

Seismic attenuation in artificial glass cracks: Physical and physicochemical effects of fluids

R. Moerig, W. F. Waite, O. S. Boyd, I. C. Getting, H. A. Spetzler

CIRES, University of Colorado at Boulder

Abstract. Attenuation and stiffness of artificial, fluid containing cracks are measured from 3 mHz to 10 Hz. The cracks are wedge-shaped; made from glass microscope slides. To explain the frequency dependence of both the attenuation and the stiffness (akin to a modulus), we need to appeal to well known fluid flow mechanisms and to the physicochemical interaction between the fluid and crack surface. By altering the wettability of the crack surfaces, surfactants change the mobility of water and thereby change the frequency dependence of the fluid flow effects by several orders of magnitude.

Introduction

In sedimentary rock, pore fluids are the main source for dissipation of seismic energy. Wave attenuation is therefore of potential use in oil exploration as well as in monitoring waste sites and ground water contamination if we understand the physical and physicochemical interaction between pore fluids and the rock matrix.

During deformation, pore fluid flow causes frequency-dependent attenuation. The flow may result from inertial effects of the pore content [Biot, 1956; Berryman, 1988] or from pressure gradients induced in the pore space [Mavko and Nur, 1979; O'Connell, 1984; Murphy et al., 1986]. Attenuation due to these flow mechanisms results from viscous shear relaxation. The relaxation frequency and magnitude of the flow effects depend on petrophysical parameters and the physical properties of the pore fluid.

In addition to flow effects, the pore fluid also interacts chemically with the solid matrix. By bonding to the rock surface, fluid molecules reduce the surface free energy [Boyd and Livingston, 1942; Van Voorhis et al., 1957] and may soften or lubricate grain contacts [Johnson et al., 1971; Adamson, 1976; Murphy et al., 1984]. A decrease in stiffness due to the reduction of adhesion forces and an increase in attenuation due to the breakage of bonds and/or the reduction of friction may result [Tittmann et al., 1980; Clark et al., 1980; Spencer, 1981; Winkler and Nur, 1982].

In partially saturated rocks, different absorption/dispersion mechanisms operate simultaneously [Clark et al., 1980; Murphy, 1982]. This makes it difficult to distinguish between the contributions of individual mechanisms to the overall attenuation. In order to isolate possible mechanisms, we make laboratory measurements on artificial samples consisting of wedge-shaped cracks made from glass microscope slides.

In this paper we show that fluid flow in cracks is governed not only by the crack geometry and the physical properties of the fluid as predicted by published fluid flow models, but also by

physicochemical interactions between the fluid and the solid. These interactions can drastically change the mobility of fluids and therefore the frequency dependence of the fluid flow effects.

Sample and Method

The artificial sample (Figure 1) consists of three soda-lime glass slides separated by stainless steel wires of different diameter. From the bending resistance of the glass slides under uniaxial compression [Cernica, 1977], we calculate a stiffness normal to the crack planes of 14 kN/m. Note that the sample represents an open system, which means the closed system stiffening mechanisms proposed by Gassmann [1951], Gist [1994] and others are not effective.

Attenuation and stiffness of the artificial sample are measured in the extensional mode using a broad band attenuation spectrometer (1 mHz-100 Hz). A detailed description of the apparatus is found elsewhere [Cherry et al., 1996]. Two equivalently constructed artificial samples are deformed in series. One serves as a reference and the other as a fluid bearing crack. We measure the amplitude and phase of the sample and reference displacements. Because the reference stiffness is known, the reference can be used as a stress gauge to calculate the sample's complex modulus. The complex modulus yields attenuation to ± 0.003 and the stiffness to better than 5%.

To saturate the sample, fluid is injected into the cracks using a syringe. Capillary forces drive the fluid to the thin end of the crack, and a liquid/gas boundary with a smooth contact line approximately parallel to the thin wire develops. Both cracks are always saturated with the same amount of fluid.

To maintain a given fluid saturation during a typical 18 hour measurement, evaporation must be prevented. A plastic bag, loosely surrounding the sample works well and prevents evaporation without materially affecting the gas pressure during deformation. Because the force applied to the sample acts through the plastic, the bag introduces additional attenuation. This additional attenuation was measured and found to be frequency independent and always less than 0.005. The attenuation values of interest are larger by an order of magnitude.

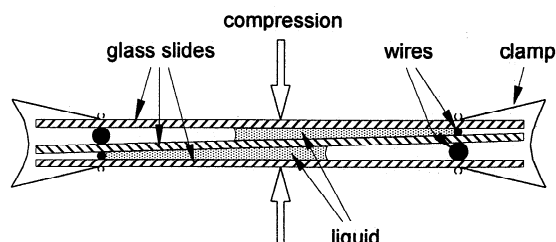


Figure 1. Schematic of the artificial sample. The sample is 75 mm long and 25 mm wide. The vertical dimension is exaggerated. The total height of the sample is 3.73 mm.

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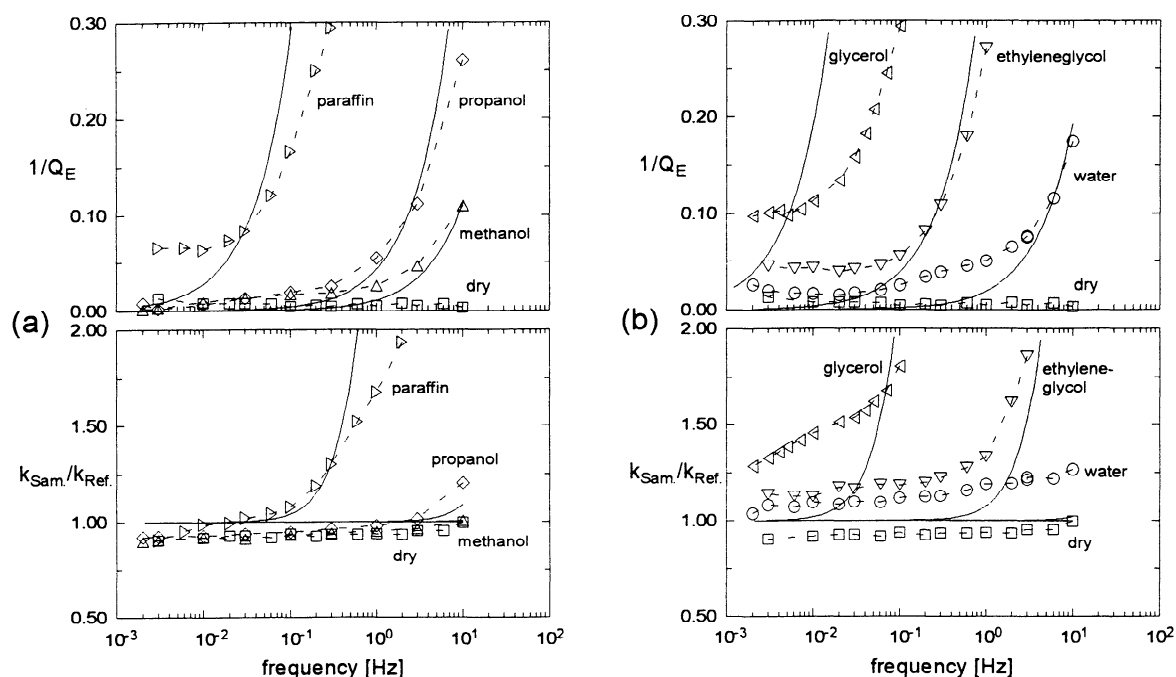


Figure 2. Attenuation $1/Q_E$ and stiffness ratio $k_{\text{Sam}}/k_{\text{Ref}}$ of partially fluid-saturated artificial samples. (a) Low surface tension fluids. (b) High surface tension fluids (cf. Table 1). Solid curves are predictions of a local fluid flow model [Murphy et al., 1986].

Results and Discussion

Effect of Vapor

Fluid vapors do not affect the properties of the artificial sample. When exposing the sample to a saturated water or propanol atmosphere, attenuation and stiffness are not distinguishable from the parameters measured on the dry sample. This means that the vapor related surface mechanisms which have been found to reduce the moduli and increase the absorption in real rocks [Tittmann et al., 1980; Spencer, 1981; Murphy, 1982] can be excluded when interpreting the data collected on our partially fluid-saturated samples.

Effect of Bulk Fluid

Figure 2 shows the attenuation $1/Q_E$ and the stiffness k_{Sam} measured on six different samples. Each sample is partially saturated with a different fluid. The saturation degrees range from 60 to 70%. The properties of the fluids are given in Table 1. The six samples have exactly the same geometry and display the same attenuation and stiffness when they are dry.

The presence of bulk fluid causes strong frequency-dependent attenuation (Figure 2). This attenuation can be thought of as the low frequency shoulder of a fluid flow attenuation peak that shifts to lower frequencies with increasing fluid viscosity (cf. Table 1). The observed viscosity dependence of attenuation demonstrates that the flow can not result from inertial effects which would produce the opposite frequency shift. The flow must result from pressure gradients induced by deformation.

To check the consistency of the data with local fluid flow mechanisms, we calculated attenuation and stiffness for the partially saturated samples. Of the various local fluid flow models available [e.g. Murphy et al. 1986; Walsh, 1995], we chose the parallel plate model of Murphy et al. [1986]. We use their equation 9 which depends on geometry, viscosity and bulk modulus of the liquid to calculate the effective stiffness. The pore space in Murphy's model is closed (expressed as a finite volume capacity), which results in a gas pressure acting against the fluid. The cracks in our sample are open and the flow is not restricted by a finite volume capacity. Therefore, in using Murphy's model, we assume an arbitrarily large volume capacity. The only parameters

Table 1. Properties of Fluids

Fluid	Density [kg/m ³]	Viscosity [mPa s]	Bulk Modulus [GPa]	Surface Tension [mN/m]	Dipole Moment [10 ⁻³⁰ C m]
Water	1000	1.0	2.20	72.0	6.24
Methanol	795	0.58	0.83	22.1	5.67
Propanol	804	2.20	1.12	23.3	5.50
Ethyleneglycol	1113	19.9	3.06	47.7	7.61
Glycerol	1261	>1000*	4.60	63.4	8.54
Paraffin	880	146	1.78	25.0	0

* Viscosity depends on water impurity. Water-free glycerol has a viscosity of 1500 mPa s. The water content of the glycerol used in this study is not known.

varied in the calculations are the viscosity and the bulk modulus of the fluid (cf. Table 1). The comparison of the model predictions (solid curves in Figure 2) with the data shows that the measured frequency-dependent attenuation is in qualitative agreement with a local fluid flow mechanism.

The measured attenuation levels off at low frequencies for all liquids, but the high viscosity liquids (paraffin, glycerol, and ethyleneglycol) level off at high attenuation values. This frequency-independent attenuation increases monotonically with the viscosity of the fluids, but does not show a simple relationship to the surface tension or the dipole moment (cf. Table 1). Both of the latter fluid properties are of importance in absorption mechanisms that are based on contact line movement [Miksis, 1988] or on the breakage of bonds [Tittmann et al., 1980]. The actual mechanism causing the measured low frequency attenuation is not yet understood.

Under static conditions or at frequencies too low for dissipative flow, the stiffness of open or partially saturated systems is generally thought to be independent of the liquid. The model predictions in Figure 2 are valid for an open system and therefore show no fluid stiffening effect at low frequencies. This prediction is confirmed for the low surface tension fluids (Figure 2a). High surface tension fluids however stiffen the open sample (Figure 2b). The magnitude of the stiffening effect is a monotonic function of the bulk modulus of the fluid. Although there is no correlation with the surface tension, we believe that the meniscus of a high surface tension fluid acts like a membrane that can stiffen the sample by sticking to the solid surfaces and inhibiting the complete release of pressure built up in the fluid during deformation.

Effect of Surface Tension

Water and other high surface tension fluids stiffen the open sample (cf. Figure 2b). If the meniscus indeed acts like a membrane, then by reducing the surface tension the magnitude of the stiffening effect should decrease.

We reduced the surface tension of water by adding a detergent (Procter & Gamble, no. 0874925-3G). The detergent concentration is 0.1% by volume. Figure 3 shows that the stiffening effect

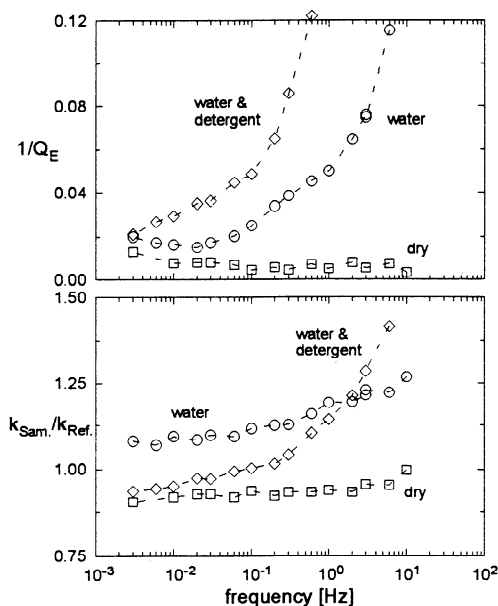


Figure 3. Attenuation $1/Q_E$ and stiffness ratio $k_{\text{Sam.}}/k_{\text{Ref.}}$ of a dry and partially water- and water/detergent-saturated sample.

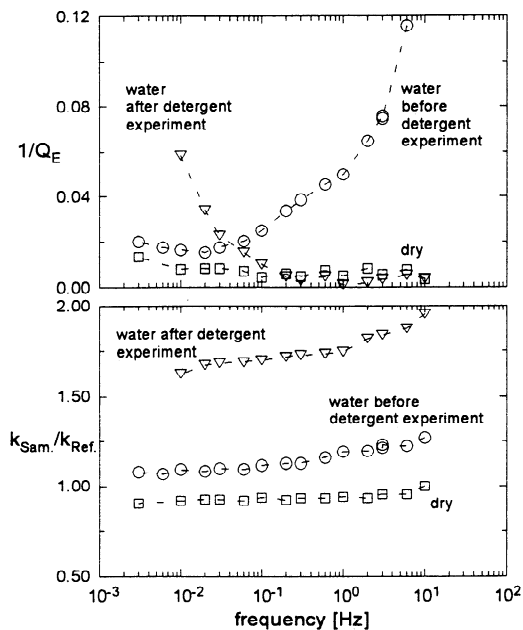


Figure 4. Attenuation $1/Q_E$ and stiffness ratio $k_{\text{Sam.}}/k_{\text{Ref.}}$ of a dry and partially water-saturated sample before and after the detergent experiment.

at low frequencies disappears when the surface tension of water is reduced.

The reduction in surface tension reduces the stiffness but also increases the attenuation (Figure 3). In terms of local fluid flow mechanisms, the measured increase in attenuation could be explained theoretically with a decrease in stiffness and/or an increase in viscosity. The predicted increase in attenuation due to the measured stiffness reduction is too small to explain the data. It is also very unlikely that a 0.1% detergent concentration could drastically change the viscosity of water. Local fluid flow models which do not consider the liquid/gas boundary and the possibility of dissipative contact line motion [e.g. Miksis, 1988], can not explain our experimental results.

Effect of Surfactant

The detergent used to reduce the surface tension is a surfactant and thus can change the properties of the solid surfaces. To check whether there is an effect on flow behavior due to possibly altered surface properties, we removed the water/detergent solution from the sample, flushed it many times with deionized water, and partially resaturated the sample with water.

While saturating the sample, the injected water did not flow to the thin end of the crack as usually observed. The contact line of the liquid/gas boundary was extremely irregular in shape. It appeared nearly impossible to force the fluid to flow to the thin end of the crack. The 0.1% surfactant solution seemingly made the initially hydrophilic surfaces hydrophobic. Finally, to ensure that the fluid stayed at the thin end of the cracks, the sample was completely saturated, then water was extracted at the thick end of the crack until the desired saturation was obtained.

In Figure 4 we compare the attenuation and stiffness of the partially water-saturated sample measured before and after the sample surface properties were altered by the surfactant. The stiffness and the frequency dependence of attenuation changed dramatically. At high frequencies (above 0.1 Hz), a short term pressure gradient induced by deformation causes fluid to flow when the surfaces are hydrophilic (before detergent experiment).

This measurement is essentially done in the relaxed part of the flow effects. The frequency-independent stiffening due to the fluid does not result from flow but can be attributed to the membrane effect of the meniscus. On hydrophobic surfaces (after detergent experiment) the short term pressure gradient does not cause the fluid to flow. The fluid does not introduce any attenuation at high frequencies but stiffens the sample drastically. At low frequencies (below 0.1 Hz) the fluid is subjected to long term pressure gradients which do cause the fluid to flow, resulting in an increased attenuation. The flow behavior observed during sample saturation suggests that this measurement occurred in the unrelaxed part of the flow effects.

For a pressurized fluid in an open system, it is not a question of whether or not fluid will flow, it is a question of the frequencies at which the flow dissipates energy. The relaxation frequencies for water in the artificial cracks which have constant geometry but have either hydrophilic or -phobic surfaces, are different by several decades in frequency (Figure 4). Therefore, we must conclude that fluid flow in cracks is not solely governed by the crack geometry and the physical properties of the fluid.

We checked the flow behavior of water before and after the sample surfaces were exposed to methanol, propanol, or acetone. In all cases we found a restricted flow of water on surfaces contaminated with carbon based molecules. The surface contamination is not detectable using infrared spectroscopy and can not be reversed by heat treatment up to 250°C for 4 hours or by applying a moderate vacuum (50 Pa) for 24 hours. We do not yet know what causes the change in flow behavior, but we suspect that long range forces between the adsorbed carbon based molecules and the water [Israelachvili, 1992] may play an important role. The resulting hydrophobic behavior of the surfaces may alter the pattern of flow and thus change the frequency band over which absorption occurs.

Conclusions

Fluid flow in cracks is not governed merely by the pore geometry and the physical properties of the fluid as predicted by most fluid flow models. Surfactants alter the properties of the liquid/gas interface as well as the wettability of solid surfaces. The interaction between solid surfaces contaminated by organic compounds and the pore fluid can change the mobility of fluids and thereby drastically changes the frequency dependence of the fluid flow effects. Because of the impact physicochemical effects have on monitoring recovery processes, waste sites, or ground water contamination, future attenuation models must include these interactions.

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- R. Moerig, W. F. Waite, O. S. Boyd, I. C. Getting, and H. A. Spetzler, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Campus Box 216, Boulder, CO 80309, USA.

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