Laboratory measurements of frequency-dependent seismic properties of cracked and fluid-saturated media

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SUMMARY

The capability to perform laboratory measurements with both low-frequency forced-oscillation and high-frequency wave-propagation methods, under conditions of independently controlled confining and pore-fluid pressure, offers the prospect of new insight into the frequency-dependent seismic properties expected of cracked and fluid-saturated rocks of the Earths upper crust. An important step in the development of such broad-band capability has been the modification of existing laboratory equipment to newly allow flexural, as well as torsional, forced-oscillation testing of cylindrical rock specimens. Flexural oscillation tests on an experimental assembly containing a fused silica control specimen yield results indistinguishable from those of numerical modelling with both finite-difference and finite-element methods – demonstrating the viability of the method. Both torsional and flexural oscillation methods along with complementary high-frequency wave propagation methods have been applied to specimens of dense polycrystalline alumina and quartzite, each thermally cracked to generate an interconnected network of cracks of low aspect ratio, and tested dry, and saturated with either argon or water. The shear and flexural moduli vary systematically with effective pressure – providing clear evidence of pressure-induced crack closure. Similarities and differences between effective moduli measured under different conditions of pore-fluid saturation are tentatively interpreted in terms of the timescales for stress-induced redistribution of pore fluid.

Key words: rock physics, seismic properties, poro-elasticity, dispersion

INTRODUCTION

Oscillating stresses associated with seismic waves are expected to cause reversible fluid flow within cracks of low aspect ratio, resulting in strongly frequency dependent seismic wave velocities and attenuation. Laboratory measurements typically made at MHz frequencies, well logging undertaken at kHz frequencies and in-situ exploration seismic (10-300 Hz) measurements are unlikely to be directly comparable as a result of this fluid flow effect. Experimental measurements over a broad range of frequencies are necessary to constrain theoretical models.

Accordingly, novel laboratory equipment at the Australian National University has recently been modified to allow both torsional and flexural oscillation measurements at sub-microstrain amplitudes, thereby providing low-frequency (mHz-Hz) constraints on both the shear and compressional wave properties of cylindrical rock specimens within the linear regime. The new flexural mode capability was first tested on experimental assemblies containing fused silica control specimens. Close consistency between the experimental data and the results of numerical modelling with both finite-difference and finite-element methods has demonstrated the viability of the new technique (Jackson et al., 2011).

For experiments with pore fluid, hollow cylindrical rods of steel and alumina provide pore fluid access to either end of the specimen enclosed within a thin-walled copper sleeve. Experiments with a fused silica control specimen of the same dimensions are being used to calibrate the mechanical response of the alumina rods in both torsion and flexure.

In parallel with such technical developments, torsional and flexural oscillation measurements have been performed on thermally cracked specimens of a dense polycrystalline alumina ceramic (Lucalox^{TM}) and quartzites from Cape Sorell Tasmania, Australia and from Alberta, Canada. These materials have been tested in forced oscillation both dry, and either argon or water saturated. Complementary high-frequency (0.6–1.0 MHz) ultrasonic wavespeed measurements have been performed at the University of Alberta.

METHOD AND RESULTS

Forced-oscillation method

Equipment for seismic-frequency torsional forced-oscillation measurements under conditions of simultaneous high pressure and temperature, described in detail by Jackson and Paterson (1993), has recently been modified to provide access also to the flexural mode by using alternative polarisations of the electromagnetic drivers and capacitance displacement transducers (FIGURE 1).

The distortion of the experimental assembly undergoing forced oscillation is measured by sensitive three-plate capacitance displacement transducers operated in pairs at locations above and below the hollow steel elastic element.

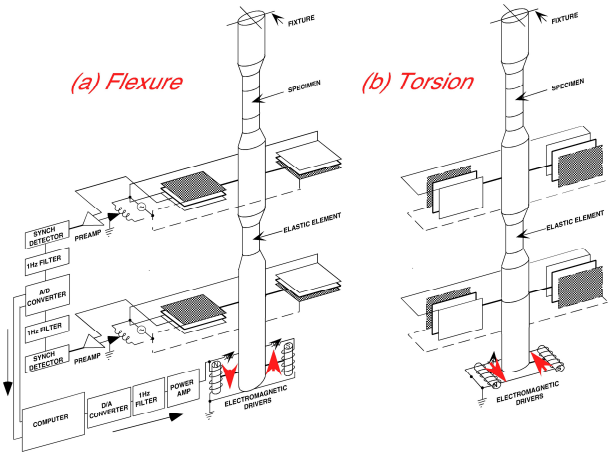

Figure 1. Experimental arrangement for forced-oscillation studies in (a) flexure and (b) torsion with alternative polarisations of electromagnetic drivers and displacement transducers.

Diagonally opposite capacitors are connected in parallel in order to maximise the sensitivity to torsional or flexural mode distortions of the column for the alternative driver/transducer polarizations, and to minimize the response to any subsidiary excitation of the flexural or extensional modes, respectively. At each measurement station, the parallel combinations of diagonally opposite capacitors, are connected to a ratio transformer to form an AC bridge. Under static operational conditions, the bridge is balanced by adjustment of the transformer ratio. The bridge out-of-balance signal associated with torsional/flexural oscillation is subject to synchronous detection, followed by low-pass (1 Hz) filtering, analogue/ digital conversion and digital data acquisition (FIGURE 1a). Calibration of the resulting voltage-versus-time signals is done by measuring the voltage offset associated with reversed switching of the transformer ratio through an appropriate increment.

The raw experimental data obtained in flexural oscillation (at periods currently between 1 and 1000 s) are thus sinusoidally time-varying displacements $d_1(t)$ and $d_2(t)$ measured by the parallel combinations of capacitance displacement transducers, located respectively above and below the elastic element (FIGURE 1a). The zero-to-peak displacement amplitudes $|d_1|$ and $|d_2|$ and their relative phase, estimated by Fourier analysis, are first used to calculate the amplitude and phase of the difference signal $d_{12} = d_2 - d_1$, representing the distortion of the elastic element. These displacements $d_i(t)$, (i = 1, 2), measured at a distance D from the axis of the specimen assembly at distances $x = l_i$ from the upper, cantilevered end of the specimen assembly, are related to the flexure $v(x)$ by

$$d_i(t) = Dv'(l_i,t),$$

$v'(l_i,t)$ being the instantaneous value of the local angle of flexure, i.e. $\partial v/\partial x$. This latter quantity can be estimated by integration of the filament elongation expression (Timoshenko and Gere, 1973) for the curvature of a thin beam:

$$\partial^2 v/\partial x^2 = -M(x)/[E(x)I(x)],$$

where M is the local value of the time-varying bending moment, E is the Young's modulus, and I the diametral moment of inertia of the circular cross-section of the beam.

Pending inversion of the experimental data for the complex Young's modulus of the specimen itself, the results of the flexural oscillation measurements are presented here as the distortion of the entire specimen assembly – comprising the specimen itself, and the hollow alumina and steel members between which they are sandwiched, all enclosed within a thin-walled copper sleeve. In comparing d_1, a measure of the flexure of the specimen assembly, to that (d_{12}) of the elastic element, we define a normalised flexural 'modulus' S_{NF} as

$$S_{NF} = |d_1/d_{12}| = |d_1/(d_2 - d_1)|$$

and the loss angle δ (rad) as the phase lag of d_1 relative to d_{12}, reflecting any strain energy dissipation associated with poroelastic or viscoelastic behaviour of the specimen. The displacements measured by the transducers in torsion are similarly related to the applied torque, the moment of inertia of the beam, and, in this case, the shear modulus G through well-established procedures (Jackson and Paterson, 1993).

Complementary high-frequency (0.6-1.0 MHz) wave-propagation measurements were made in the University of Alberta laboratory using piezoelectric P- and S-wave transducers, glued either directly to the sample, or to aluminium end-pieces pressure-coupled to it.

Pore-fluid system

We have newly constructed and tested a system for the delivery, pressurisation and monitoring of pore fluid – either argon gas or condensed pore fluids such as water. For this purpose, a cylindrical rock specimen of 15 mm diameter is sandwiched between hollow ceramic and steel rods enclosed within an annealed copper tube of 0.25 mm wall thickness, that is sealed with an O-ring at either end to exclude the argon pressure medium. The hollow ceramic and steel rods connect the pore space within the jacketted specimen to the upper and lower pore-fluid reservoirs. This arrangement allows independent variation of confining and pore-fluid pressures to 200 MPa. The capacity to isolate the upper and lower reservoirs provides for the in situ measurement of permeability through observation of the return to equilibrium following the imposition of a small fluid-pressure differential between the two reservoirs (Brace et al., 1968). Use of this procedure prior to each set of forced oscillation measurements guarantees the attainment of pore-pressure equilibrium throughout the specimen. A pore-fluid volumometer, previously used in the ANU Rock Physics laboratory, allows measurement of pressure-dependent changes in pore-fluid volume and hence storage capacity (Zhang et al., 1994).

Thermally cracked materials

Three precision-ground cylinders of translucent Lucalox™ polycrystalline alumina, each of diameter 15 mm and length 50 mm and thermally cracked by heating to 1400º C followed by quenching in liquid nitrogen, were stacked to from a specimen of total length 150 mm. The cracks are of low aspect ratio (of the order 0.0001), with micron-wide cracks typically extending only part way towards the centre of the cylinder. The overall crack porosity was determined both by direct measurement and by mercury porosimetry to be 0.03%.

Thermally cracked samples of Cape Sorell (Tasmania, Australia) and an Alberta (Canada) quartzite were similarly prepared by heating to 1100º C and quenching in either liquid nitrogen or water – resulting in relatively isotropic distributions of cracks with average apertures of 1 μm, aspect ratios << 0.1, and total porosities of ~2%.

Torsional and flexural mode forced-oscillation measurements were made on the fractured specimens, tested either dry or saturated with either argon or water, under confining (P_c) and effective pressures $P_{eff} = P_c - P_f$ ranging between 10 and 190 MPa (where P_f is the pore fluid pressure). Ultrasonic measurements were performed for a similar range of effective pressures.

Representative results for cracked alumina

The effective moduli for the cracked alumina specimen, measured in torsion and in flexure, are essentially independent of oscillation period for the range 1-100 s (e.g. FIGURE 2), but vary systematically with effective pressure (FIGURES 2 and 3). Both the shear modulus and the normalized flexural modulus initially increase markedly with increasing effective pressure, becoming more mildly pressure-independent for effective pressures above ~50 MPa.

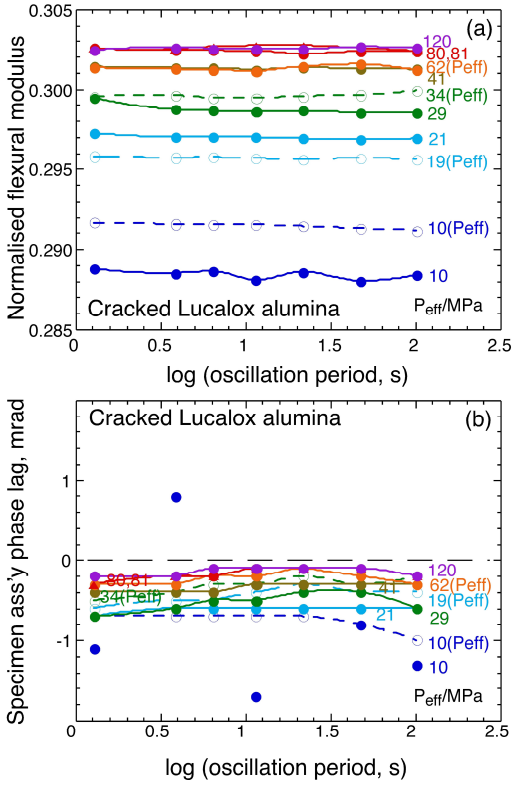

Figure 2. (a) Normalised flexural modulus and (b) associated phase lag for the specimen assembly containing the cracked alumina specimen, tested dry and argon-saturated, over the indicated ranges of oscillation period and effective pressure.

The similar behaviour evident in FIGURE 3 for dry and argon- and water-saturated conditions, along with the lack of any variation of modulus with oscillation period, suggest that these conditions sample the saturated isobaric regime (O'Connell and Budiansky, 1977). Ultrasonic measurements on the same material yield a pressure independent S-wave velocity of 5746 m/s for the uncracked core of the cylindrical specimen for a shear modulus G of 130 GPa. That this value is closely consistent with the maximum forced-oscillation shear modulus of 128 GPa for P_{eff} = 160 MPa indicates that 160 MPa is sufficient pressure to close most of the thermally induced fractures.

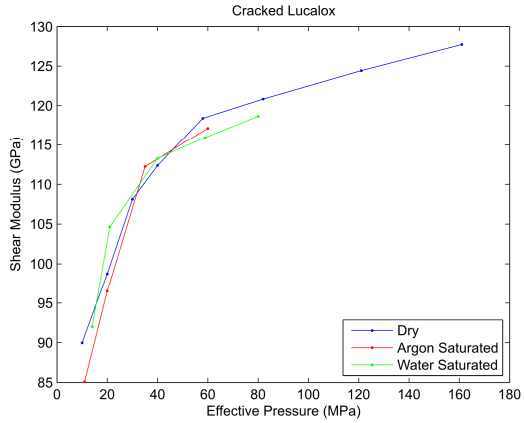

Figure 3. Shear modulus of the cracked Lucalox™ alumina sample, measured at 11.5 s period, versus effective pressure. Results are shown for tests conducted without pore fluid (dry), and either argon- or water-saturated.

Representative results for the cracked quartzites

For the Cape Sorell quartzite, the shear modulus G measured in torsional oscillation varies systematically with confining pressure, but not without some hysteresis – higher values of G being measured during the (later) decreasing pressure cycle (FIGURE 4). A closely similar trend with effective pressure is observed under conditions of argon saturation. The measured modulus reaches a maximum value of 35 GPa at an effective pressure of 190 MPa, while measurements on uncracked Cape Sorell quartzite by Lu and Jackson (1998) give a shear modulus of 41 GPa under similar conditions – consistent with the notion of pressure-induced closure of most of the thermally induced cracks.

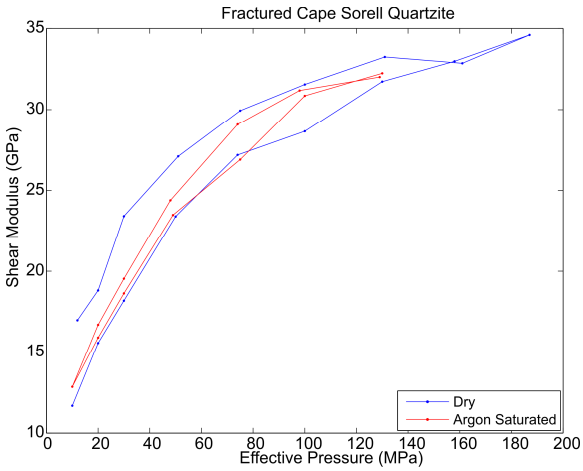

Figure 4. Shear modulus of the cracked Cape Sorell quartzite sample, measured at 11.5 s period, versus effective pressure. Results are shown of measurements made without pore fluid (dry) and argon-saturated.

The normalized flexural modulus also varies systematically with effective pressure – with closely consistent results for dry and argon-saturated conditions (FIGURE 5). The markedly higher values of the normalised flexural modulus for water-saturated conditions are tentatively attributed to stiffening associated with saturation with the much more incompressible pore fluid. Preliminary results show that, while little frequency dependence is observed in the low frequency band (0.01-1 Hz) for either of the cracked quartzite samples under the different saturation regimes, significant dispersion (frequency dependence of wavespeed) exists between the low-frequency and high-frequency measurements.

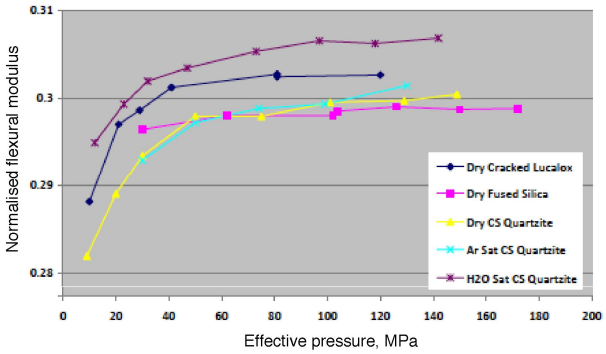

Figure 5. A comparison of the normalized flexural modulus for the cracked Cape Sorell quartzite, tested dry, and Ar- and water-saturated with results for assemblies containing the fused silica control specimen and the cracked Lucalox alumina specimen.

CONCLUSIONS

Saturation of crack/pore networks with fluids of appropriate viscosity and incompressibility, coupled with broadband measurement of seismic properties (c.f. Adam et al., 2009; Adelinet et al., 2010), has the potential for systematic exploration of the frequency dependent behaviour associated with fluid flow on spatial scales ranging from the grain size to that of laboratory-sized specimens, and beyond. Substantial progress towards this so-far elusive goal has been demonstrated in the preliminary experiments reported here. It has been shown that low-frequency flexural-oscillation experiments, combined with related torsional-oscillation measurements, have the potential to constrain both the Young's and shear moduli and hence both compressional and shear wave behaviour. Recent progress towards inversion of the flexural modulus of the assembly for the Young's modulus of the specimen will be described. We have demonstrated that thermal cracking of synthetic and natural geological materials provides a mechanism for generation of networks of interconnected cracks of uniformly low aspect ratio. The marked increases with increasing effective pressure of both the shear modulus and the normalised flexural modulus – especially at relatively low effective pressures provide evidence of progressive crack closure. Similar moduli, measured dry and argon saturated, are consistent with saturation with a relatively compressible fluid under saturated isobaric fluid-flow conditions. The substantial stiffening observed in flexural oscillation of water-saturated samples is tentatively attributed to the fact that water is much more incompressible than argon at the same pore-fluid pressure. Ongoing work involving saturation of simple cracked media with fluids of higher viscosity and therefore longer fluid-flow timescales is seeking to address critical issues such as the distinction between local (squirt) and global (specimen-wide) fluid flow.

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REFERENCES

Adam, L., Batzle, M., Lewallen, K.T., and van Wijk, K., 2009, Journal of geophysical Research, 114, B06208.

Adelinet, M., Fortin, J., Gueguen, Y., Schubnel, A., and Geoffeoy, L., 2010, Geophysical Research Letters, 37, L02303.

Brace, W.F., Walsh, J.B., and Frangos, W.T., 1968, Journal of geophysical Research, 73, 2225.

Jackson, I. and Paterson, M.S., 1993, Pure and Applied Geophysics, 141, 445.

Jackson, I., Schijns, H., Schmitt, D.R., Mu, J., and Delmenico, A., 2011, Review of Scientific Instruments, 82, 064501.

Lu, C. and Jackson, I., 1998, *Pure and Applied Geophysics, 153*, 441-473.

O'Connell, R.J. and Budiansky, B., 1977, Journal of Geophysical Research, 82, 5719.

Timoshenko, S.P. and Gere, J.M., 1973. *Mechanics of Materials*. (Van Nostrand Reinhold, London).

Zhang, S., Paterson, M.S., and Cox, S.F., 1994, Journal of Geophysical Research, 99, 15741.