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CORRELATION OF ULTRASONIC VELOCITY AND ROCK STRENGTH

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January 12, 1983

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Livermore
Laboratory

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

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CORRELATION OF ULTRASONIC VELOCITY AND ROCK STRENGTH

ABSTRACT

Ultimate strength and shear wave velocity of dry, 50% saturated, and saturated Paintbrush tuff samples from the Nevada Test Site (NTS) are measured as a function of pressure up to 400 MPa. A linear relationship exists between the ultimate strength (τ) and shear modulus (μ) for the dry tuff at pressures from 0.1 to 20 MPa and from 100 to 300 MPa, with values of $d\tau/d\mu$ of about 1.25×10^{-2} and 2.6×10^{-2} , respectively. At pressures between 20 and 100 MPa a linear relationship also exists with a much greater value of $d\tau/d\mu$, of about 9.9×10^{-2} . For the half-saturated tuff, under undrained testing conditions, a similar linear relationship exists at pressures up to 20 MPa. At pressures between 20 and 300 MPa the data of the partially saturated tuff have too much scattering to deduce a meaningful relation. No such correlation can be found for the saturated tuff sample under undrained testing conditions. If similar relations could be found for other rock types and under other controlled experimental conditions, such as at a fixed pore fluid pressure (drained test) or temperature, then the results would be very valuable for the estimation of the in situ strength of rock masses.

INTRODUCTION

Mechanical properties of rock such as ultimate strength and moduli are among the essential input data to model studies which seek to understand the response of a ground medium to a designed loading. One of the applications where accurate prediction of rock behavior is necessary involves the complete containment of an underground nuclear explosion. Although mechanical properties of rock samples can be determined in the laboratory, there are cases for which rock samples from a test site cannot be obtained for laboratory measurement. One example is that case where one might wish to monitor underground nuclear test activity of a foreign country. In the case of our domestic test program, the in situ ultimate strength of the rock mass

at a potential site for device testing has to be estimated from laboratory-measured data and remote or nondestructive techniques, such as seismic exploration.

The purpose of this study is to ascertain if there is a useful correlation of laboratory-determined mechanical properties--especially the ultimate strength and the ultrasonic wave velocity of rocks. If a correlation of ultimate strength and ultrasonic velocity could be established for a particular rock type, the in situ ultimate strength of that rock type could be estimated from the field seismic velocity data obtained by other geophysical methods. Correlations of ultimate strength and seismic velocity for a family of rock types can provide an estimate of the bounds of in situ ultimate strength of a medium petrologically comparable to the rock types studied. They can also provide an estimated average in situ ultimate strength of a rock mass consisting of a mixture of the rock types studied.

Imai et al.¹ reported a linear relation between dynamic shear modulus and ultimate strength from data for fill clay, alluvial clay, alluvial peat, Kanto loam, diluvial clay, and Tertiary mudstone. Schock² summarized the velocity and ultimate strength data of several rock types at 0.1 MPa, including granite, carbonates, sandstone, shale, and tuff. He demonstrated that the unconfined shear strength could be estimated to within a factor of 2 by using shear modulus, if rock type and density were known. However, Schock stated that for the low-strength tuffs the strength cannot be estimated to better than a factor of 10. The ultimate strength of Devonian shale, measured by Heard,³ and dynamic shear modulus, determined by Lin,⁴ also show a linear relationship.

In this study, we have measured the ultimate strength and ultrasonic shear wave velocity of Paintbrush tuff from Area 12, NTS, as a function of confining pressure to 0.3 GPa. We present a correlation of the ultimate strength and the dynamic shear modulus calculated from shear wave velocity data.

ROCK DESCRIPTION AND SAMPLE PREPARATION

The Paintbrush tuff used in this study is a well-consolidated ash-fall tuff from Area 12, NTS. Minerals in the rock, determined by x-ray analysis,

are clinoptilolite, quartz, potassium and sodium feldspar, and cristobalite.⁵ The grain size distribution of the tuff ranges from very fine (about 0.1 mm) to about 2 mm. The dry bulk density of the samples range from 1.374 to 1.508 Mg/m³. These densities are consistent with those reported by Brethauer et al.⁶ The averaged grain density is about 2.5 Mg/m³ (Ref. 7). This is in good agreement with that reported by Brethauer. The total porosity of the Paintbrush tuff is about 40%.

Right cylinder samples 1.9 cm in diameter were cored from blocks of Paintbrush tuff outcrops in Area 12 of NTS. The cylinders were cut into sections with lengths of about 4.0 cm for the determination of ultimate strength, and 2.5 cm for the ultrasonic shear wave velocity measurement. The two ends of each sample were ground parallel to within 0.02 mm.

The samples were then dried in a vacuum oven at 30°C until their weight remained essentially unchanged for one day. The dry bulk density was calculated from this weight and the sample dimensions. In our experiments, we used samples with three different water contents: dry, 50% saturated (by weight), and 100% saturated. To prepare the wet samples, we immersed the dry samples in water at a confining pressure of about 0.7 MPa for one or two days. The saturated samples were then weighed to get saturated density. The samples to be tested as 100% saturated were then kept in water until testing. The samples to be tested as 50% saturated by weight were then air dried until the proper weight was obtained.

The samples for measuring ultimate strength were encapsulated in a tygon jacket of 0.32-cm wall thickness with hardened steel end pieces at each end of the sample. A pair of PZT shear wave ultrasonic transducers, with a natural frequency of 1 MHz, were mounted at the ends of the samples for the determination of shear wave velocity. The rock-transducer assemblies were then encapsulated in Scotch cast (Schock et al.⁸).

EXPERIMENTAL PROCEDURES

In this study, the ultimate strength and ultrasonic wave velocity were determined separately. The experimental procedures for measuring ultimate strength and ultrasonic wave velocity have been reported elsewhere.⁸⁻¹⁰ Briefly, to measure the ultimate strength of rock at various confining

pressures, the jacketed sample is placed in a pressure vessel in contact with an internal load cell. The confining pressure in the pressure vessel is independently controlled by an intensifier and maintained constant during a test. Axial load is applied to the sample by a piston inserted into the ascending pressure vessel. We use an X-Y recorder to record the axial load and the axial displacement of the piston as measured with a linear potentiometer. Shear stress is determined by dividing the axial load by the cross sectional area of a sample at the confining pressure at which the sample is tested (using the compression data shown in Table 1). To calculate the ultimate strength of a sample the maximum load on the load-vs-displacement curve is used when a sample exhibits brittle failure. When a sample exhibits ductile deformation and work hardening is present, we arbitrarily assign the shear stress at a permanent shortening of 5% as the ultimate strength of the sample. The ultimate strength of a sample is then further corrected for the changing of the cross section area due to shortening, assuming that the sample has undergone constant-volume deformation before failure. For the wet samples, no drainage is provided for water during the loading period.

To determine the shear wave velocity under pressure, the sample assembly in Scotch cast is placed in a piston-cylinder vessel with confining pressure

Table 1. Estimated volumetric compression, $(-\Delta V/V_0)$, length correction (Fl), and density correction (Fd) of Paintbrush tuff.

Pressure (MPa)	$(-\Delta V/V_0)$ (%)	Fl	Fd
0.1	0	1.0	1.0
2.5	0.12 ^a	0.9996	1.0012
5.0	0.20 ^a	0.9993	1.0020
10.0	0.48 ^a	0.9984	1.0048
20.0	0.96 ^a	0.9968	1.0097
40.0	2.0	0.9932	1.020
60.0	3.4	0.9889	1.035
80.0	4.8	0.984	1.050
100.0	6.0	0.980	1.064
150.0	7.0	0.977	1.075
200.0	7.8	0.974	1.085
250.0	8.0	0.973	1.087
300.0	8.9	0.970	1.098
350.0	9.4	0.9687	1.104
400.0	9.96	0.967	1.111

^a Measured value.

generated by an advancing piston. A manganin coil, calibrated against a 0.7-GPa Heise gauge, is used to measure the confining pressure. The travel time of a shear wave pulse is measured by using an oscilloscope and a time-interval counter. The corrected sample length (see below) is divided by the travel time to yield the shear wave velocity of the sample at various pressures. Dynamic shear modulus at pressure is calculated by multiplying the square of shear wave velocity at that pressure by the corrected bulk density (see below) of the same sample.

To correct the effect of compression on the length and density of a sample under pressure we need to know the pressure-volume behavior of the tuff. We have measured the volumetric strain of dry Paintbrush tuff samples, under hydrostatic compression to 30 MPa. For pressure greater than 30 MPa we use the averaged pressure-volume data of Diamond Mine tuff, NTS,¹¹ to estimate the compression of Paintbrush tuff. The Diamond Mine tuff has a porosity of about 33%, which is about 0.8 of that of the Paintbrush tuff. We therefore multiply the volumetric strain data of Diamond Mine tuff by a factor of 1.2 to obtain the estimated volumetric strain of Paintbrush tuff at pressures relevant to this study. Table 1 lists the estimated volumetric strain and the correction factors of sample length (F_l) and density (F_d) of Paintbrush tuff. F_l in Table 1 will be multiplied by the initial sample length to obtain the corrected sample length at pressure. Similarly, F_d multiplies by the bulk density at 0.1 MPa to yield the corrected density at pressure.

EXPERIMENTAL RESULTS

1. Shear Wave Velocity and Dynamic Shear Modulus

Typical corrected shear wave velocity (V_s) of a dry Paintbrush tuff sample is shown as a function of confining pressure in Fig. 1. At pressures below 20 MPa the shear wave velocity increases rapidly with pressure, similar to that of rock with narrow grain boundary microcracks. At pressures between 20 and 60 MPa the shear wave velocity becomes constant or even decreases with increasing pressure. At pressures above 60 MPa, the velocity again increases with pressure similar to that of a low porosity solid. Upon unloading from 400 MPa, the velocity at pressure remains greater than that observed for

Figure 1. Corrected shear wave velocity (V_s) of a dry Paintbrush tuff as a function of confining pressure (P).

loading at all pressures down to about 25 MPa. When pressure is released below 20 MPa the shear wave velocity drops to a value below the initial value. The differences in loading-unloading behavior are almost certainly due to permanent crush-up (lowering porosity) of the tuff. At the lowest pressure, separation of grains occurs. When a sample is removed from its cast after a run, it is completely disintegrated.

The corrected shear wave velocity and the calculated dynamic shear modulus of all of the dry Paintbrush samples studied are summarized in Table 2. Although the velocity data at pressures greater than 100 MPa are obtained from samples with smaller dry bulk density, the effect of density on velocity is not significant.

Figure 2 shows one typical example of the corrected shear wave velocity for the Paintbrush tuff samples containing 50% water saturation as a function of confining pressure. To correct the sample length due to compression we arbitrarily assume that the 50% water-saturated sample has about half the volumetric strain of the dry sample under pressures up to 400 MPa. This

Table 2. Corrected shear wave velocity (V_S) and dynamic shear modulus (μ) of dry Paintbrush tuff as a function of pressure.

Pressure (MPa)	$V_S \pm 1 \text{ sd}$ (km/s)	Density $\pm 1 \text{ sd}$ (Mg/m ³)	$\mu \pm 1 \text{ sd}$ (GPa)	No. of samples
0.1	1.598 $\pm$ 0.046	1.508 $\pm$ 0.009	3.855 $\pm$ 0.238	4
2.5	1.644 $\pm$ 0.043	1.510 $\pm$ 0.009	4.081 $\pm$ 0.225	4
5.0	1.684 $\pm$ 0.043	1.511 $\pm$ 0.009	4.285 $\pm$ 0.226	4
10.0	1.726 $\pm$ 0.042	1.515 $\pm$ 0.009	4.513 $\pm$ 0.233	4
20.0	1.756 $\pm$ 0.041	1.523 $\pm$ 0.009	4.696 $\pm$ 0.245	4
60.0	1.747 $\pm$ 0.035	1.561 $\pm$ 0.009	4.764 $\pm$ 0.218	4
100.0	1.757 $\pm$ 0.028	1.605 $\pm$ 0.009	4.955 $\pm$ 0.180	4
100.0	1.787 $\pm$ 0.035	1.518 $\pm$ 0.005	4.848 $\pm$ 0.167	3
150.0	1.912 $\pm$ 0.034	1.534 $\pm$ 0.005	5.608 $\pm$ 0.170	3
200.0	2.025 $\pm$ 0.031	1.548 $\pm$ 0.005	6.349 $\pm$ 0.158	3
250.0	2.106 $\pm$ 0.009	1.551 $\pm$ 0.005	6.879 $\pm$ 0.030	3
300.0	2.176 $\pm$ 0.004	1.557 $\pm$ 0.005	7.372 $\pm$ 0.026	3

Figure 2. Corrected shear wave velocity (V_s) of a 50% saturated Paintbrush tuff as a function of confining pressure (P).

Figure 3. Shear wave velocity (V_s) of a saturated Paintbrush tuff as a function of confining pressure (P).

assumption is based on the reasoning that pore fluid pressure may play some role at pressures greater than 100 MPa (see next section). The shear wave velocity shown in Fig. 2 may be under-corrected, but the difference is no more than 1 to 2%. Figure 2 indicates a variation of v_g with respect to pressure similar to that shown in Fig. 1. On the 50% saturated sample, however, the velocity increases much more slowly with increasing pressure than does the dry sample at pressures greater than 100 MPa. Figure 2 also shows a much smaller velocity than that of Fig. 1 even though these two samples have similar dry bulk densities. This is probably due to the increase in density due to saturation, whereas the shear modulus of a sample is little affected.

The corrected shear wave velocity and dynamic shear modulus of the 50% saturated Paintbrush tuff are summarized in Table 3. Here the values of μ are calculated by using the corrected wet density of the samples. At pressures higher than 100 MPa, the much greater standard deviations of shear wave velocity and dynamic shear modulus are due to the wide range of density of the three samples used in the tests.

The shear wave velocity of a Paintbrush tuff sample 100% saturated with water is shown in Fig. 3 as a function of confining pressure. Compaction of the saturated sample under these pressures is probably small because of the nature of the test (undrained). No correction is made to the velocity and density of this sample. The saturated sample appears to have a smaller velocity than for the dry and half-saturated samples. The variation of velocity with pressure is also less for the saturated sample than for the others. However, at high pressure, the increase in velocity with increasing pressure seems to indicate that compaction occurs in some isolated cavities which are not initially saturated (Fig. 3).

Table 4 shows the shear wave velocity and the dynamic shear modulus of the saturated sample. The values for μ of the saturated sample change very little in the pressure range from 4.6 to 100 MPa.

2. Ultimate Strength

The ultimate strength ($\tau = (\sigma_1 - \sigma_3)/2$, where σ_1 is the axial stress; σ_3 is the confining pressure) of dry Paintbrush tuff is shown in Fig. 4 as a function of confining pressure. Similar to the shear wave velocity shown in Fig. 1, the ultimate strength increases rapidly with

Table 3. Corrected shear wave velocity (V_s) and dynamic shear modulus (μ) of 50% saturated Paintbrush tuff as function of pressure (P).

P (MPa)	$V_s \pm 1 \text{ sd}$ (km/s)	Wet density $\pm 1 \text{ sd}$ (Mg/m ³)	$\mu \pm 1 \text{ sd}$ (GPa)	No. of samples
0.1	1.493 $\pm$ 0.064	1.641 $\pm$ 0.007	3.667 $\pm$ 0.303	5
2.5	1.555 $\pm$ 0.040	1.642 $\pm$ 0.007	3.969 $\pm$ 0.204	5
5.0	1.576 $\pm$ 0.039	1.643 $\pm$ 0.007	4.079 $\pm$ 0.20	5
10.0	1.591 $\pm$ 0.040	1.645 $\pm$ 0.007	4.160 $\pm$ 0.209	5
20.0	1.599 $\pm$ 0.040	1.649 $\pm$ 0.007	4.202 $\pm$ 0.211	5
40.0	1.549 $\pm$ 0.050	1.657 $\pm$ 0.007	3.945 $\pm$ 0.255	5
60.0	1.578 $\pm$ 0.024	1.670 $\pm$ 0.007	4.090 $\pm$ 0.130	5
80.0	1.654 $\pm$ 0.019	1.682 $\pm$ 0.007	4.492 $\pm$ 0.117	5
100.0	1.729 $\pm$ 0.016	1.694 $\pm$ 0.007	4.899 $\pm$ 0.096	4
100.0	1.597 $\pm$ 0.140	1.688 $\pm$ 0.44	4.238 $\pm$ 0.842	3
200.0	1.643 $\pm$ 0.134	1.706 $\pm$ 0.44	4.480 $\pm$ 0.848	3
250.0	1.671 $\pm$ 0.110	1.707 $\pm$ 0.44	4.620 $\pm$ 0.750	3
300.0	1.699 $\pm$ 0.091	1.716 $\pm$ 0.44	4.759 $\pm$ 0.639	3

Table 4. Shear wave velocity (V_s) and dynamic shear modulus (μ) of saturated Paintbrush tuff as function of pressure (P).

P (MPa)	V_s (km/s)	Wet density (Mg/m ³)	μ (GPa)	No. of tests
0.1	1.166	1.791	2.435	1
4.6	1.329	1.791	3.163	1
10.0	1.364	1.791	3.332	1
15.9	1.366	1.791	3.342	1
20.0	1.333	1.791	3.182	1
41.1	1.333	1.791	3.182	1
60.7	1.360	1.791	3.313	1
100.0	1.398	1.791	3.500	1
200.0	1.487	1.791	3.960	1
300.0	1.606	1.791	4.619	1

Figure 4. Ultimate strength (τ) of dry Paintbrush tuff as a function of confining pressure (P).

increasing confining pressure at pressures less than 20 MPa. The increase of τ with σ_3 decreases somewhat when σ_3 lies between 20 and 60 MPa. But at higher pressures, τ again increases rapidly with σ_3 . The behavior of Paintbrush tuff is similar to that of Diamond Mine and Diamond Dust tuff.^{11,12} The deformation mode of the rock changes from brittle failure, at low pressure, to ductile deformation at a pressure between 10 and 20 MPa.

When the Paintbrush tuff is 50% saturated, the ultimate strength (Fig. 5) shows behavior similar to that shown in Fig. 4, but with a somewhat lower value of τ , at pressures below 100 MPa. At greater pressures, however, τ of the 50% saturated tuff (Fig. 5) is much smaller than that of a dry tuff. At these pressures, the tuff exhibits much more scattered results in ultimate strength. The brittle-to-ductile transition of the 50% saturated tuff occurs at a pressure of about 10 MPa, slightly less than that of a dry sample.

Figure 6 shows the relation between the ultimate strength and confining pressure of fully saturated Paintbrush tuff. The value for τ of saturated tuff is essentially unchanged with respect to pressure and is much weaker than the dry and half-saturated tuff. The rock shows brittle failure at all pressures investigated. It is apparent that the pore pressure in the wet samples increases to near the confining pressure for confining pressures greater than ~60 MPa.

3. Correlation of Ultimate Strength and Dynamic Shear Modulus

Figure 7 shows the plot of τ vs μ of the dry Paintbrush tuff. In this figure, each point is a value of μ from Table 1 and τ from Fig. 4 at the same pressure. The error bars associated with each point in Fig. 7 are the one standard deviation of μ and scattering of τ . We see from Fig. 7 that the data can be fitted with three straight line sections corresponding to pressures of below 20 MPa, 20 to 100 MPa, and above 100 MPa. The slopes of these three straight lines indicate a $d\tau/d\mu$ of about 1.25×10^{-2} for pressures below 20 MPa, 9.9×10^{-2} for pressures between 20 and 100 MPa, and 2.53×10^{-2} for pressures above 100 MPa.

For the Paintbrush tuff with 50% saturation, we plot in Fig. 8 the values of μ from Table 2 with the τ from Fig. 5 at the same pressure. At pressures below 20 MPa there is still a linear trend between τ and μ of the wet

Figure 5. Ultimate strength (τ) of 50% saturated Paintbrush tuff as a function of confining pressure (P).

Figure 6. Ultimate strength (τ) of saturated Paintbrush tuff as a function of confining pressure (P).

Figure 7. Correlation between ultimate strength (τ) and shear modulus (μ) of dry Paintbrush tuff.

Figure 8. Correlation between ultimate strength (τ) and shear modulus (μ) of 50% saturated Paintbrush tuff.

Figure 9. Correlation between ultimate strength (τ) and shear modulus (μ) of saturated Paintbrush tuff.

Paintbrush tuff. This line represents a $d\tau/d\mu$ of about 6.3×10^{-3} . At higher pressures, due to the wide scattering of the data points, no linear relation can be established between τ and μ .

Figure 9 shows a similar plot of τ and μ of the 100% saturated Paintbrush tuff at various pressures up to 300 MPa. No obvious relations can be found between τ and μ for these rock samples. This is due to the large effects of pore fluid pressure upon both τ and μ .

DISCUSSION AND CONCLUSIONS

The results of this study indicate that a linear relation can be established between τ and μ of dry and 50% saturated Paintbrush tuff at confining pressures below 20 MPa. A similar relation can be found for the dry tuff at pressures above 100 MPa. No such relation can be found for 50% saturated tuff, at pressures greater than 60 MPa, or for saturated tuff at all pressures when tested under undrained conditions. At pressures between 20 and 100 MPa, a linear relationship between τ and μ may still exist for the dry tuff but the line is almost vertical (Fig. 7). This may be attributed to the creation of secondary cracks due to the collapsing of voids in the sample. This argument is also supported by the apparent weakening of the samples in the pressure range of 20 to 60 MPa. For the 50% saturated tuff samples at pressures above 20 MPa, the shear modulus decreases with increasing pressure, to a pressure of 60 MPa, then rises slowly with pressure. This is probably due to the same mechanism as that for the dry samples. At pressures above 100 MPa the irregular variation of ultimate strength of the half-saturated tuff samples with respect to pressure is probably due to the effect of pore pressure.

It is obvious that for a more complete understanding of the subject as well as for increased usefulness of wave velocity as a quantitative predictive tool, more work should be done on other rock types and other experimental conditions, such as a drained test for partially saturated and saturated rock samples, control of pore fluid pressure, and temperature. By so doing and if linear relations could also be established for a wider range of rock types, then the result could be extremely valuable to the solving of various geophysical and engineering problems. It is understood that a relationship

between field seismic velocity and laboratory ultrasonic wave velocity has to be established.

In order that the seismic velocity sounding can be used to estimate the in situ ultimate strength of a rock mass (assuming that the relation between these two properties is known), we are still dependent upon the resolution of field shear wave velocity measurements. The Paintbrush tuff that we studied shows an increase of shear wave velocity for only about 10% in the range of pressure (0.1 to 20 MPa) where τ and μ have useful linear relations. A rather high resolution power is needed in the field shear wave velocity measurement to obtain useful strength data. King and Paulsson¹³ recently reported that borehole acoustic velocity logs in granitic rocks can provide determinations of compressional and shear wave velocities to $\pm 0.3\%$. If these resolutions could be accomplished for this tuff, then values for τ could be estimated to $\pm 15\%$.

ACKNOWLEDGMENTS

This work was supported by the Containment Program of LLNL. The author is grateful for critical comments by H. Heard, W. Durham, M. Costantino, and B. Bonner. L. McKague helped arrange the x-ray analysis of mineral composition. C. Slettvoll determined the grain density of the tuff sample.

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