Temperature- and pressure-dependent dynamic and static elastic moduli

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ABSTRACT: The differential characteristics of temperature- and pressure-dependent dynamic and static elastic properties are investigated in a range of temperature and confining pressure for porous sandstone. Results show that the dynamic and static Young's moduli increase against confining pressure, whereas the dynamic one decreases and the static one increases against temperature, respectively. The ratios of static and dynamic elastic properties for the Young's modulus decrease against the ratio of thermal stress to confining pressure. The opposite result is observed for the Poisson's ratio. We demonstrate that the progressive crack closure of primary microcracks associated with the limited expansion of cement material is dominant in the range of experimental pressure and temperature, instead of the development of new microcracks during thermal treatments. Therefore, the axial and radial strains decrease with increasing pressure and temperature, which reduces the static Poisson's ratio but increases the static Young's modulus.

Keywords: Dynamic and static moduli, Temperature and pressure dependence, Microcracks, Strain amplitudes.

1 INTRODUCTION

Knowledge the elastic properties of rocks is essential in the characterization of the mechanical properties (Batzle et al. 2006). Elastic properties from slow deformation of a rock are typically determined from stress and strain data, referred to as the static elastic properties, while requires access to the rock mass, which is expensive and time consuming. Elastic properties can also be calculated from elastic wave velocity. Inversion of these data gives the dynamic elastic properties. However, the dynamic and static elastic properties are generally not equal and consequently, for the purposes of subsurface geomechanical modeling and petroleum reservoir geomechanics (Cheng & Johnston 1981), the differences between the dynamic and static elastic properties should be understood.

Although many works deal with the effect of temperature or pressure on the dynamic and static moduli in porous rocks (e.g. Winkler et al. 1979; Fjær 2009; Zhang et al. 2019), the joint effects of temperature and pressure remains largely unaddressed. This study elaborates the differential characteristics between static and dynamic moduli induced by the joint effects of temperature and pressure for porous sandstone. We demonstrate that temperature and pressure significantly affect the microstructure evolution of porous rocks, which in turn affects the static and dynamic moduli.

2 THEORETICAL BACKGROUND

Assuming the material is isotropic, the dynamic moduli from ultrasonic tests (non-destructive procedure) can be determined from the bulk density (ρ) and P- and S-wave velocities (V_P and V_S),

$$\upsilon_{DY} = \frac{(V_P)^2 - 2(V_S)^2}{2(V_P)^2 - 2(V_S)^2} \tag{1}$$

$$E_{DY} = \frac{\rho(V_S)^2(3(V_P)^2 - 4(V_S)^2)}{(V_P)^2 - (V_S)^2} \tag{2}$$

where υ_{DY} and E_{DY} are the dynamic Poisson's ratio and Young's modulus, respectively. Under the axial loading condition with a constant confining pressure, the static moduli from mechanical measurements (destructive procedure) can be typically calculated from the stress–strain curve,

$$\upsilon_{ST} = -\frac{\Delta\varepsilon_r}{\Delta\varepsilon_a} \tag{3}$$

$$E_{DY} = \frac{\Delta\varepsilon_d}{\Delta\varepsilon_a} \tag{4}$$

where υ_{ST} and E_{DY} denote the static Poisson's ratio and Young's modulus, respectively, and $\Delta\varepsilon_a$, $\Delta\varepsilon_r$, and $\Delta\varepsilon_d$ represent increments in axial strain, radial strain, and differential stress (subtracting axial stress from hydrostatic stress), respectively.

3 EXPERIMENTAL METHODOLOGY

3.1 Materials

The sandstone sample is normatively cut into approximatively 2.54 cm in diameter and 5.00 cm in length with bulk density of 2.17 g/cm^3. The porosity is about 17.6% at room temperature. The mineral compositions of porous sandstone are characterized using the X-ray Diffraction analysis. The results show that sample consists of 46% quartz, 33% plagioclase, 13% orthoclase, 6% clays (64% kaolinite and 36% illite), and 1% calcite.

3.2 Experimental Procedures

We conduct dynamic and static measurements using a servo-hydraulically controlled triaxial testing apparatus, AutoLab 1500 manufactured by New England Research Inc., as shown in Figure 1. The system has a maximum axial pressure of 823kN and a maximum confining pressure of 68 MPa. Dynamic and static measurements for the sandstone are performed at room-dry condition. The entire sample assembly is placed inside the confining vessel. There is a hydrostatic gap between the top of the standard platen and the hydraulic piston. When the vessel is filled with the hydraulic oil, the sample is under the hydrostatic stress condition. The axial stress is controlled by axial stress pump to move the hydraulic piston. The differential stress will increase when the piston touches the top platen. The tests are conducted while the confining pressure increases from 10 to 50 MPa at an increment of 10 MPa with a rate of 0.1 – 0.2 MPa/min. The differential stress is maintained at a constant stress of 15 MPa by controlling simultaneously the hydrostatic and axial stresses. For static measurements, the amplitude change of differential stress is 15 MPa. For each pressure–cycle measurement, the temperature increases step wise by staying at the constant temperature of 25, 43, 63, 83, and 103°C with a low heating rate of 0.1°C – 0.2°C/min. When both the pressure and temperature are balanced, acoustic waveforms are collected to give compressional and shear wave velocities. With increasing axial compressions under the constant confining pressure, the radial and axial compression curves of stress and strain are collected to determine static elastic properties. These two measurements for static and dynamic elastic parameters are mutually independent, which are controlled by static and ultrasonic measurements of automatic programs, respectively.

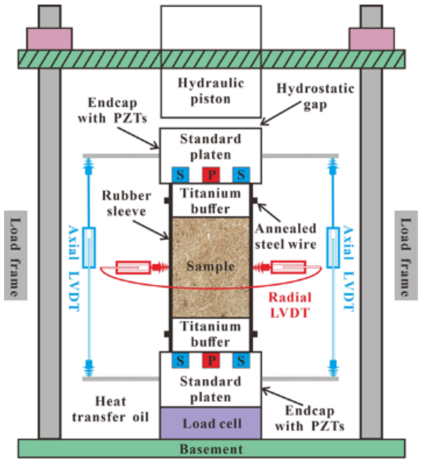

Figure 1. Schematic of the servo-hydraulically controlled triaxial testing apparatus.

4 RESULTS

4.1 Young's Modulus

Figure 2 shows the Young's moduli against confining pressure under different temperatures. We see that the dynamic Young's modulus increases from (21.4, 20.6, 20.1, 19.3, 18.9) GPa to (28.6, 27.7 27.2, 27.0, 26.5) GPa against confining pressure under the temperature of 25, 43, 63, 83, and 103°C, while decreases from (21.4, 23.5, 25.4, 27.0, 28.6) GPa to (18.9, 21.8, 23.9, 25.7, 26.5) GPa against temperature under the confining pressure of 10, 20, 30, 40, and 50 MPa, respectively. The possible explanation is because the dynamic moduli of porous rocks are estimated from elastic waves that interact with cracks only within the propagation path (Blake & Faulkner 2016). The static Young's modulus, however, increases with both increasing pressure and temperature. It increases from (13.6, 13.8, 13.9, 14.1, 14.3) GPa to (18.6, 19.0, 19.9, 20.3, 21.1) GPa against confining pressure and from (13.6, 15.5, 16.8, 17.6, 18.6) GPa to (14.3, 17.0, 19.0, 20.3, 21.1) GPa against temperature, respectively. Unlike dynamic elastic properties, the static ones are probably influenced by all microcracks within the sample (Blake & Faulkner 2016).

We find that the axial strain amplitude decreases with increasing confining pressures because of the closure of microcracks (see Figure 3). The axial strain amplitude also decreases with increasing temperatures that can be attributed to the joint effects of new microcracks and the change of preexisting microcracks. Elastic wave velocities (dynamic elastic properties) decrease with increasing temperatures, implying that the assumption of the development of new microcracks and extended preexisting microcracks, which can add to axial strains. Within the experimental temperature range, the preexisting microvoids and microcracks inside the rock also decrease owing to the thermal expansion in minerals, which strengthens the compactness of grains and reduces axial strains. That is, the decreased preexisting microcracks during heating plays a more important role than the extended preexisting microcracks and the development of new microcracks, yielding the reduction in laxial strains and making the static Young's modulus less than its intrinsic value (Walsh et al. 1965). This explains the different tendency of variations between static and dynamic Young's modulus against temperature.

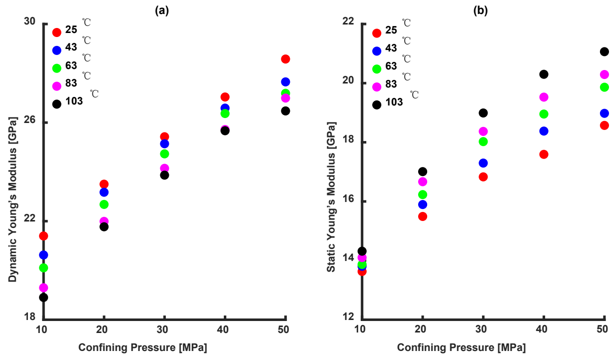

Figure 2. Young's moduli against confining pressure for (a) dynamic and (b) static tests.

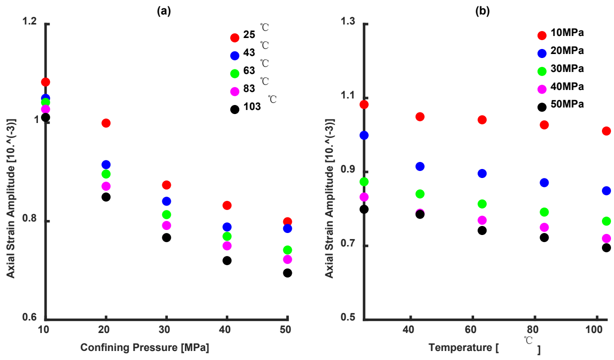

Figure 3. Axial strain amplitudes against (a) confining pressure and (b) temperature.

4.2 Poisson's ratio

Figure 4 shows the Poisson's ratio against confining pressure under different temperatures. We see that the dynamic Poisson's ratio decreases from (0.21, 0.20, 0.21, 0.20, 0.21) to (0.19, 0.17, 0.17, 0.178, 0.178) against confining pressures under the temperature of 25, 43, 63, 83, and 103℃, while becomes relatively constant (slight increase) from (0.21, 0.19, 0.18, 0.18, 0.19) to (0.21, 0.20, 0.19, 0.19, 0.18) against temperatures under the confining pressure of 10, 20, 30, 40, and 50 MPa, respectively. The static Poisson's ratio, however, significantly decreases with both increasing confining pressure and temperature. It decreases from (0.30, 0.27, 0.25, 0.23, 0.22) to (0.27, 0.23, 0.21, 0.19, 0.19) against confining pressure and from (0.30, 0.28, 0.27, 0.27, 0.27) to (0.22, 0.21, 0.19, 0.18, 0.19) against temperature, respectively.

The increase in S-wave velocity is greater than that in P-wave velocity with increasing pressure, yielding the decrease in the dynamic Poisson's ratio (see Figure 4). We find that the radial strain decreases with increasing pressure and temperature. Instead of the extended preexisting microcracks and developed microcracks, the closure of microcracks against confining pressure and the domination of decreased preexisting microcracks during thermal treatments are responsible for the reduction in both radial and axial strains (see Figures 3 and 5). Radial strains are more sensitive to temperature and confining pressure than axial strains, ultimately reducing the static Poisson's ratio. Figure 5 shows the amplitude ratios of radial to axial strains against confining pressure and temperature, respectively. This probably explains the variations in static Poisson's ratio against confining pressure and temperature.

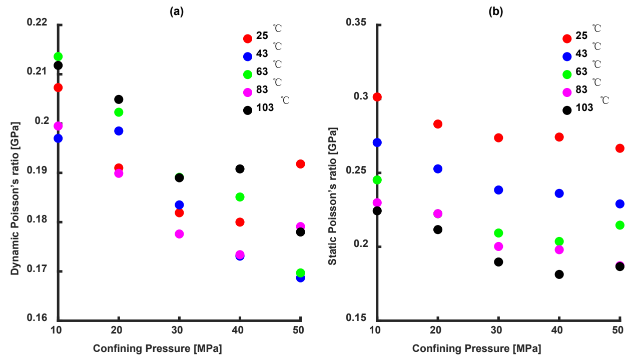

Figure 4. Poisson's ratios against confining pressure for (a) dynamic and (b) static tests.

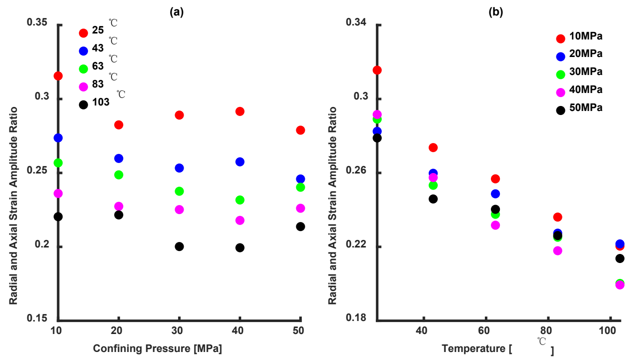

Figure 5. Amplitude ratios of radial to axial strains against (a) confining pressure and (b) temperature.

4.3 Relationship Between Static and Dynamic Moduli

Thermal stress is the stress caused by the temperature increment and adds to the body independent of volume under the isothermal process (Anderson et al. 1991). The addition of thermal stress with an increase in temperature is of central importance for characterizing the thermoelastic behavior of minerals. It is defined as the multiplication of the effective bulk modulus, coefficient of volume thermal expansion, and temperature increment (Anderson et al. 1991). Considering the thermal stress exerted by an increase in the temperature and confining pressure applied, Yang et al. (2022) propose an exponential empirical trend to correlate the static and dynamic moduli. Figure 6(a) – 6(b) show the ratios of static and dynamic Young's modulus and Poisson's ratio against the ratio of thermal stresses to confining pressures, respectively. We observe that the static and dynamic Young's modulus ratios ultimately tend to be (0.6498 – 0.6620) at the relatively higher ratios of thermal stress to confining pressure (above 1.4), but increase to (0.7812 – 0.7957) at the relatively lower ratios of thermal stress to confining pressure (below 1), respectively. Namely, the behavior of static Young's modulus will approach to those of the dynamic moduli with increasing confining pressures. For the equivalent static and dynamic Young's modulus at these temperatures, however, the ratio will equal to 0.00695, 0.02068, 0.03478, and 0.05154, respectively. We find that the static and dynamic Poisson's ratios ultimately tend to be (1.3900 – 1.5230) with increasing thermal stress in the thermal stress-controlled range, but inclined to be (0.9502 – 1.0450) in the confining pressure-dominant range, respectively. The static Poisson's ratio is dominant for experimental temperatures and confining pressures, but will tend to be less than the dynamic Poisson's ratio at higher confining pressures where the ratio of thermal stress to confining pressure becomes 0.08106, 0.2044, 0.3447, and 0.3118 for 43, 63, 83, and 103°C, respectively. Namely, the static Poisson's ratio will be greater than dynamic one with increasing thermal stress. This can be explained by the decreased preexisting microcracks, which imposes greater effects on the static Poisson's ratio than the dynamic one.

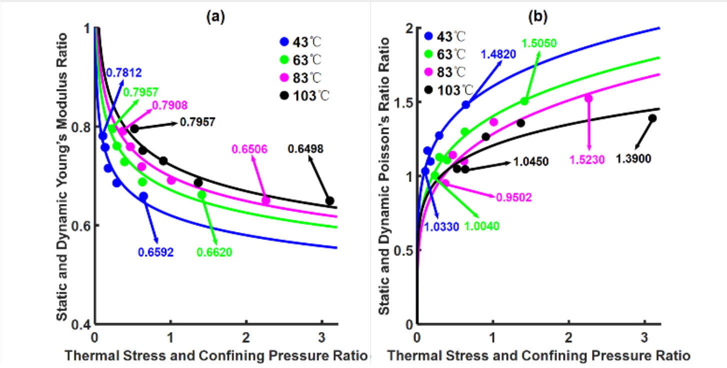

Figure 6. Variations of the ratio of static and dynamic (a) Young's modulus and (b) Poisson's ratios against the ratio of thermal stress to confining pressure under different temperatures.

CONCLUSION

Compared Poisson's ratio, the dynamic and static Young's moduli show an opposite tendency against confining pressure and temperature. These can be attributed by the closure of microcracks and domination of decreased preexisting microcracks for experimental temperatures and pressures, instead of the extended preexisting microcracks and developed microcracks during thermal treatments, which can reduce both radial and axial strains, ultimately leading to the increase in static Young's modulus but the decrease in static Poisson's ratio. This implies the joint effects of confining pressure and thermal stress has a greatly influence on the elastic properties of rocks.

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REFERENCES

Anderson, O.L., Isaak, D.L., & Oda, H. 1991. Thermoelastic parameters for six minerals at high temperature. Journal of Geophysical Research: Solid Earth 96 pp. 18037-18046. DOI: 10.1029/91JB01579

Batzle, M.L., Han, D.H., & Hofmann, R. 2006. Fluid mobility and frequency-dependent seismic velocity–direct measurement. Geophysics 71 (1) pp. N1-N9. DOI: 10.1190/1.2159053

Blake, O.O., & Faulkner, D.R. 2016. The effect of fracture density and stress state on the static and dynamic bulk moduli of Westerly granite. Journal of Geophysical Research: Solid Earth 121 pp. 2382-2399. DOI: 10.1002/2015JB012310

Cheng, C.H, & Johnston, D.H. 1981. Dynamic and static moduli. Geophysical Research Letters 8 (1) pp. 39-42. DOI: 10.1029/GL008i001p00039

Fjær, E. 2009. Static and dynamic moduli of a weak sandstone. Geophysics 74 (2) pp. WA103-WA112. DOI: 10.1190/1.3052113

Walsh, J.B. 1965. The effect of cracks in rocks on Poisson's ratio. Journal of Geophysical Research 70 (20) pp. 5249-5257. DOI: 10.1029/JZ070i020p05249

Winkler, K., Nur, A., & Gladwin, M. 1979. Friction and seismic attenuation in rocks. Nature 277 pp. 528-531. DOI: 10.1038/277528a0

Yang, J., Fu, L.Y., Zhang, Y., & Han, T.C. 2022. Temperature- and pressure-dependent pore microstructures using static and dynamic moduli and their correlation. Rock Mechanics and Rock Engineering 55 pp. 4073-4092. DOI: 10.1007/s00603-022-02829-4

Zhang, L., Ba, J., Fu, L.Y., Carcione, J.M., & Cao, C. 2019. Estimation of pore microstructure by using the static and dynamic moduli. International Journal of Rock Mechanics and Mining Sciences 113 pp. 24-30. DOI: 10.1016/j.ijrmms.2018. 11.005