Experimental relations between stress and fracture properties on synthetic anisotropic media

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Summary

Elastic anisotropy due to aligned cracks has been the subject of many seismic physical modeling experiments. In earlier investigations, different experimental approaches have taken into account the size, shape and density of cracks. In this paper we present a physical study of the aspect ratio as a function of applied uniaxial stress. We carried out pulse transmission measurements of P- and S-wave velocities in a reference model without inclusions and in a model with penny-shaped neoprene inclusions. The reference model is an anisotropic matrix that consists of stacked plexiglass plates. Rubber discs were used as inclusions in that anisotropic matrix leading to secondary anisotropy. We recorded ultrasonic seismic data using P-wave transducers with central frequency 120 kHz and S-wave transducers with 90 kHz. We compressed the physical models using pressures ranging from 3 to 15.8 MPa. Full crack closure occurs at stress 14.6 MPa normal to model faces. Our analysis indicates three different regimens for the behavior of the inclusions. These results suggest a different dependence of the crack aspect ratio on uniaxial stress at the low state of stress than usually described in the literature. Though our results are not extensive, they show that simple experimental approaches might provide valuable insight into the behavior of cracked rocks at reservoir stress levels.

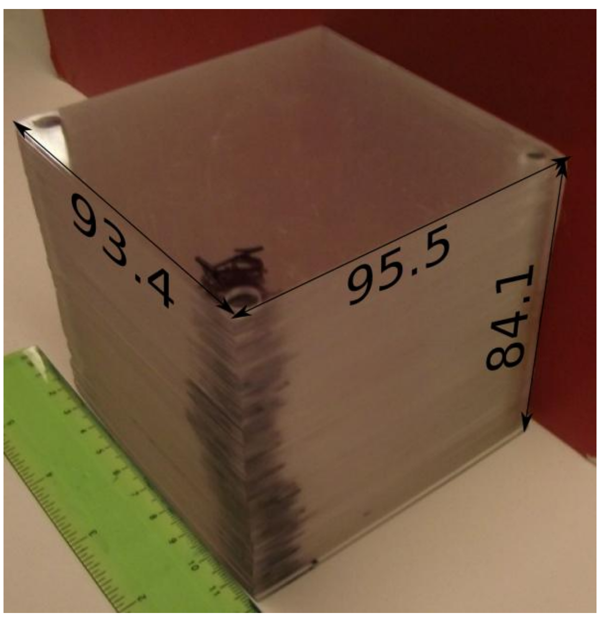

Figure 1 - Reference model with dimensions in milimeters.

Introduction

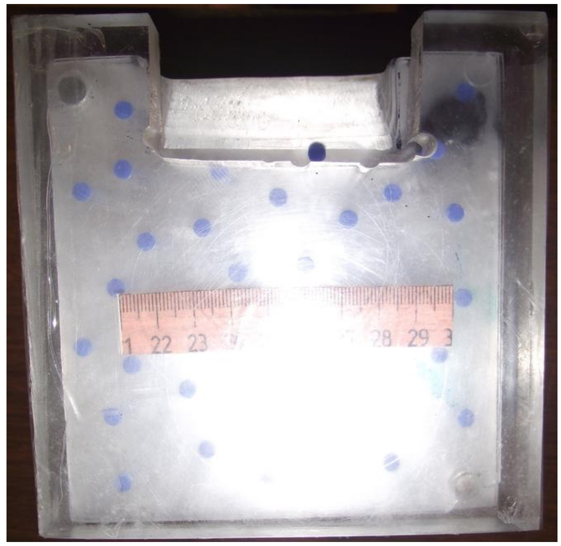

Figure 2 - Model with inclusions before compression.

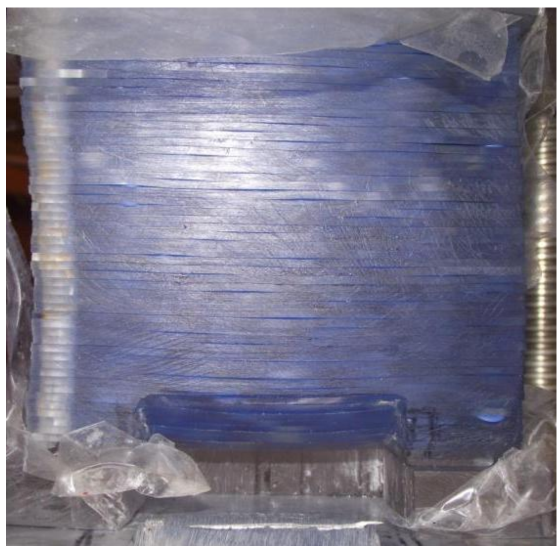

Figure 3 - Model with inclusions at maximum compression.

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In the presence of confining stresses or fluid pressure, naturally occurring cracks are subject to distortions in

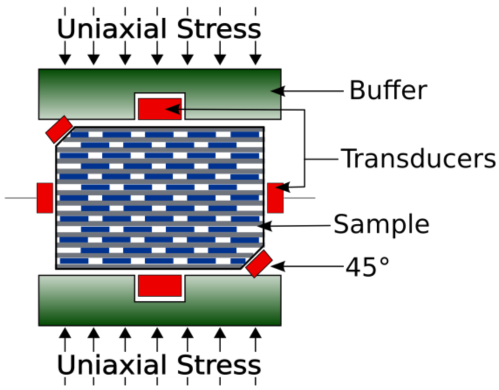

Figure 4 - Schematic of composite model and experimental setup.

orientation and shape (Nelson, 2001). Thus, changes in the distribution of cracks due to changing stress might affect the elastic properties of the medium as well as fracture properties (Eftekharifar, 2011; Far, 2011). To evaluate the effect of uniaxial stress on crack aspect ratio and crack density, we performed an experimental investigation in a layered model of stacked plexiglass plates which was later modified through the inclusion of penny-shaped neoprene discs. This anisotropic background medium built of plexiglass represents the host rock and the rubber discs represent weakly filled cracks (De Figueiredo, 2011). Over these anisotropic backgrounds, we determined P- and S-wave velocities using transmitted ultrasonic pulse techniques. From these velocities we calculated several medium parameters, allowing a thorough elastic characterization of the medium, according to procedures delineated by De Figueiredo (2011), Omoboya (2011) and Stewart (2011). We studied the effect of stress on crack aspect ratio and crack density. For this purpose, we followed a modified version of the methodology of Olson (2003), carrying compression from 3 to 15.8MPa. One observation is that under low stress there are two regimens that dictate the behavior of the neoprene inclusions. Furthermore, our results have shown that the Mavko *et al.* (2009) relations are satisfied only past 14.6MPa.

Experimetal Setup

The construction of the models as well as the ultrasonic measurements were carried out at the Allied Geophysics Laboratories (AGL) at University of Houston. The models consisted of 55 stacked, 1.5mm thick plexiglass plates, perforated at the corners for addition of a slip-prevention device (see Figure 1). We used the same type of plexiglass plates for the construction of the cracked and uncracked models. For construction of the model with inclusions, we placed 30 neoprene rubber discs (V_P = 1650m/s) between

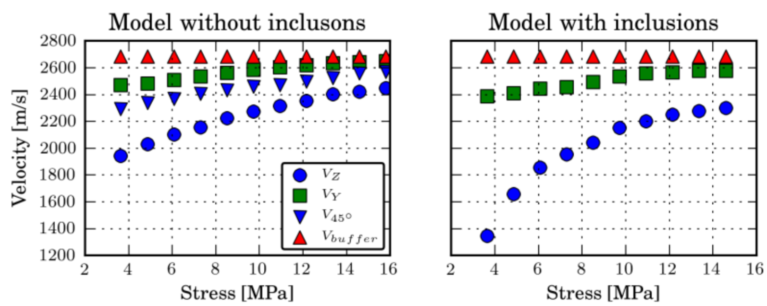

Figure 5 - P velocity measured with transducer of 120 kHz central frequency.

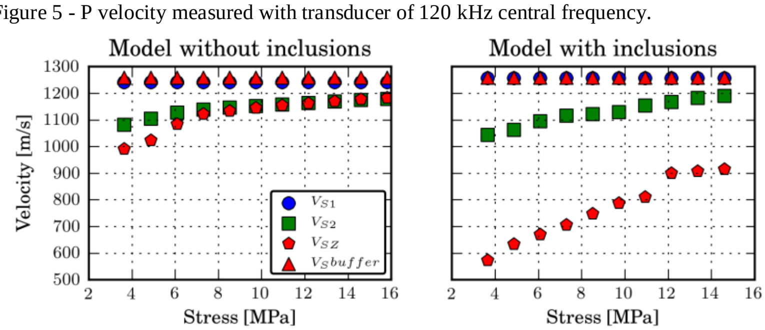

Figure 6 - S velocity measured with transducer of 90 kHz central frequency.

each pair of plexiglass plates, with the addition of a millimeter scale to allow the measurement of the inclusion diameter during the whole experiment (see Figure 2). To guarantee that all inclusions had constant diameter, we used hole punchers to cut the neoprene rubber disks.

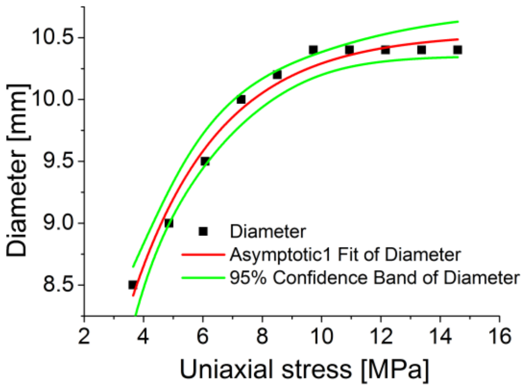

Figure 7- Inclusion diameter as function of uniaxial stress. Red line is a fitted curve. Green line is the 95% confidence band.

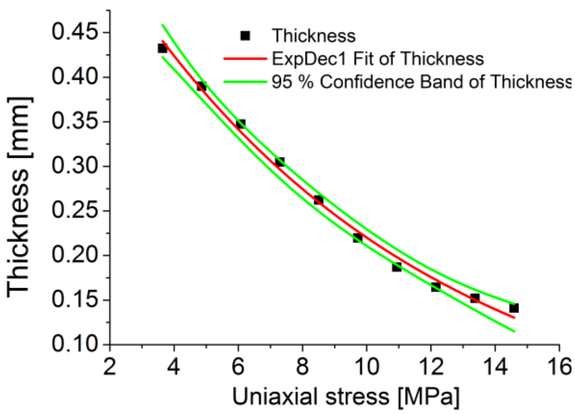

Figure 8 - Inclusion thickness as function of uniaxial stress. Red line is a fitted curve. Green line is the 95% confidence band.

Since the plexiglass plates and neoprene discs adhere well, diameter variation is assumed to be uniform for all discs in the model. The crack density ε can be estimated according to the Hudson (1981) formula,

$$\varepsilon = \frac{NV_c}{V} = \frac{N\pi hr^2}{V}$$

where N is the number of cracks, V_c is the volume of a single crack, and V is the volume of the model. For our penny-shaped cracks, $V_c=\pi hr^2$, where r is the crack radius and h is the crack aperture or inclusion thickness.

For the ultrasonic experiments, we arranged the source and receiver S-wave transducers on opposite sides of the model with initial shear wave polarization parallel to the inclusions. Figure 4 shows a schematic depiction of the experimental setup. We then rotated both transducers in 18 steps of 10° to change the polarization. Polarizations at 0 and 180° represent fast S-waves (S_1) while those at 90° represent slow S-waves (S_2). There is a delay of 2.7μs for the S-wave transducers and of 2.9μs for the P-wave transducers. The analog ultrasonic signal was digitalized using a scale factor of 1:10,000. For the velocity computation the scaled delay time was subtracted from the observed arrival time. The accuracy of the time picking was ±0.2μs, which yields an error in the estimated velocities of ±4m/s. The experiment incremented the stress in several steps from 3MPa up to 15.8MPa, using the same device as Omoboya (2011).

Besides determining the P, S_1, and S_2 velocities in the model itself, we also measured them in a plexiglass block called the *buffer*. This buffer is used for support during compression and to establish reference velocities. The latter measurement also served for quality control, assuring that sample and transducer were effectively coupled during the whole experiment. Despite the large reduction in thickness of the rubber discs, there was no permanent deformation to the rubber discs.

Results

After data acquisition and processing we calculated the medium velocities and crack parameters as a function of the applied stress. The P- and S-wave velocities calculated as described above are depicted in Figures 5 and 6. We observe that the P- and S-waves in both the reference model and the model with inclusions exhibit different regimes of linear variation with stress. In the pure Plexiglas model, at about 6-7MPa a stronger linear variation turns into a slightly weaker one. In the model containing penny-shaped neoprene inclusions, there are three linear regimes, separated at about 6-7MPa and 11-12MPa. Though all velocities increase with increasing stress, their behavior in the different regimes is quite different. The horizontal P-wave velocity (V_Y) varies the least. It shows first an increase of the slope and than a decrease. The diagonal P-wave velocity ($V_{45°}$) shows the strongest variation. Its slope decreases at both transition points. The S_1 velocity exhibits almost no slope change at the first transition point, but a very strong decrease at the second one. Finally, the slope of the S_2 velocity first decreases and then increases again. Without inclusions, the S velocity measured across the plates (S_Z) rapidly approaches the value of the slow S velocity (S_2). The fast S velocity (S_1) is identical to the S velocity measured in the buffer.

A possible explanation for the regime changes in the model with inclusions could be that at 6-7MPa the plexiglass plates start to get in contact, and at 11-12MPa the air has been completely forced out of the model. The behavior below 12MPa could be associated with the soft inclusion compression while past that boundary it could be

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interpreted as being exclusive effective-media behavior. In the reference model, there are no inclusions, so the air should be forced out much earlier, starting the effective-medium regime already at 6-7MPa. These three regimes are even better visible in Figure 9, which depicts crack density as a function of the increasing stress applied to the model with inclusions. Here we were able to fit a sigmoid curve to the data. The inflection points of this sigmoid correspond to the changes in slope of the velocity curves. The diameter of the inclusions predictably increases with increasing stress asymptotically approaching a value of 10.53 mm (see Figure 2), which is slightly different from the value of 10.37mm described by Marcondes *et al.* (2012). The exponential behavior for the diameter seems to agree with the observations of Gurevich *et al.* (2011). This value was obtained from the parameters of the exponential function we were able to fit to the data. Fit residuals were in the order of magnitude of the linear measurement error.

The aspect ratio exhibits an exponential dependence on stress, asymptotically reaching a value of 0.006. In our experiment, the system was open to atmosphere, so we consider pore pressure to be zero.

As seen on Figure 8 the experiment was conducted in the linear elastic domain, relative to the neoprene rubber, only until 10.8 MPa.

Conclusions

We have studied the dependence of crack parameters and medium velocities on stress in a physical modeling experiment. Due to our experimental setup and choice of materials, we were only able to produce a range in compression values that is small compared to those found at reservoir depths. Despite that, we believe that our data is representative of the behavior of unconsolidated sediments under low stresses. We found different regimes of linear dependence. Our results are slightly different from those of Olson (2003). We believe that an explanation for the difference lies in the greater variation in aspect ratios found in nature versus the limited range of our experiment. Throughout the experiment, it became clear that current crack models do not account properly for large aspect ratios subject to low stresses. Regarding the two regime boundaries, the first one (at 6-7 MPa) can be attributed to the air being purged from the models. The second boundary (at 11-12 MPa) is attributed to the models entering effective media behaviour, but the rubber was already past its linear elastic limit.

Our results are consistent with theoretical results as well as other empirical data, such as those from Mavko *et al.* (2009) and Olson (2003), especially towards the upper range of stresses we applied. Our results for both the reference model and the model with inclusions, the increasing compression works to suppress the anisotropic behaviour imposed by the presence of soft inclusions. The reference model, constituted exlusively by plexiglass plates presents a clearly VTI behaviour under low pressure and evolves to an almost isotropic behaviour. The model with inclusions has initially a behaviour which is more strongly VTI than the reference model. With progression of applied stress, the anisotropy of the model with inclusions decreases, tending to the initial anisotropy of the reference model.

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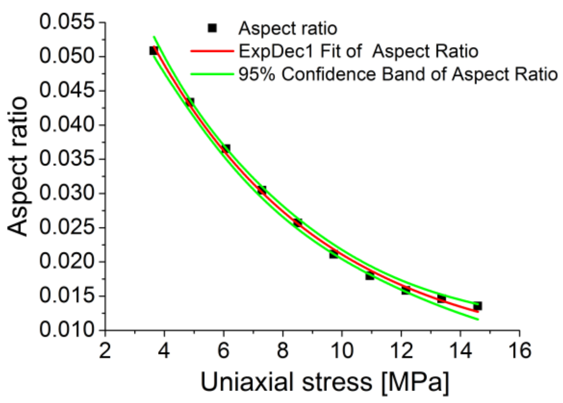

Figure 10 - Inclusion diameter as function of uniaxial stress. Red line is a fitted curve. Green line is the 95% confidence band.

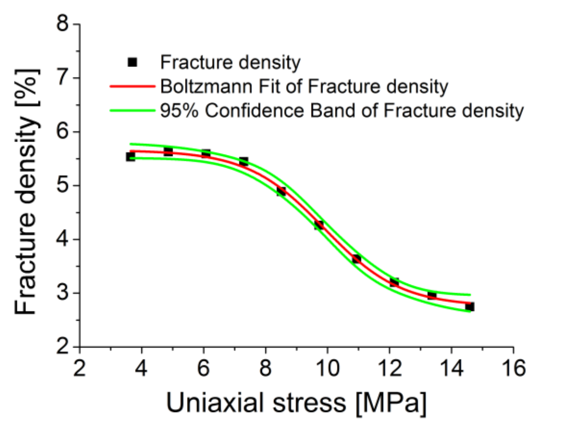

Figure 9 – Fracture density as function of uniaxial stress. Red line is a fitted curve. Green line is the 95% confidence band.

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