LABORATORY MEASUREMENTS OF ATTENUATION IN ROCKS AT ULTRASONIC FREQUENCIES

by

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ABSTRACT

The spectral ratio method is used to calculate the quality factor (Q) in porous rock samples at ultrasonic frequencies (0.3 - 1.5 MHz). The data were collected using the pulse transmission technique with aluminum used as a high Q standard. The data set consists of dry, water and benzene saturated rocks at differential pressures from zero to one kilobar. Two sandstones, Berea and Kayenta, Bedford limestone, and Webatuck dolomite are studied. Water and benzene were chosen as pore fluid saturants to contrast the effects of two different pore fluids (density, compressibility, viscosity, dielectric constant, and wetting properties) at ultrasonic frequencies. The main features observed are: 1) The quality factor Q increases with increasing confining pressure; at low pressures the rate of increase is larger. 2) Q for saturated samples is generally lower than for dry samples. 3) The introduction of a fluid saturant into a dry rock increases S-wave attenuation more than P-wave attenuation. 4) In general, given the measurement error and the fact that these results are preliminary, the differences in attenuation between the two fluid saturations, water and benzene, are not large. Nevertheless, we observe that benzene-saturated attenuations are slightly higher than water-saturated values, particularly at lower pressures (less than 500 bars) for the P-wave.

INTRODUCTION

The contribution of pore fluid to attenuation in rocks has been a subject of interest and intensive study (Bulau et al., 1984; Murphy, 1982; Spencer, 1981; Winkler and Nur, 1979; Mavko and Nur, 1979; Johnston et al., 1979; Johnston and Toksöz, 1980; O'Connell and Budiansky, 1977; Biot, 1956a,b; Wyllie et al., 1962).

Pore fluid can contribute to attenuation in many ways: inertial decoupling, pressure induced flow; viscoelastic relaxation; local flow between adjacent pores ("squirt flow"); and wetting of grain surfaces that can contribute to chemical and physical attenuation mechanisms. Although these mechanisms have been studied extensively, neither the experimental data nor the theoretical studies have been able to determine quantitatively the relative significance of different mechanisms (see summary in Toksöz and Johnston, 1981). Attenuation in fully or partially saturated rocks is greater than attenuation in dry rocks. For dry rocks, attenuation (Q⁻¹) varies by orders of magnitude whether the rock is "air dry" (containing at least a monolayer of water) or totally outgassed by high-vacuum and thermal pulsing.
Gonguet et al.

(Pandit and King, 1979; Clark et al., 1980). These data confirm the role of water on the scale of monolayer thicknesses.

Going from air-dry to fully fluid saturated case, attenuation increases (Johnston et al., 1980; Toksöz et al., 1979; Winkler and Nur, 1979). The largest effect of saturation occurs in $Q_s'$. In the air-dry case $Q_p' \approx Q_s$ and in fully saturated case $Q_s < Q_p'$. Partial saturation may reduce $Q_p'$ relative to full saturation, but this effect is generally small (Winkler and Nur, 1979; Johnston and Toksöz, 1980; Frisillo and Stewart, 1980).

There is little experimental data on attenuation with fluids other than water and brine. Wyllie et al., (1962) measured resonant bar attenuation in alundum rods (25% porosity) saturated with soltrl and water and found that attenuation was lower with soltrl saturation. Nur and Simmons (1969) measured the relative change in ultrasonic signal amplitudes transmitted through glycerin- and water-saturated Barre granite as a function of temperature and concluded that a resonant peak existed as a function of fluid viscosity. Spencer (1981) measured the low-frequency phase-lag between stress and strain in Navajo sandstone with a sequence of different fluids and correlated increasing attenuation with larger reductions in surface free energy of silica when immersed in the various fluids, with water being the highest. Bulau et al., 1984, measured resonant bar attenuation with water and iso-octane and noted that attenuation with water was higher.

To evaluate whether water versus another type of liquid pore fluid affects ultrasonic attenuation significantly, we made a systematic study of the dynamic bulk and shear moduli, $(K, \mu)$, and the quality factors, $Q_p$ and $Q_s$, in dry, water- and benzene-saturated rock samples. Measurements are made over a hydrostatic confining pressure range up to 1 kbar. Rock samples include sandstones (Berea and Kayenta), a limestone (Bedford) and a dolomite (Webatuck). The measurements are made at ultrasonic frequencies (200-1500 kHz).

The effects of water versus benzene on P- and S-wave velocities and dynamic and shear moduli are discussed elsewhere in this report (Coyner and Cheng). In short, the differences between velocity measurements with benzene and water are not easily interpreted strictly on the basis of density, compressibility, or viscosity differences. At low pressures water-saturated P- and S-wave velocities are higher than benzene-saturated values. At high pressures (greater than about 300 to 500 bars) in the sandstones the water-saturated velocities tend to fall below the benzene-saturated values. Conversion of velocities into dynamic shear and bulk moduli as a function of pressure indicates that the effect is concentrated in the shear modulus. Water-saturated bulk moduli are consistently higher than benzene-saturated values while water-saturated shear moduli, initially slightly higher at low pressures, fall below benzene-saturated values and even the dry shear moduli at higher pressures. In this paper a portion of the signal waveforms collected by Coyner (1984) were analyzed for P- and S-wave ultrasonic attenuation with the hope that a similar effect would be measured. Contrary to what was expected, benzene-saturated attenuation is higher than with water, particularly at low pressures for the P-wave. At high pressures water-saturated attenuation tends to be slightly higher although the amount is on the order of experimental error.
ATTENUATION MEASUREMENTS

In this study we determine attenuation of P- and S-waves using ultrasonic pulse transmission and the spectral ratio method. In this method, a jacketed sample is placed in the pressure vessel with source and receiver transducer attached. The sample is cylindrical, 5.08 cm (2 inches) long by 7.62 cm (3 inches) diameter. The source and receiver piezoelectric crystals are contained within a titanium alloy housing. Details can be found in Coyner (1984).

Ultrasonic P- and S-wave signals are propagated through cylindrical cores or rock. An aluminum cylinder, same size as the sample, is used as a high-Q standard for calculation of the spectral ratio. Center frequencies of the signals are approximately 400 to 850 KHz depending on pressure and sample. Temperatures are laboratory ambient. Confining pressures are systematically cycled up to levels of 1000 bars and pore pressures are either vacuum (20 μm Hg) or 100 bars for the benzene and water saturations. The difference between confining and pore pressures is taken to be the "effective" pressure in determining attenuation. Each sample was first measured vacuum dry over a cycle of confining pressure, then saturated with benzene reagent (100 bars) and again measured over a cycle of confining pressure. Samples were then removed from the sample apparatus, soaked and washed with acetone, and dried for at least 24 hours in a vacuum at 80°C. Next the sample was rejacketed, measured dry again as a check for repeatability, and then measured over a cycle of confining pressure after saturating with water at 100 bars pore pressure.

Attenuation values were determined using the spectral ratio technique (Toksöz et al., 1979). Specially developed transducers provide broadband P- and S-waves. Examples of waveforms for dry, benzene- and water-saturated Kayenta sandstone at 100 bars are shown in Figure 1 and a fit using the spectral ratio is shown in Figure 2.

The experimental procedures used for both the sample and the aluminum reference are similar. Therefore, we have relative measurement of attenuation and such we minimize the effects of the transducer, the coupling between transducer, titanium holders and the sample. The Q of aluminum is about 150,000 (Zemanek and Rudnick, 1961), roughly 3 to 4 orders of magnitude higher than those of rocks in this study, and is constant with frequency (Savage and Hasegawa, 1967).

For plane waves, wave amplitudes can be expressed as:

\[ A_1(f) = G_1(f,x) e^{-\alpha_1(f)x} e^{i(2\pi ft-k_1x)} \]

and

\[ A_2(f) = G_2(f,x) e^{-\alpha_2(f)x} e^{i(2\pi ft-k_2x)} \]

where \( A = \) amplitude, \( f = \) frequency, \( x = \) distance of propagation, \( k = 2\pi f / v = \) wavenumber, \( v = \) velocity, \( G(f,x) = \) a geometrical factor which includes beam spreading. Subscripts 1 and 2 refer to the reference and the rock sample respectively. \( \alpha(f) = \) the attenuation factor and related to Q by
Taking the ratio of amplitudes given by equations (1) and (2) and the natural logarithm of this ratio gives

\[
\ln\left(\frac{A_1}{A_2}\right) - \ln\left(\frac{G_1}{G_2}\right) = (\alpha_2 - \alpha_1)x.
\]

If we assume that \(\alpha\) is a linear function of the frequency, i.e., constant \(Q\), then

\[
\alpha(f) = \gamma f,
\]

where \(\gamma\) is a constant, and

\[
Q = \frac{\pi}{\gamma u}.
\]

We can rewrite (4) as

\[
\ln\left(\frac{A_1}{A_2}\right) - \ln\left(\frac{G_1}{G_2}\right) = (\gamma_2 - \gamma_1)xf.
\]

The term \(\ln(A_1/A_2)\) is the ratio of the spectral amplitudes of the reference to the sample. The term \(\ln(G_1/G_2)\), may be frequency dependent because of beam spreading.

\[
F(f) = (\gamma_2 - \gamma_1)xf,
\]

where \(F(f) = \ln\left(\frac{A_1}{A_2}\right) - \ln\left(\frac{G_1}{G_2}\right)\). Since \(Q\) of the standard is very high, \(\gamma_1\) can be taken equal to 0.

For plane waves the geometric factors \(G_1\) and \(G_2\) have similar frequency dependence, \(\ln(G_1/G_2)\) is independent of frequency. In this experiment the transducer diameter is 2.5 cm (1 inch), and the sample diameter is 7.62 cm. As a result the energy beam spreads and this spreading is dependent on frequency. Seki et al., (1956) and Papadakis (1975) studied the beam spreading problem for a cylindrical source. They found that amplitude decrease due to beam spreading is about 1 db per \(a^2/\lambda\), where \(a\) = source diameter and \(\lambda\) = wavelength. The beam spreading correction is highest at lower pressures where velocities are low and decreases with increasing velocity. Correction to \(Q\) due to spreading is always less than 10 percent and generally within the limits of error. For the preliminary attenuation values in this paper diffraction corrections have not been made. In the analysis of data P- and S-wave pulses are selected visually. The duration of pulses is between 4 and 6 microseconds and in the average correspond to 450 digital samples. The window is tapered by a cosine window (over 10 time samples at each end) and Fourier transformed. The natural log of the amplitude ratios are computed...
versus frequency. Attenuation constant, $\gamma$, is determined over the frequency interval where both the sample and reference spectra have adequate power (i.e. when signal to noise ratio is high). An example of spectra, the ratio, and frequency window over which a least squares linear fit is made are shown in Figure 2. The data quality is good for all samples.

RESULTS

The four samples for which $Q$ values are determined include Kayenta ($\rho=23.1\%$) and Berea ($\rho=17.8\%$) sandstones, Bedford limestone ($\rho=11.9\%$), and Webatuck dolomite ($\rho=0.5\%$). Sample descriptions for all but the Webatuck dolomite are given at in the Appendix of the paper by Coyner and Cheng elsewhere in this report. Webatuck dolomite is a foliated metamorphic dolomite. The properties of the saturating fluids are given in Table I.

In Figure 3 is plotted the calculated P- and S-wave attenuation ($1000/Q$) for dry, benzene-, and water-saturated Kayenta sandstone as a function of the difference between confining and pore fluid pressure. Fluid-saturation increases attenuation for both P- and S-waves. The increase in S-wave attenuation is proportionally larger, however, especially at higher pressures. Attenuation in the benzene saturated sample is higher than for the water saturated case for both the P- and S-waves except at higher pressures (greater than 400 bars) for the S-waves. Attenuation of the P-waves in the benzene-saturated sample is greater than that of the S-waves, particularly at lower pressures (less than about 300 bars).

In order to separate the P-wave attenuation into bulk and shear attenuation (Spencer, 1979) we calculated $Q_E$ and $Q_K$ using observed $Q_P$, $Q_S$, and Poisson's ratio $\nu$ from the velocity data.

$$Q_E = \frac{(1+\nu)}{(1-\nu)(1-2\nu)+2\nu(2-\nu)} \frac{Q_P}{Q_S}$$ (9)

$$Q_K = \frac{(1+\nu)}{3(1-\nu) - 2(1-2\nu)} \frac{Q_P}{Q_S}$$ (10)

with

$$\nu = \frac{u_P^2 - 2u_S^2}{2(u_P^2 - u_S^2)}$$ (11)

The calculated bulk and extensional attenuations versus pressure are shown in Fig. 4. These again show that benzene-saturated rock has the highest attenuation. For bulk attenuation the benzene-saturated values are approximately twice as large as the water-saturated values which are in turn slightly larger than dry.

In Figure 5 is plotted the P- and S-wave attenuations for the dry, benzene-, and water-saturated Berea sandstone as a function of confining pressure. In Figure 6 is
plotted the bulk and extensional attenuations versus pressure. Compared with the Kayenta sandstone, attenuations are lower and the difference between benzene- and water-saturated attenuation smaller. At lower pressures P-wave attenuation for benzene-saturated Berea sandstone is higher than the water-saturated case while S-wave attenuation is only slightly higher at the first two data points. At higher pressures water-saturated attenuation is slightly larger than for benzene for both P- and S-waves. Benzene-saturated bulk attenuation (Figure 6) is larger than for the water-saturated case. Compared with the Kayenta sandstone water-saturated bulk attenuation is proportionally greater than the dry.

In Figure 7 is plotted the P- and S-wave attenuations for the dry, benzene-, and water-saturated Bedford limestone as a function of confining pressure. In Figure 8 is plotted the bulk and extensional attenuations versus pressure. Compared with either of the sandstones the effects of fluid saturation are much less. Benzene-saturated attenuation is only slightly higher than water-saturated for the S-wave and for the P-wave at low pressures.

The important observation in this data is that benzene-saturated attenuation is often higher than in the water-saturated sample, particularly for the P-wave at lower pressures. The reduction of water-saturated shear modulus so apparent in the velocity data for the sandstones is not strongly reflected in the shear attenuation. This contrasts with the resonant-bar results of Bulau et al (1984), where attenuation for iso-octane saturated Coconino sandstone was found to be lower than for the water-saturated sample. An important point to consider is the relative wetting characteristics of benzene versus water on silicate and carbonate surfaces. Even though the standard precautions were taken to ensure complete saturation (vacuum drawn on one end of the sample while fluid saturant introduced at the other end; pore fluid pressure at 100 bars) it is possible that benzene did not fully penetrate and wet the small pore and cracks of the sample, particularly the clay-rich Kayenta sandstone in going from a vacuum dry to fully saturated condition. Therefore an attenuation mechanism which depends on partial-saturation (Mavko and Nur, 1979) may be present. This may explain the higher P-wave attenuation but not the higher S-wave attenuation, which has not been observed in partially-saturated rock at ultrasonic frequencies (Spencer, 1979; Johnston, 1978).

Finally, we consider dry and benzene-saturated attenuation data for Webatuck dolomite (Figures 9 and 10). Velocity and strain data for this rock indicate that cracks are dominant in the porosity distribution. Because of the abundance of fine cracks attenuation decreases rapidly with increasing pressure and reaches very low values at high pressures. P-wave attenuation in the dry rock is higher than in the benzene-saturated rock while the opposite is true for the S-wave attenuation at low pressures (less than about 150 bars). The lower P-wave and bulk attenuation in the benzene-saturated rock may reflect unrelaxed stresses in the fluid at ultrasonic frequencies (O’Connell and Budiansky, 1977; Murphy, 1982). Crack geometry and surface interactions between water and matrix minerals (silica, feldspar and clay versus carbonates) apparently play an important role.

**CONCLUSIONS**

Our preliminary measurements of ultrasonic attenuation for several rocks as a function of pressure for vacuum dry, water and benzene saturated conditions confirm previous observations while raising questions concerning water versus non-aqueous
pore fluid saturants. Our observations show that for the Kayenta and Berea sandstones, benzene-saturated attenuation, in particular for P-wave, is larger than water-saturated attenuation. For the S-wave the same relationship holds although the differences are less. In addition, as pressure increases the differences decrease. Crack geometry and surface interactions between water and matrix minerals (quartz, feldspar, clay, and carbonates) may play an important role in how fluids affect attenuation. Speculations on relative significance of different mechanisms on attenuation must await in depth analysis of all results, including data from other rocks.

Table 1

Comparison of water and benzene properties:

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<td>kbar</td>
<td>12.1</td>
<td>22.3</td>
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</table>
REFERENCES


Savage, J.C. and Hasegawa, H.S., 1967, Evidence for a linear attenuation mechanism: Geophysics, 6, 1003-1014


Figure 1. P- and S-wave signals transmitted through Kayenta sandstone at 100 bars net confining pressure for dry, benzene-, and water-saturations.
Figure 2. Spectral ratio (long-short dash) with amplitude spectra for aluminum (dashed line) and vacuum dry Kayenta sandstone (solid line) at 500 bars confining pressure.
Figure 3. P- and S-wave attenuation (1000/Q) versus differential pressure for vacuum dry, benzene-, and water-saturated Kayenta sandstone.
Figure 4. Extensional and bulk attenuation versus differential pressure for vacuum dry, benzene-, and water-saturated Kayenta sandstone.
Figure 5. P- and S-wave attenuation versus differential pressure for vacuum dry, benzene- and water-saturated Berea sandstone.
BEREA SANDSTONE

Figure 6. Extensional and bulk attenuation versus differential pressure for vacuum dry, benzene-, and water-saturated Berea sandstone.
Figure 7. P- and S-wave attenuation versus differential pressure for vacuum dry, benzene-, and water-saturated Bedford limestone.
Figure 8. Extensional and bulk attenuation versus differential pressure for vacuum dry, benzene-, and water-saturated Bedford limestone.
Figure 9. P- and S-wave attenuation versus differential pressure for vacuum dry, benzene-, and water-saturated Webatuck dolomite.
WEBATUCK DOLOMITE

Figure 10. Extensional and bulk attenuation versus differential pressure for vacuum dry, benzene-, and water-saturated Webatuck dolomite.