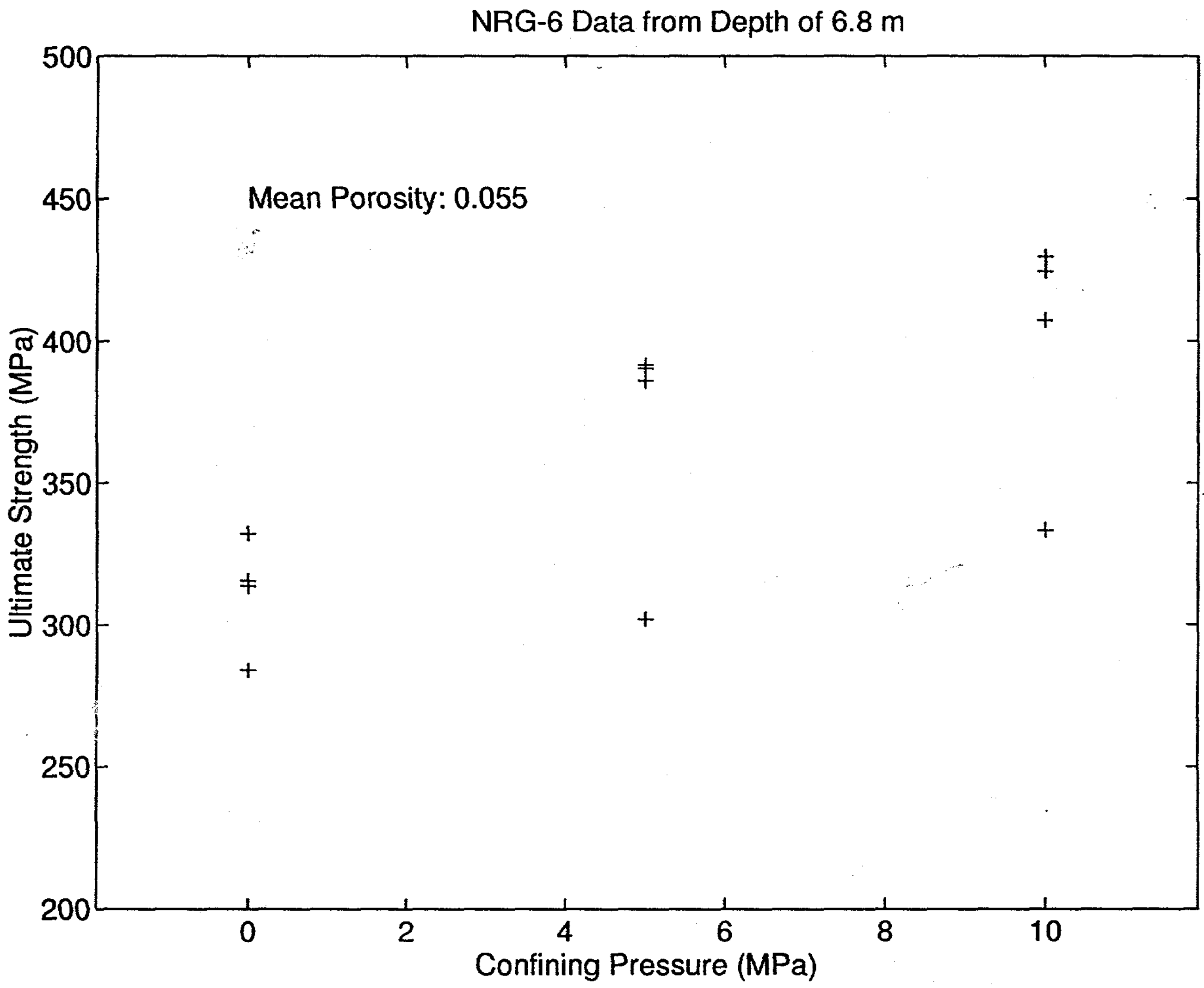

NRG-6 Data from Depth of 6.8 m
Mean Porosity: 0.055
Ultimate Strength (MPa)
500
450
400
350
300
250
200
0
2
4
6
8
10
Confining Pressure (MPa)

FIGURE 5

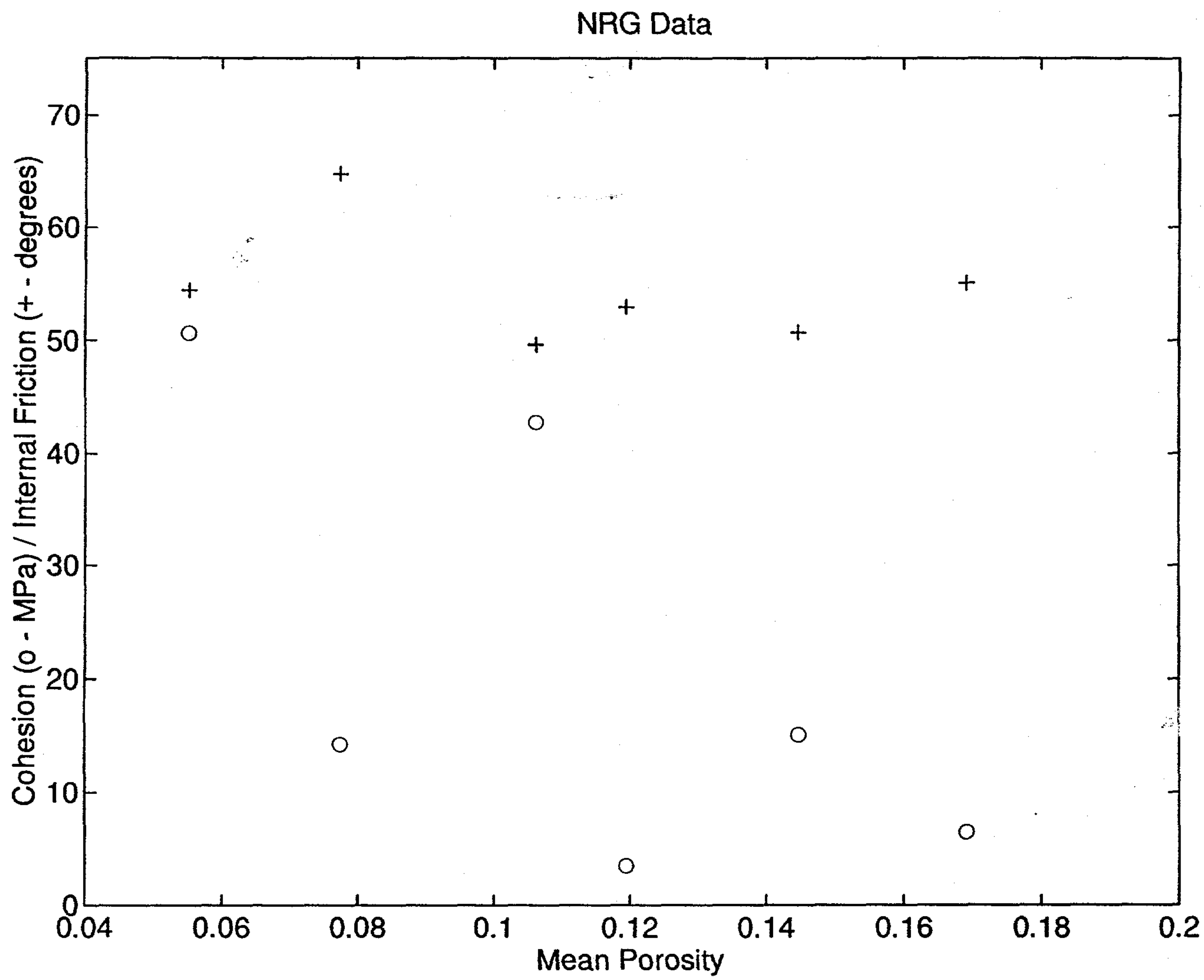

NRG Data
Cohesion (o - MPa) / Internal Friction (+ - degrees)
Mean Porosity
0
10
20
30
40
50
60
70
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

FIGURE 6

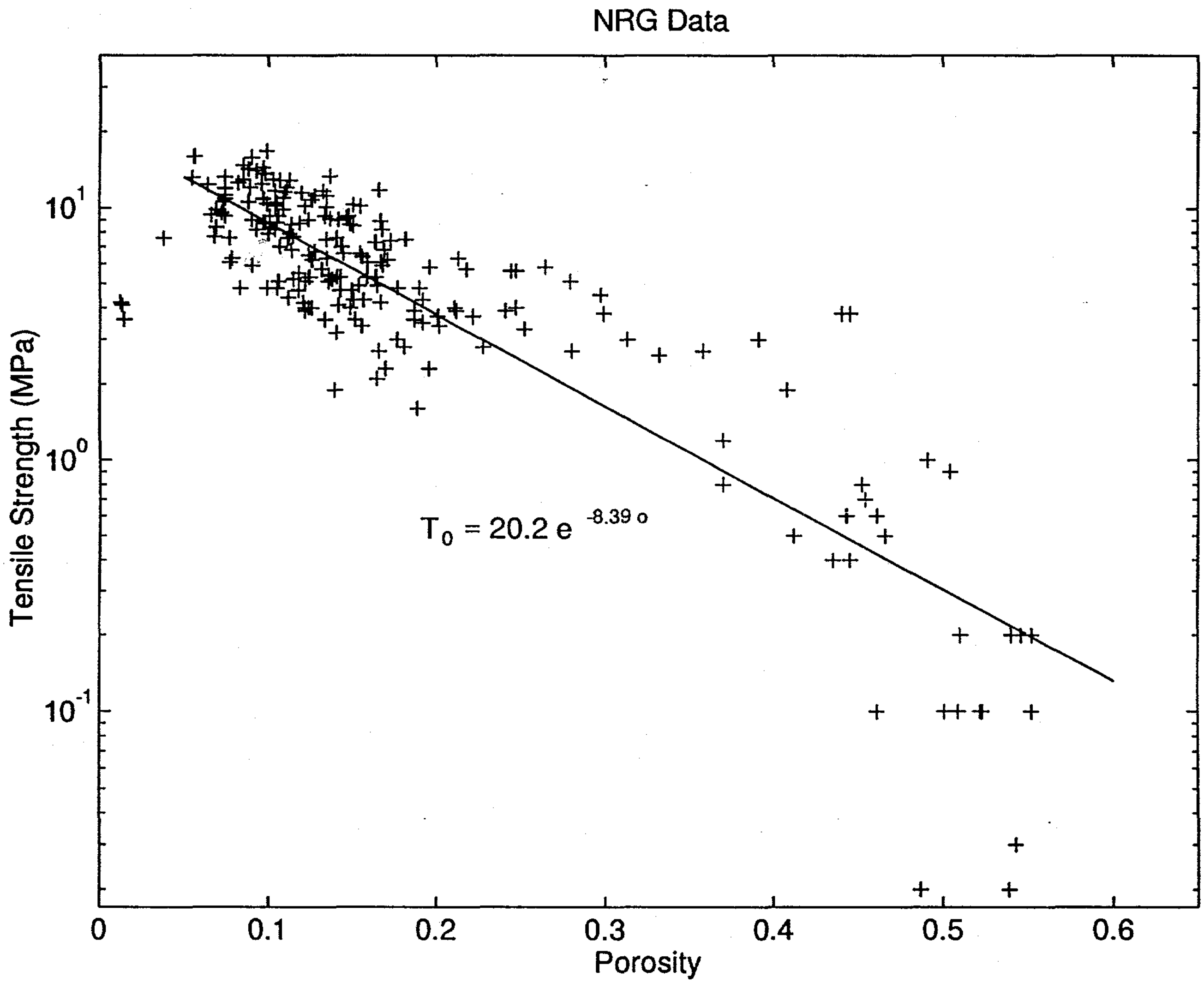

NRG Data
Tensile Strength (MPa)
Porosity
$T_0 = 20.2\ e^{-8.39\ o}$
10^1
10^0
10^-1
0
0.1
0.2
0.3
0.4
0.5
0.6

FIGURE 7