Experimental results on the combined effects of frequency, pressure and pore fluid on the dispersion of elastic waves in porous rock.

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1 Introduction

When cracks and pores are connected within a rock, stress can induce fluid flow from one inclusion to another one. Because cracks are more compliant than equant pores, a stress wave builds up a higher fluid pressure within a crack than within a pore, and consequently fluid flows from crack to pore at a local scale. At low frequencies, fluid pressure has time to reach equilibrium. The elastic moduli are in that case relaxed moduli, those moduli are defined within the framework of poroelastic theory (drained or undrained moduli). Such a situation can be expected at seismic frequencies. However, in laboratory conditions, most of elastic waves data are obtained in the MHz range. Clearly, in such a high frequency range, there is no time for fluid pressure equilibrium to take place (even at local scale). The elastic moduli are unrelaxed moduli in that case. They are not those accounted for by poroelasticity, but they may be calculated from effective medium theory.

In this study, we investigate the frequency effect on two rocks: a porous basalt and a porous sandstone. The elastic bulk moduli were measured at high frequency ($\sim$ 1MHz) and at low frequency ($\sim$ 0.1Hz). Such measurements were done under confining pressure and with different nature of pore fluids. Finally, the experimental results obtained on the basalt are discussed using a simple quantitative model for calculating high and low frequencies moduli in a bimodal porous rock.

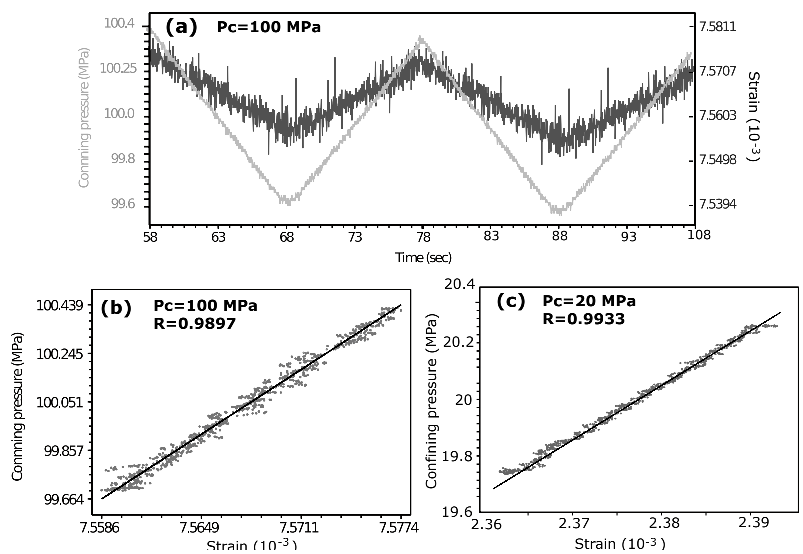

Figure 1: Oscillation tests done on the basalt sample: (a) confining pressure Pc and strain versus time over two periods for Pc = 100 MPa ; (b) Confining pressure versus volumetric strain during oscillation : as the oscillations are small, the behaviour of the basalt is purely elastic and the bulk moduli can be directly deduced form the slope. In this figure the mean confining pressure is 100 MPa (c) Confining pressure versus volumetric strain, in this experiment the mean confining pressure is Pc = 20 MPa

2 Experimental Methods

A block of basalt extracted on a road outcrop in the Reykjanes Peninsula and a block of Fontainebleau sandstone have provided the samples for the experimental investigation.

The first sample is an alkali fresh and young (less than 10000 years) basalt with a connected porosity of about 8%. The pore distribution is bimodal: crack porosity is 1%, and equant pores porosity is 7%, the permeability is 10^{-15} m^2.

Fontainebleau sandstone is an Oligocene arenite found in the region of Ile de France near Paris, formed by pure quartz grains that are well sorted and have an almost constant grain size of around 250 μm. The connected porosity is 13% and the permeability is 190.10^{-15} m^2.

Bulk moduli have been measured on saturated samples and on dry samples at low (0.01 Hz) and high (1 MHz) frequencies. At low frequencies, the measurement is obtained by small oscillations (less than 1 MPa) of the confining pressure (Figure 1). At high frequencies, the time of flight of a pulse is measured using PZT sensors, so that the P and S wave velocities are obtained and provide the high frequency modulus. The experiments have been carried out on jacketed samples (cylinders of 80 mm x 40 mm) at a constant pore pressure p=10 MPa, and at room temperature. The confining pressure was variable from P=15 up to P=200 MPa.

3 Experimental Results

3.1 Results on the basalt sample

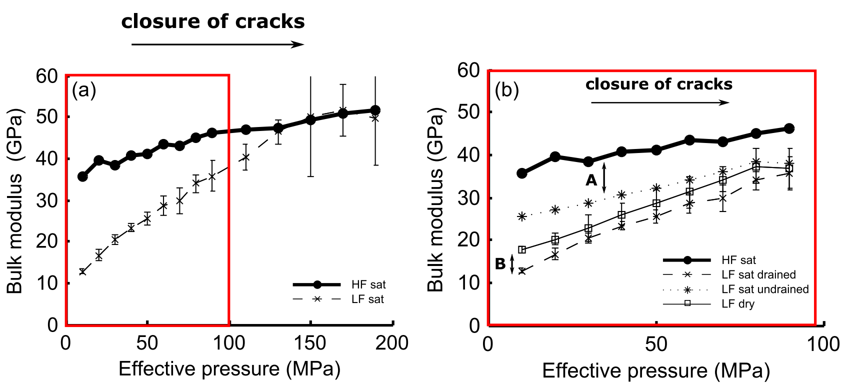

Figure 2: Bulk modulus obtained from high-frequency (HF) velocity inversion and low-frequency (LF) oscillation tests (Icelandic basalt); sat = water saturated conditions. (a) All experimental results over the 0-190 MPa range. (b) HF, LF saturated (drained and undrained) and dry moduli over the 0-100 MPa interval. Two effects are highlighted: A (frequency effect), and B (small physico-chemical effect).

The results (Figure2) show that there is a significant difference between the low frequency, undrained, bulk modulus and the high frequency saturated bulk modulus. The first one is expected to be the appropriate modulus for sufficiently low frequency elastic waves (frequency range of seismology to seismics). The second one is an unrelaxed modulus that can be measured in the MHz range. From Figure 2, it is clear that the difference between both moduli decreases when pressure increases. Beyond 150 MPa, this difference becomes too small to be detected. Independent measurements show that this pressure evolution corresponds to crack closure (Figure 3). Indeed porosity, derived from strain data, decreases by about 1% from P=0 to P=200 MPa. This is in agreement with the P and S wave velocity variations. It is expected that crack closure should result in elastic wave velocities increase. This is exactly what is observed on Figure 3. The overall conclusion is that crack closure wipes out the dispersion effect. It is thus inferred that the dispersion effect is due to the existence of cracks.

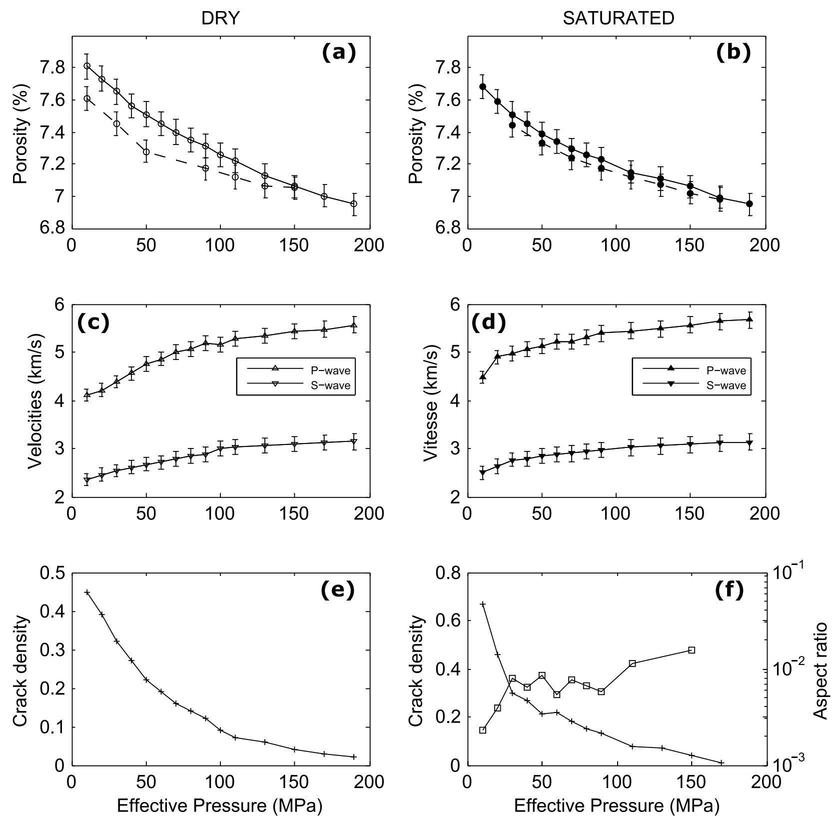

Figure 3: Mechanical data (porosity decreases), elastic-wave velocities, and effective medium inversion data for the triaxial experiment performed on the investigated basalt. The data are obtained in (left) dry and (right) saturated conditions, respectively. (a–b) Porosity evolution, where unloading is indicated as a dashed line. (c–d) P– and S–wave velocities (HF). (e–f) Inverted parameters from the effective medium model used by Fortin et al. (2007): crack density in dry and saturated conditions, aspect ratio in saturated conditions.

3.2 Results on the Fontainebleau sample

For Fontainebleau sandstone, different pore fluids were used : gaz, water and glycerine. Figure 4 shows the results for glycerine as pore fluid. The black curve is the data obtained from the oscillation tests: it is the drained bulk mudulus and this modulus is similar to the bulk modulus obtained from velocity inversion in the dry case (not shown on the Figure). The undrained modulus (dashed red curve) is obtained from the drained modulus and the Biot-Gassman equations. The high frequency saturated bulk modulus (red curve) is obtained from velocity inversion. As for the results obtained on the. basalt, Figure 4 shows that there is a significant difference between the undrained bulk modulus and the high frequency saturated bulk modulus. We can define the modulus K (saturated) dispersion as the quantity: $D = \frac{K^{HF} - K^{LF}}{K^{LF}}$. The dispersion is about $\sim 23\%$ at a confining pressure of 10 MPa and is reduced to $D \simeq 8\%$ at a confining pressure of 90 MPa, i.e as cracks are closed. Again the overall conclusion is that crack closure (or the closure of pore with small aspect ratio) wipes out the dispersion effect

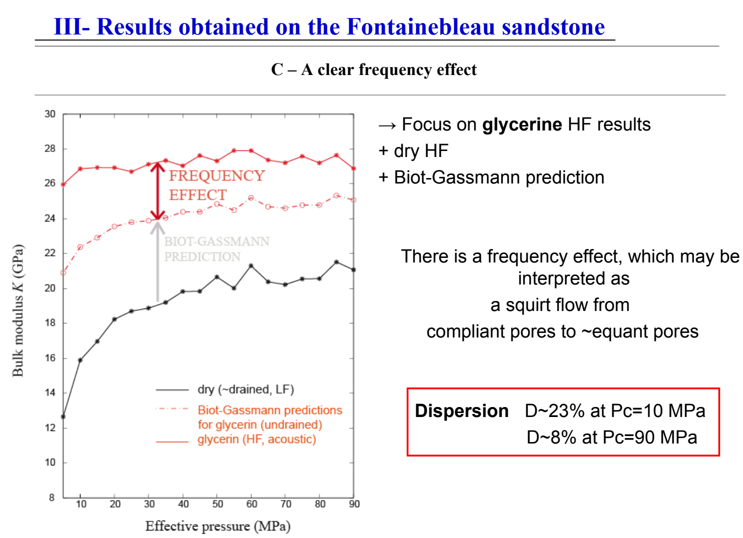

Figure 4 :Bulk modulus obtained from high-frequency (HF) velocity inversion and low-frequency (LF) oscillation tests (Fontainebleau sandstone)

4 Discussion

The experimental results leads to a simple quantitative model for calculating high and low frequencies moduli in a bimodal porous rock. Effective Medium Theory provides a way to derive unrelaxed (i.e., high frequency) moduli for both dry and saturated porous rocks. Assuming equant pores to be spherical, and cracks to be spheroidal with an aspect ratio $\xi = w/c$ (where w and c are the lengths of the spheroid semi-axis), exact relations are known to express effective moduli, within the framework of the non-interaction approximation. Combining these results with Biot-Gassmann equation provides furthermore the relaxed undrained modulus. In the present case of a bimodal porosity, the crack fraction R is the controlling parameter. R is defined as: $R = \Phi_{cr}/\Phi_T$ where Φ_{cr} is the crack porosity, and Φ_T the total porosity. Figures 5 and 6 show how D is predicted to vary with R for different crack aspect ratio values.˙ Bulk dispersion D (Figure 5) is predicted to be zero if there is no crack, and zero also if there are only cracks. The maximum value of D depends on aspect ratio. It can be as high as 30% for $\xi = 0.01$. The maximum is calculated to occur near R = 0.2. What can be done is to check the bulk dispersion data against theoretical predictions. There is only one free parameter which is the crack aspect ratio. Figure 6 shows how theoretical predictions and experimental data can be compared, and which aspect ratio range is compatible with the data. This comparison is done with the results obtained on the basalt sample. The comparison between experimental data and theoretical is that the aspect ratio should be close to 0.01. This agrees nicely with independent results derived from elastic wave velocities data (Figure 3)

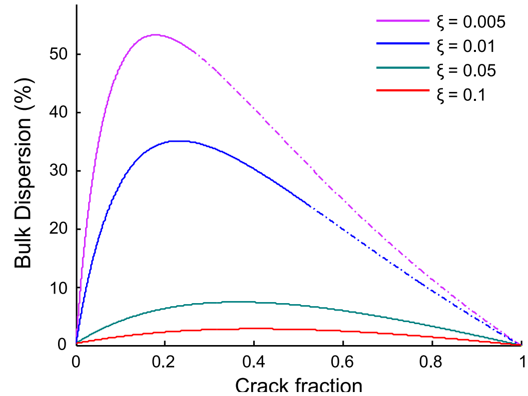

Figure 5 : Numerical results obtained from a crack and pore effective medium model. Predicted bulk dispersion D: dispersion increases when aspect ratio decreases. Bulk dispersion is zero when only cracks, or only pores, are present.

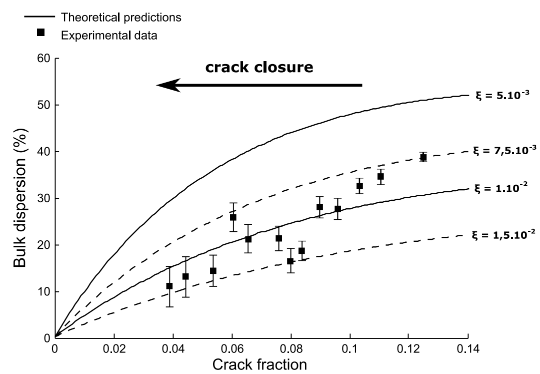

Figure 6 : Comparison between experimental data obtained on the basalt and theoretical predictions for bulk dispersion in a cracked porous rock. Aspect ratios ξ are indicated. The experimental data are from Figures 2 and 3. It is assumed that equant porosity is constant and crack porosity only varies with pressure.)

References

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