An exploratory study of the seismic properties of thermally cracked, fluid-saturated aggregates of sintered glass beads

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SUMMARY

A synthetic rock analogue with simple microstructure was used to advance our understanding of the influence of cracks and pore fluids on seismic properties. The glass beads with ~ 300 μm diameter were sintered near the glass transition with average 1~2% porosity and subsequently quenched from high temperature into water at room temperature to introduce cracks with uniformly low aspect ratio α ~ 0.0007. Jackson-Paterson attenuation apparatus, with independently controlled confining and pore-fluid pressure systems, was used for both torsional and flexural mode forced oscillations at seismic frequencies to extract shear and Young's modulus respectively, with or without the presence of pore fluids (e.g. argon, water) of varying viscosities. By perturbing the pore pressure at either end of the cracked specimen by ~5 MPa, permeability was obtained by analysing the evolution curve for pore fluid re-equilibration. Shear modulus is found lower with longer oscillation periods for the cracked and argon pore fluid saturated material possibly indicating the transition from the saturated isolated to saturated isobaric regime, with minimal strain-energy dissipation 1/Q < 0.003. The averaged elastic moduli for different oscillation periods and permeability are discovered to be extremely sensitive to variation of effective pressure. The crack closure effects can be observed easily at the effective pressure level at ~ Eα, consistent with the theoretical prediction.

Key words: rock physics, seismic properties, glass beads, poroelasticity, dispersion

INTRODUCTION

Much of the upper part of the crystalline continental crust, to the depth of about 15 km, is pervasively cracked. The extensive presence and migration of fluids within the crack network can introduce difficulties in interpreting seismological data in the upper crust. The importance of precise interpretation of seismological findings with the presence of fluids has been raised to a higher level in the context of global warming with the new applications ranging from the geothermal energy exploration and utilisation to the carbon dioxide monitoring in sequestration projects.

The stiffness of rocks is significantly affected by the presence of cracks and pore fluids, the latter able to increase the effective stiffness of cracks. The reversible pore-fluid flow within the crack network, as the seismic waves propagate through, could make the elasticity of studied rocks strongly frequency dependent. The maximum stiffness of fluid-saturated rocks can be expected at the highest frequency of measurement.

The impact of cracks and fluid saturants on the elasticity of rocks has been systematically studied with both theoretical modelling (e.g. Schubnel & Gueguen, 2003) and experiments (e.g. Fortin, et al., 2005) since 1920s. Most of the theories have remained largely untested experimentally, and the limited laboratory attempts have still mainly focused on the MHz frequency band with the ultrasonic methods. The well-logging data (kHz), the in-situ exploration seismic (Hz), and the passive seismic (mHz-Hz) may not be comparable with the results measured at MHz level if there is appreciable seismic velocity dispersion.

By using the versatile Jackson-Paterson Attenuation Apparatus (mHz-Hz) at the Australian National University (Jackson & Paterson, 1993; Jackson et al., 2011) and the ultrasonic pulse transmission apparatus (MHz) at the University of Alberta, a broadband measurement on the glass-bead studied samples is planned. The attenuation apparatus allows the access to the natural seismic domain with both torsional and newly developed flexural forced-oscillation modes, from which the shear and Young's modulus can be extracted respectively.

Soda-lime silica glass beads, as the synthetic analogue for the natural sandstones with a similar percentage of silica but much simpler microstructure, with 300 ~ 350 μm diameters were sintered at glass transition temperature. The uniformly distributed cracks with low aspect ratio (~0.0007) were introduced by quenching the heated samples into liquid water at room temperature.

This extended abstract briefly reviews the methods used for glassbead specimen fabrication, and the preliminary results obtained from forced-oscillation experiments at mHz-Hz.

METHOD AND RESULTS

Forced-oscillation method

Jackson-Paterson Attenuation Apparatus is used to measure the response in displacement to the applied oscillating torque or bending force from the electromagnetic driver at seismic frequencies, or mHz range. The apparatus comprises independently controlled confining pressure and pore-fluid pressure systems, with argon as confining pressure gas medium and argon, water etc. as pore fluids ranging widely in viscosity and therefore also in timescale for fluid flow. The rock specimen is frictionally coupled with an elastic standard by confining pressure and the displacement associated with distortion of the experimental assembly of both specimen and elastic standard are measured by two pairs of three-plate capacitance transducers connected with a ratio transformer to construct an AC bridge. The measured out-of-balance bridge voltages in both torsional and flexural modes can be converted into displacements by calibration factors obtained from routine calibration immediately before and after the forced-oscillation experiments. Fast Fourier Transform can be performed to extract amplitudes and phases from the displacement time series to further provide the normalised compliance S_N by referring to the elastic standard (displacement of specimen / displacement of elastic standard) and phase lag δ (rad) between them. After comparing with a pure elastic fused silica reference with the same dimensions under the same experimental conditions to negate the contributions of all the components except just the specimen, the shear modulus μ and internal friction 1/Q can be extracted (Jackson and Paterson, 1993).

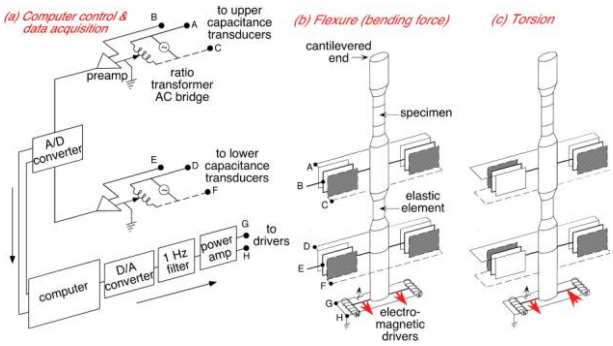


Figure 1. Experimental arrangement for (a) computer control and data acquisition system and forced-oscillation studies in (b) flexure (bending force) (c) torsion modes with alternative polarisations of electromagnetic drivers and displacement transducers.

With the newly modified capability for flexural-mode forced oscillation, the normalised flexural "modulus" S_{NF} and loss angle δ (rad) can be obtained, and a complementary filament elongation model for flexure of thin beam with both finite-difference and finite-element methods can be used to extract the modelled Young's modulus with the observed S_{NF} (Jackson et al., 2011).

Pore-fluid re-equilibration method

The in-situ permeability measurements can be achieved by the pore-fluid re-equilibration method performed with the independent pore-fluid system within the Jackson-Paterson Attenuation Apparatus. A 5 MPa perturbation of pore-fluid pressure is made to either upper or lower reservoir, the rate constant A (s^{-1}) for exponential pore-fluid re-equilibration measured in situ can be further inverted into the permeability (m^2) (Lu, 1996, 1998; Lu and Jackson, 2006; Olin, 2011).

Sintering and thermal cracking of glass beads

Simpler synthetic analogues of natural upper crustal rocks can enable us to better control the chemical composition and microstructures, and therefore bypass the mineralogical and physical complexity of natural rocks. Soda-lime silica glassbead specimens, as the synthetic analogue of natural sandstones, can be made by sintering glass beads (containing ~75% silica by weight) with diameters between 300 and 350 μm loaded within a cylindrical glass mould at 700 °C for 18 hours. The resultant specimens have nearly equant pores with 1 ~ 2% porosity.

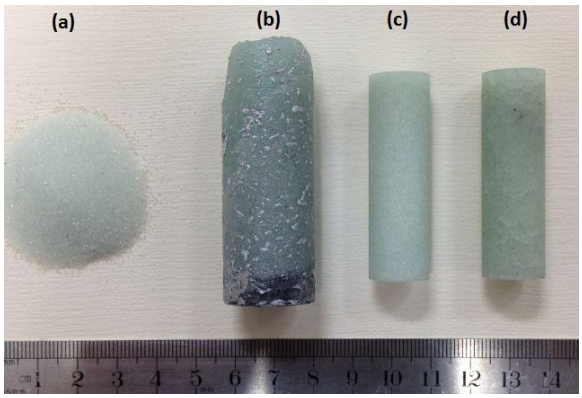


Figure 2. (a) The soda-lime silica glass beads with diameters between 300 and 350 μm; (b) the glassbead specimen sintered at 700 °C for 18 hours; (c) the ground and polished glassbead specimen with 15 mm diameter and 50 mm length; (d) the cracked glassbead specimen by quenching from 500 °C into liquid water at room temperature.

Cracks can be simply introduced by quenching precisely ground cylindrical specimens of 15 mm diameter and 50 mm length from ~500 °C into liquid water, retaining their overall mechanical integrity despite the development of interconnected networks of cracks with low aspect ratio α ~ 0.0007 (Olin, 2011).

Representative results I – permeability

The pore-fluid re-equilibration method was used to measure the in-situ permeability of the glassbead specimens both before and after thermal cracking. The permeability of cracked specimens is systematically higher than for crack-free material, and significantly effective-pressure dependent as the effective pressure ($P_{eff} = P_c - P_f$) plays a vital part in the crack closure mechanism.

The permeability of the cracked specimens decreases from 4.4 × 10^{-19} m^2 to 1.4 × 10^{-19} m^2 as the P_{eff} increases from 9 to 90 MPa and eventually superimposes on the uncracked specimens curve after the cracks all effectively closed by the high P_{eff}.

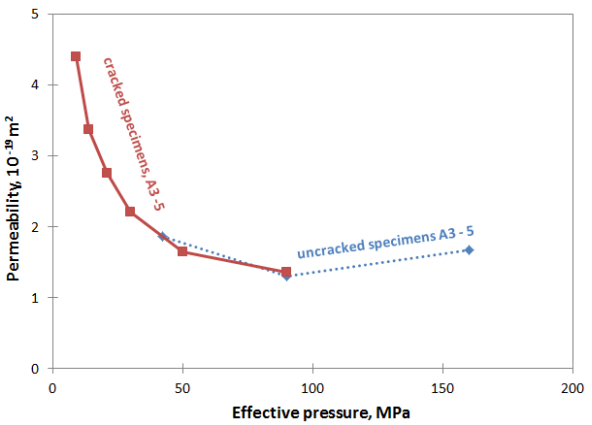


Figure 3. The in-situ measured permeability of both cracked and uncracked glassbead specimens A3-5.

Representative results II – elasticity

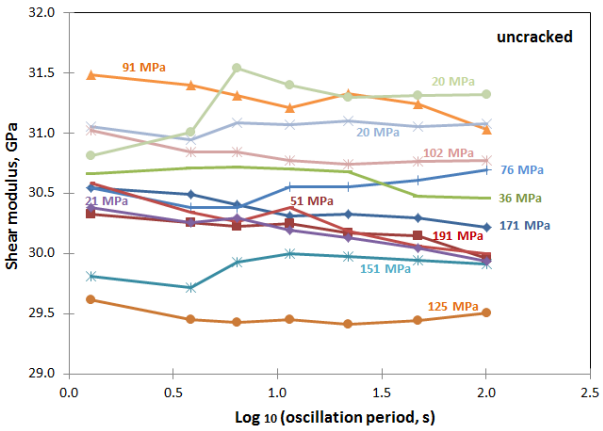
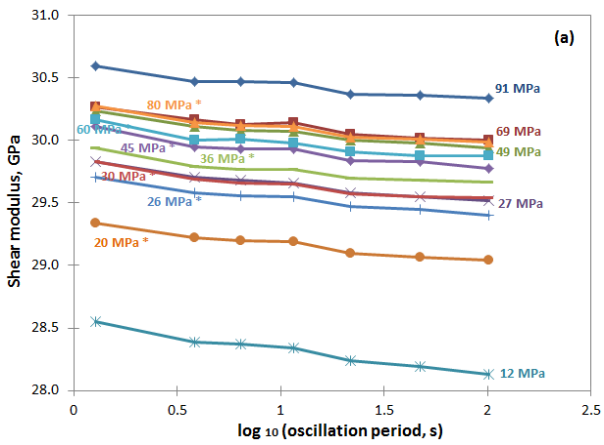


Figure 4. The shear modulus of the glassbead specimens A3-5 measured before the thermal cracking.

In comparison with the modulus measured for uncracked glassbead specimens A3-5, the influence on elasticity introduced by thermal cracking can be observed. The band of shear modulus for uncracked specimens lies between 29.5 GPa to 31.5 GPa (Fig. 4), and is consistently lowered to 28.5 GPa to 30.5 GPa (Fig. 5(a)) by subsequently introduced cracks.



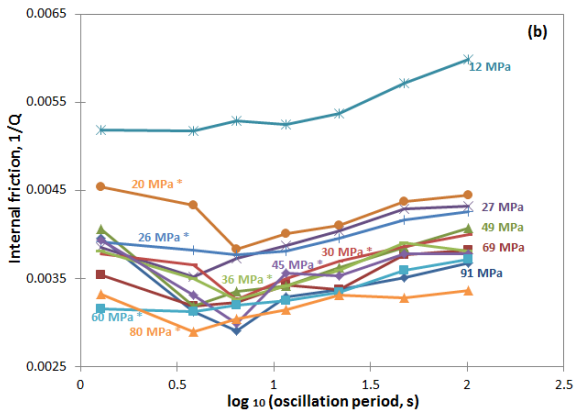


Figure 5. (a) The shear modulus of the cracked and argon pore fluid saturated glassbead specimens A3-5 measured at different torsional forced-oscillation periods and different P_{eff}, and the P_{eff} with asterisk symbols indicates the increasing P_{eff} process; (b) the internal friction measured on specimens A3-5.

The systematic trend of lower shear modulus can be found at longer oscillation periods in Fig. 5(a) may indicate the existence of the transition from the saturated isolated regime to the saturated isobaric regime as the longer oscillation periods were able to provide sufficient time for fluid redistribution between the adjacent pores and cracks for pore-fluid pressure re-equilibrium to give lower shear moduli. The maximum value for shear modulus can be expected at the highest measuring frequency in the subsequent ultrasonic measurement at the University of Alberta.

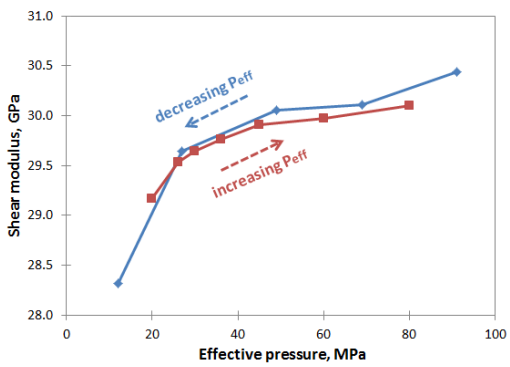


Figure 6. The P_{eff} dependence of the shear modulus of the cracked and argon pore fluid saturated glassbead specimens A3-5 for both increasing and decreasing P_{eff} processes.

Values of the period-averaged shear modulus are plotted against P_{eff} (Fig. 6). The significant P_{eff} dependence of shear modulus and the crack closure effect at $P_{eff} = E\alpha$ (Walsh, 1965) (i.e. ~50 GPa × 0.0007 = 35 MPa) can be observed. Some minor hysteresis effects can be explained by the irreversible part of the crack closure and re-opening processes.

The normalised flexural modulus S_{NF} defined as the ratio between the angle of flexure across the specimen and that for the elastic standard is significantly P_{eff} dependent and has the general trend of decreasing S_{NF} with increasing P_{eff} accompanied with some fluctuation and hysteresis effects for both pressurisation and depressurisation (Fig. 7(a)). The

Young's modulus E can be extracted by the filament elongation model for flexure of thin beams from the measured S_{NF}. E of the cracked and argon pore fluid saturated glassbead specimens A3-5 is distributed within the narrow band near 45 GPa. The errors of modelled results can originate from the uncertainties in calibrations for inverting the electrical out-of-balance signal (V) into displacement (mm) (Fig. 7(b)).

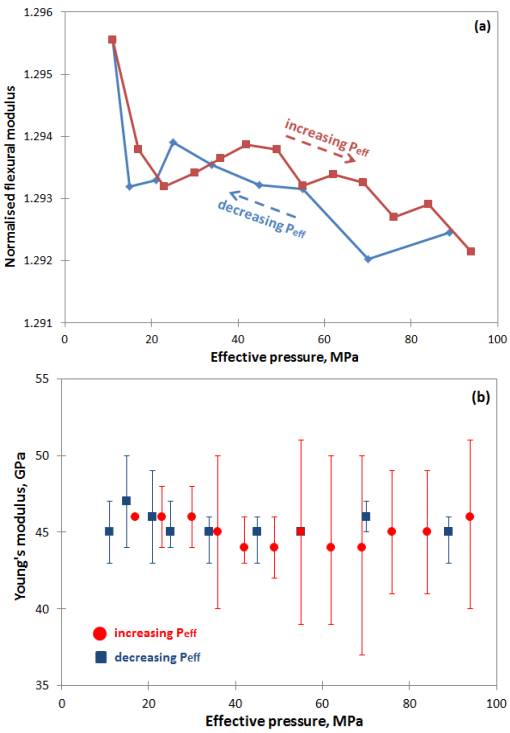


Figure 7. (a) The P_{eff} dependence of the normalised flexural modulus (S_{NF}) for cracked, argon pore fluid saturated glassbead specimens A3-5; (b) The modelled Young's modulus E from the measured S_{NF} with error bars using the finite difference methods.

CONCLUSIONS

The progress of the research reported here shows the potential to fabricate the synthetic glassbead specimens and develop interconnected cracks of uniformly low aspect ratio by the thermal method. This enables us to study the seismic properties of cracked and fluid saturated materials with relatively simple microstructure avoiding the complexities of natural geological materials. Saturation with fluids ranging widely in viscosity (thus different time scales for fluid flow) tested at different oscillation frequencies from mHz to MHz provides the experimental possibilities to prove the theoretical framework of different fluid flow regimes within the cracked materials. The P_{eff} for crack closure for the glassbead specimens A3-5 agrees with the theoretical estimation of 35 MPa (Walsh, 1965). The shear modulus obtained from the torsional mode forced oscillation shows systematic weakening effects through introducing cracks. The permeability is P_{eff} dependent and markedly decreasing with gradually increasing P_{eff} below the crack closing pressure and gradually levelled off after crack closure. The crack closure and re-opening effects can be re-confirmed by the marked change in both shear and flexural modulus at ~ 35 MPa. The systematic decrease of the shear modulus at longer oscillation periods may imply the transition from the saturated isolated regime to saturated isobaric regime which is distinguished from the measurements conducted on a single glassbead specimen (Olin, 2010) or cracked alumina (Schijns et. al, 2012), for both of which only the saturated isobaric regime was identified across the whole frequency band. Ongoing work will focus on improving sealing condition of the apparatus for longer duration measurements enabling the tests with water or glycerine as pore fluids which need longer time for re-equilibration. Further complementary tests at ultrasonic frequencies will be conducted at the University of Alberta. The porosity will also be measured there with mercury porosimetry to give more accurate estimation compared with the preliminary results of 1 ~ 2% using optical microscopy.

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REFERENCES

Fortin, J., Schubnel, A., and Gueguen, Y., 2005, Elastic wave velocities and permeability evolution during compaction of Bleurswiller sandstone: International Jorunal of Rock Mechanics & Mining Sciences, 42, 873-889.

Jackson, I. and Paterson, M.S., 1993, A high-pressure, high temperature apparatus for studies of seismic wave dispersion and attenuation: Pure and Applied Geophysics, 141, 445-466.

Jackson, I., Schijns, H., Schmitt, D. R., Mu, J. and Delmenico, A., 2011, A versatile facility for laboratory studies of viscoelastic and poroelastic behaviour of rocks: Review of Scientific Instruments, 82, 064501.

Lu, C., 1996, Shear mode anelasticity of thermally cracked and fluid-saturated rocks: Ph.D. Thesis, Australian National University

Lu, C. and Jackson, I., 1998, Seismic frequency laboratory measurements of shear mode viscoelasticity in crustal rocks, Part II, Thermally stressed quartzite and granite: Pure and Applied Geophysics, 153, 441-473.

Lu C., and Jackson I., 2006, Low-frequency seismic properties of thermally cracked and argon-saturated granite: Geophysics, 71(6), 147-159.

Olin M., 2010, Low-frequency seismic properties of synthetic sandstone: Bachelor Thesis, Australian National University.

Walsh J.B., 1965, The effect of cracks on the compressibility of rocks: Journal of Geophysical Research, 70, 381-389.

Schijns, H., Jackson, I., and Schmitt, D., 2012, Laboratory measurements of frequency-dependent seismic properties of cracked and fluid-saturated media: 22nd Meeting, ASEG, Brisbane, Extended Abstracts.

Schubnel, A., and Guéguen, Y., 2003, Dispersion and anisotropy of elastic waves in cracked rocks: Journal of Geophysical Research, 108(B2), 2101, doi:10.1029/2002JB001824.