Effect of thermal shock on P and S wave speeds in a low-porosity quartz sandstone

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Summary

Thermal shock is expected to have a substantial influence on rock's elastic behavior because of the induced cracks. Here, an experiment was carried out to measure the velocity of P- and S- waves at various confining pressures for the same dry quartz rich sample before and after it was damaged by thermal shock. When we compared the sample before and after applying thermal shock, the wave velocity, elastic modulus, crack density and damage parameter show similar trends with changing pressure. Both events show a rapid change before 80 MPa of confining and much slower linear change after 80 MPa.This implies most of the thermal cracks have been closed at 80 MPa and only some inner pore space left. Young's modulus showed a non-linear relationship with the pressure change. Crack density and damage degree can be derived from the Kachanov (1993) model for dry rocks. Therefore we can gain a general understanding about the effects of the thermal shock on quartz rich sample.

Introduction

Thermal shock is named for the rapid temperature change and the induced thermal gradient can cause the expansion of the rock by different amount, followed by cracking, breaking, or even shattering of the rock sample. Such damage could be expected from various geothermal or enhanced petroleum recovery methods in which the rock mass could be subject to relatively rapid heating or cooling. As we know, the presence of the cracks in rocks strongly influences the rock's physical properties including the elastic velocity, elastic modulus and mechanical strength properties. Moreover, its evolution is strongly dependent on the effective pressure. With increasing pressure, the cracks will gradually close which makes the wave travels faster and the rock sample stiffer. The velocity would keep increasing until the pressure is large enough to close all the cracks.

In this paper, we use the ultrasonic transmission method to measure the velocity behavior of the initial dry rock sample and the shocked sample under various pressures. We will focus on the effect of the 650℃ heating shock on the rock properties including the velocity and the elastic modulus. Further, based on the Kachanov's model, we calculate the crack density with the pressure's change and from this relationship the effect of the thermal shock are shown more directly.

Method and Experiment

A cylindrical shaped Canadian quartzite sample of 25mm in diameter was made approximately parallel into 58.17mm in length. Then the end faces of the sample were ground and polished precisely with the wet grinder to make a flat and parallel end face. Before putting the sample into the pressure vessel, the sample was first put into an oven at 70°C for drying under vacuum for nearly 50 hours. Then the elastic waves were measured as a function of confining pressure. After this first set of measurements was completed, the sample was heated in a furnace at 650°C for 90 minutes, and then quenched into cold water to induce thermal shock. The reason for the chosen temperature is because it is above the quartz α / β transition which can induce drastic cracks in sample [Reusche, 2003] due to changes in the volume of the quartz crystal.

The sample was firstly placed between a pair of transducers and jacketed in clear Tygon® tubing. The tube and the rubber o-rings that surround the aluminum buffer were tightened by iron hose clamps. Figure1a shows a completely prepared sample which is ready to put into the pressure vessel. To ensure good results of S wave, we first test the angle of the transducer pair to achieve proper polarization and mark this relative position of the transducers. The experiments were carried out at room temperature under drained conditions. The red pressure vessel which can provide nearly 500 MPa for confining pressure in maximum is showed in Figure 1b. The wave was generated by pulse generator and the received signal was amplified. We picked the first peak on the oscilloscope as the wave travel time which had an accuracy of 10 ns in time, this corresponds to an uncertainty of about ±20 m/s in velocity. During an experiment, we changed the pressure cyclically. First, we increased the confining pressure from 0 MPa to 300 MPa, and then decreased the pressure back to 0 MPa. Before each measurement, we need to wait for at least 5 minutes in order for the sample to equilibrate.

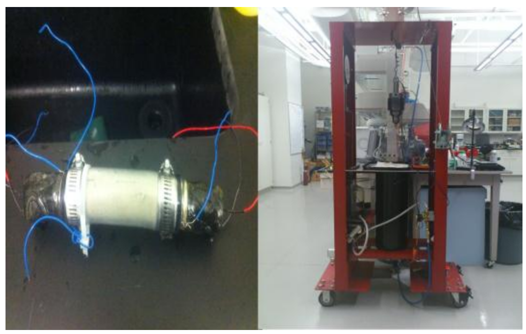
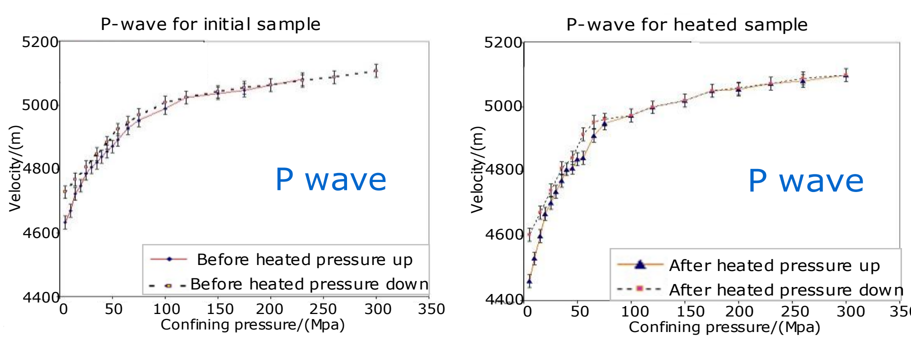


Figure 1 (a) Completely set-up sample. (b) The pressure vessel

Results

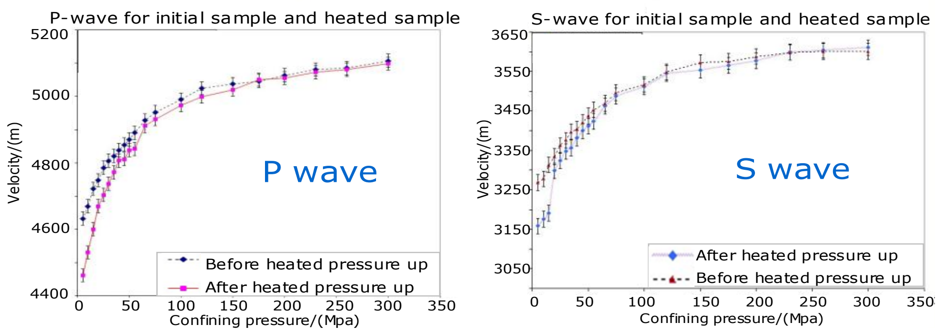
Figure 2 shows the raw data for the before and after P wave velocity measurements. The trend of the velocity with increasing pressure can be generalized as having two main regimes. At low pressures, the trend is nonlinear with the velocity increasing with pressure. This trend shifts to a more linear increase at about 80 MPa of confining pressure, this linear increase is consistent with that expected for a low porosity sandstone. Comparison of the up and down cycles further displays an obvious hysteresis (i.e. the velocity during depressurization is higher than that during the initial pressurization).



(a) (b)

Figure 2. Wave velocity with pressure change. (a) P wave velocity for initial sample. (b) P wave velocity for heated sample.

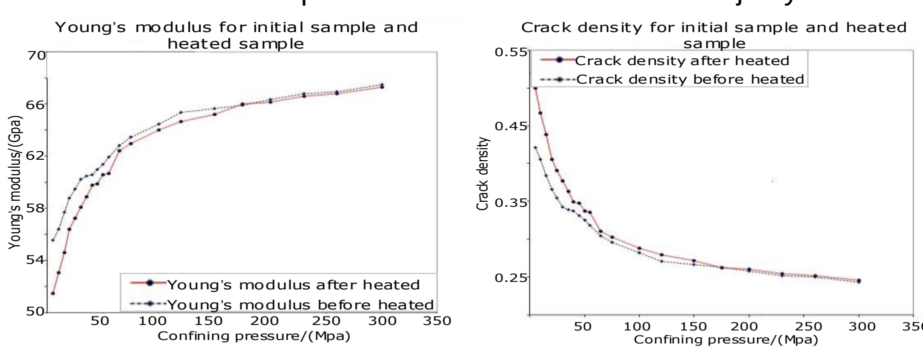
Figure 3 shows the comparison between the P- and S- wave velocities for the initial undamaged and the heat shock damaged rock. In figure 3a, P wave velocity of the heated rock decreases much more than the initial sample because of the influence of shocked cracks. During low pressure loading(less than 80Mpa), the wave velocity of both initial and heated sample changes rapidly. This nonlinear trend is mainly resulting from the closure of pore space and cracks with different aspect ratio, crack surface and geometry structures. While the heated sample increases more rapidly than the initial one because besides the initial cracks, thermal shock induces more cracks and now there is more space available for collapsing. As the pressure is elevated above 80 MPa, the two curves nearly come into one point which implies most of the shock induced cracks have been closed. In rock physics, this pressure is defined as “crack closure pressure”. This is because at this pressure, most of the cracks have been closed and the velocity in the later period is mainly affected by the pore space inside. Although the velocities change slowly at higher pressure, the curve still continue to increase even at the maximum pressure 300 MPa because the pore space inside the rocks is not completely closed. For S wave in figure 3b, it behaves much similar to P wave.



(a) (b)

Figure 3 Wave velocity comparison (a) P wave velocity for initial sample and heated sample. (b)S wave velocity for initial sample and heated sample

In addition to the velocity measurements, the elastic moduli was calculated to show the sample’s mechanical property change. Young’s modulus E describes the rock’s linear compressibility in responses to the application of a uniaxial stress. Based on the assumption that the sample is isotropic and homogenous, E can be calculated with the measured velocities. Figure 4a shows the change of Young’s modulus under pressure loading. The red and black lines represent the heated sample and initial sample respectively. The original point of the red line is smaller than the black line and it shows a much big difference with the pressure change. This shows the thermally shocked rock was less stiffened and the pressure loading made a deeper influence to the shocked sample. During the loading pressure increase, both curves increase and behave in a non-linear trend. But the red line changes more quickly and the slope is steeper. As mentioned above, this is the result of thermal shock which induces more cracks and makes more space available for collapse. As the pressure passes 80 MPa, the two curves are almost at the same point due to the closure of the majority thermal shocked cracks.



(a) (b)

Figure 4 Modulus Comparison and Crack density comparison (a) Young's modulus for initial sample and heated sample (b) Crack density for initial sample and heated sample

The crack density parameter ε was firstly introduced by Walsh [1965] as $\varepsilon = \frac{1}{V}\sum_i l_i^3$ where V is the bulk volume of the rock sample and *l* is the radius of each crack. If we assume the cracks are randomly distributed in an isotropic medium and the cracks are flat spheroids with no interaction, Kachanov's crack model can be used to calculate the crack density as a function of elastic modulus $(\frac{E}{E_0})^{-1} = 1 + \varepsilon \frac{16(1-\nu_0^{\ 2})}{9(1-\nu_0/2)}$ where *E* and E_o are the Young's moduli of the cracked rock and the undamaged rock, respectively and ν_o is the Poisson's ratio of the undamaged rock. is the Young's modulus for undamaged rock and G_0 is t*he shear modulus for undamaged rock.* Figure 4b shows the crack density of the initial and heated rock. After thermal treatment, the crack density increases by almost 25%. This phenomenon strongly demonstrates the previous information obtained by modulus comparison and velocity comparison that much more cracks formed due to thermal shock. Moreover, two general trends can be noticed: a progressive decrease with confining pressure loading followed by a quasi-constant change. The rapid increase result from the closure of different cracks and the following constant period is the result of the collapse of the inner pore space.

Conclusion

The velocities of P- and S- waves of the initial and 650℃ thermal shocked rock were measured under confining pressures from 5 MPa to 300 MPa. According to the behavior of elastic velocity, elastic modulus and crack density, we can understand the effect of thermal shock. From the raw elastic wave velocity data, the obvious hysteresis phenomenon can be noted. By comparing the wave velocity, elastic modulus and crack density, the heated sample was observed to behave differently from the initial sample. The shocked sample was damaged further (with a higher crack density) causing the P and S waves to slower than before. But with pressure loading, a change was observed followed by a slower linear change because of the closure of cracks. The break pressure is at 80 MPa where most of the cracks have collapsed and two samples behave similarly under higher pressure loading.

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