Seismic Frequency Wave Speed Measurements on Micro-cracked, Fluid-saturated Synthetic Rock

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Summary

Seismic properties of saturated, cracked rock are expected to be strongly frequency dependent as a result of reversible fluid flow within the crack porosity at all scales caused by the oscillating stress induced by seismic waves. Laboratory measurements, typically made with frequencies on the order of MHz, must systematically overestimate in-situ seismic wave velocities that are typically measured with frequencies on the order of mHz-kHz, a range of frequencies applicable to earthquake teleseisms (< 10 Hz) through active exploration seismic and microseismic investigations (~10 to 300 Hz), mine seismology (~1 kHz) and finally geophysical logging (~ 10 kHz). Forced flexural and torsional oscillation of core samples in the laboratory allows measurement of seismic properties at lower frequencies (0.001-1 Hz) that are more directly comparable to typical in-situ frequencies. Here we describe progress in the development of flexural oscillation methods at the Australian National University (ANU) laboratory for use alongside the established torsional mode capability, as well as preliminary results from a thermally cracked synthetic sample of polycrystalline alumina.

Introduction

Pore fluids affect seismic wave speeds by increasing the effective stiffness of the pore, and thus the overall stiffness of the rock, when compressed by passing seismic waves. The stiffness of the rock can be related to seismic wave speeds by the Christoffel equations. The amount of additional stiffness induced by the pore fluid when compressed by a seismic wave depends strongly on the frequency of the seismic wave and the viscosity of the fluid. Maximum stiffness is achieved when the frequency is high enough that the pore fluid does not have sufficient time to flow. For this reason, measurements conducted in the laboratory with ultrasonic transducers (MHz) can be expected to measure higher stiffnesses and seismic velocities than measurements made using sonic logging (kHz), active source in-situ seismic (Hz) and passive source seismic (≤ Hz). Measurements can also be expected to be sensitive to the pore pressure; as the effective pressure changes (confining pressure minus pore pressure) the crack apertures and distribution of fluid within the fracture network will change, causing changes in the rock stiffness and seismic velocities.

Numerous theoretical models exist which predict the frequency dependence of the seismic velocity based on factors such as pore fluid viscosity, fluid density, rock porosity, permeability, crack aspect ratio and tortuosity of fractures (e.g. Biot 1956a; Biot 1956b; Geertsma and Smit 1961; Mavko and Jizba 1991). Despite this extensive theoretical investigation of frequency dependence, the effect of fluid saturation on wave speeds through liquid saturated rock remains largely untested experimentally. As interest in time-lapse seismic monitoring of petroleum production, geothermal energy, geological CO_2 sequestration, repositories for nuclear waste, etc. grows, the ability to accurately characterize fracture networks, pore pressure and fluid flow within low porosity crystalline rock becomes increasingly important. Although numerous high frequency (ultrasonic) measurements exist, very few lower seismic band frequency measurements have ever been made in the controlled laboratory environment.

This abstract briefly reviews development of the experimental method to obtain seismic frequency measurements, and shows the initial results of a series of seismic band measurements of the mechanical moduli of fractured, fluid saturated synthetic rock.

Method

The experimental assembly is a cylindrical beam comprised of steel, polycrystalline alumina, and the fractured specimen encased within a copper jacket. The top of the beam is held fixed while the bottom is driven using time-varying electromagnetic drivers, with the polarization of the applied forced depending on whether the apparatus is operating in flexural or torsional mode (fig. 1). The resulting flexure or torsion is measured at two locations within the beam using parallel plate capacitors.

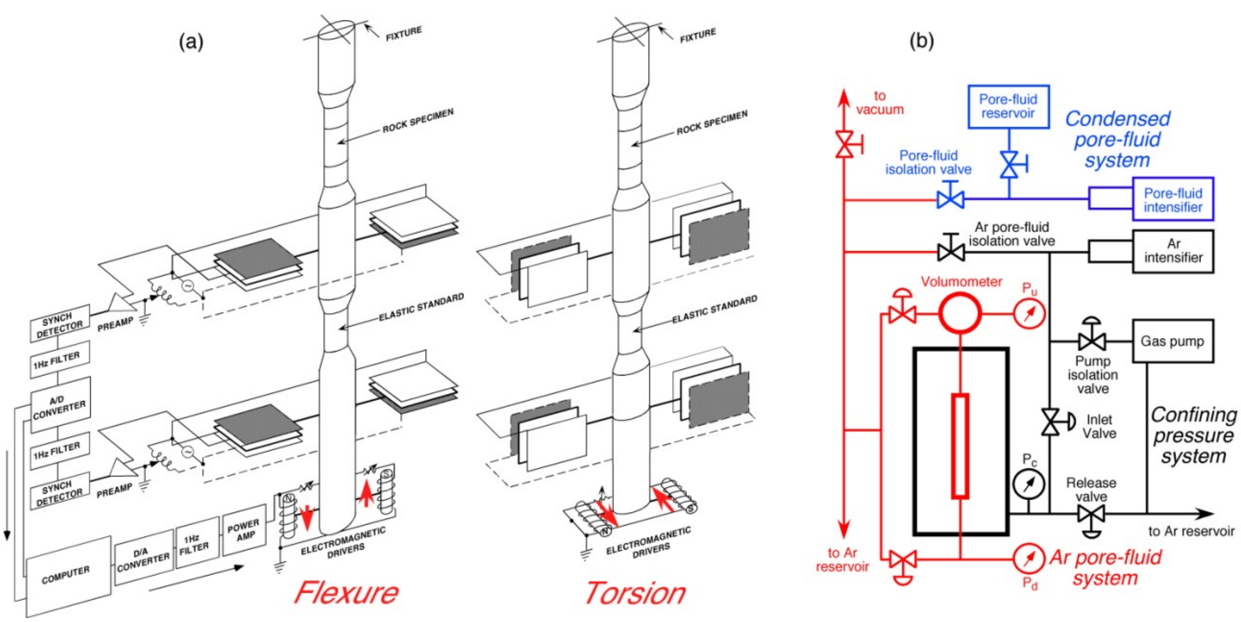

Figure 1. Experimental arrangement for forced-oscillation studies in torsion and flexure with alternative driver/displacement transducer polarizations.

The displacement, d, at the tranducers caused by the flexure of the beam at x_i can be related to Young's modulus, E, by:

$$d(t) = -D\int_0^{x_i} \frac{M(x,t)}{E(x)I(x)}\,dx$$

where D is the radial distance from the centre of the beam to the point of measurement, M is the local value of the time-varying bending moment and I is the moment of inertia of the beam. The displacement measured by the transducers in torsion can similarly be related to the applied torque, the moment of inertia of the beam, and, in this case, the shear modulus [Jackson and Paterson 1993; Jackson et al. 1984].

A synthetic cylindrical sample of Lucalox™ polycrystalline alumina, with diameter 1.5 cm and length 5 cm, is heated to 1400º C and quenched in liquid nitrogen to produce thermal cracking (fig. 2). The induced cracks are spaced ~5 mm apart and are of low aspect ratio (of the order 0.0001), with micron wide cracks extending tens of millimeters. The overall porosity of the fractured sample is measured by mercury porosimetry, and confirmed by measurements before and after thermal cracking, to be 0.03%. The cracks show a random orientation but extend only through the outer 2/3 of the sample. Since the moment of inertia of the sample depends on the radius, r, of the cylindrical sample raised to the fourth power,

$$I = \frac{\pi r^4}{4}$$

the effect of the uncracked core on the overall results is expected to be low, with the forced oscillation measurements predominantly measuring the characteristics of a fractured sample.

(a) (b)

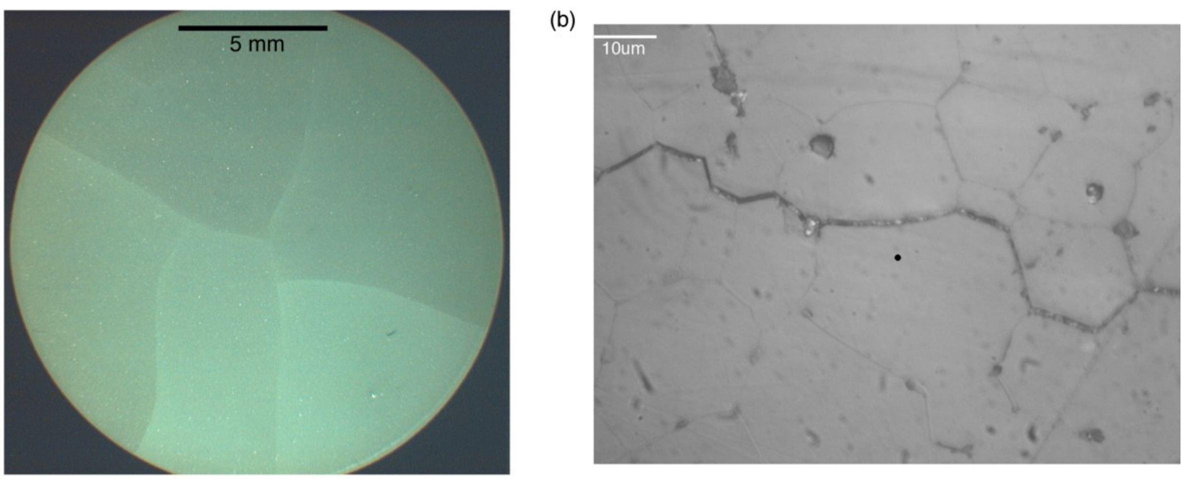

Figure 2. (a) Crack network in Lucalox polycrystalline alumina quenched from 1400°C into liquid nitrogen. (b) Representative micron-wide crack at higher magnification showing grain-boundary control of the thermal cracking.

Torsional and flexural mode measurements of the unsaturated fractured specimen are made at confining pressures of 10-160 MPa. The fractured sample is saturated with argon gas and further measurements are made with confining pressure at 80 MPa, and pore pressures of 10-70 MPa. Torsional mode measurements with confining pressure of 80 MPa and pore pressures of 0-65 MPa are made on the sample after it is saturated with water (fig. 3).

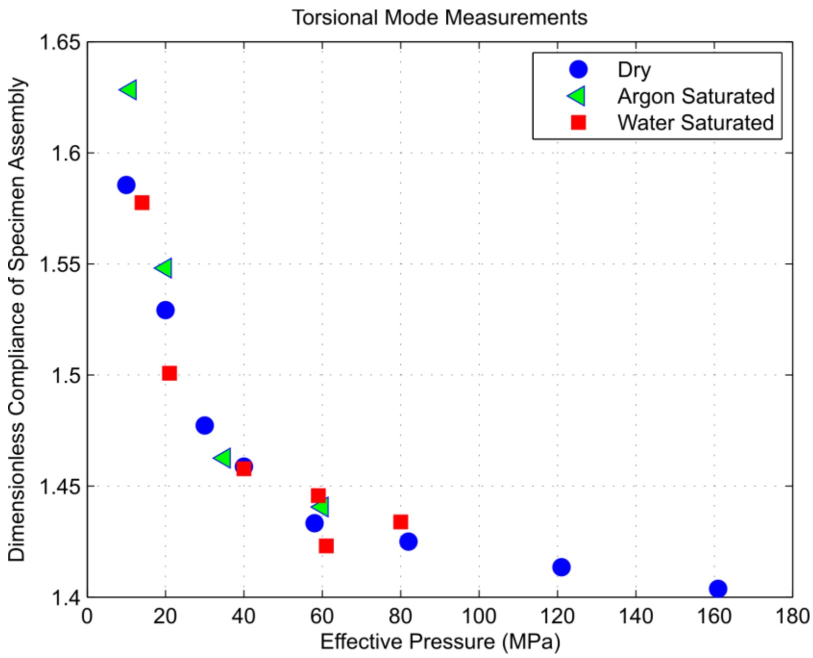

Figure 3. Dimensionless normalized compliance of the cracked Lucalox™ sample vs. effective pressure in torsion measured at 0.1 Hz.

Conclusions

The dimensionless compliance of the specimen assembly is observed to decrease markedly in torsion as a result of progressive fracture closure at pressures of ~10-60 MPa. The compliance is inversely related to the shear modulus, and corresponds to an increase in shear modulus. These results are consistent between the dry, argon and water saturated measurements. Similar results are observed over the same pressure range in flexure, corresponding to an expected increase in Young's modulus. Preliminary results of modeling the relative amplitudes and phase of the measured angles of flexure will allow inference of the complex Young's modulus of the specimen. The Young's modulus results, in conjunction with measurements of the shear modulus obtained from the torsion data, allow the calculation of seismic velocities in the specimen.

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