Introduction

Rock physics plays an important role in linking the elastic parameters extracted from seismic and well logs data to reservoir properties, such as porosity, pore structure, shale content, water saturation, pressure, etc. The effect of porosity (Al-Dousari et al., 2016; Assefa et al., 2003), pressure (Jones and Nur, 1983), saturation (Kahraman, 2007), permeability and clay content (Klimentos, 1991) on seismic velocities are well established by using different laboratory techniques based on ultrasonic velocity measurements. It is well-established that the crack geometry/ pore shape influences the permeability of reservoirs and can also be a controlling factor that influences the impact of pressure and saturation on elastic properties. However, due to the complexity in pore structure and rock minerals it is hard to measure the direct impact of pore geometry on elastic properties using laboratory techniques and the vast majority of studies are based on numerical analysis. Kuster and Toksöz (1974), and Berryman (1980) used scattering theory to describe the effect of oblate, spherical and ellipsoidal inclusions on elastic properties. Xu and Payne (2009) modelled the elastic properties of carbonate rocks and showed that the velocity difference can be as high as 40 percent for samples that share the same porosity and this observation highlights the importance of studying the effects of pore shape particularly when we consider that 60 percent of hydrocarbon accumulation in the world is found in carbonate reservoirs.

The most practical method for studying the effect of pore geometry is to build physical models with different pore shapes and conduct experiments (Huang et al., 2016; Mahmoudian et al., 2015). In recent years, the advent of 3D printing technology gives us the ability to print almost any physical models. Huang et al. (2016) built a model with penny-shaped inclusions using 3D printing technology to study the impact of fluid substitution with water. The same models are used by Dande et al. (2018) to study the impact of water, light oil, and heavy oil on seismic velocities and anisotropy. In this study, we utilize an sPro 60 3D printer that uses the 3D Selective Laser Sintering (SLS) technique to print our physical models. We printed 4 cubic models, one model without any inclusions referred as the solid model and three models with embedded ellipsoidal inclusions with different pore aspect ratios equal to 1, 0.33 and 0.16. To study the impact of pore aspect ratio, we fix the pore volume (porosity) of all inclusion at 20%. We measured the velocities of all models using a transmission ultrasonic measurement setup and compare the results with Kuster and Toksöz (1974), and Berryman’s (1980) theories. The results imply that flatter pores (smaller aspect ratio) reduce the velocity of the medium.

Theory and Method

Kuster and Toksöz (1974) rely on two main assumptions - pores are smaller than the wavelength and multiple scattering effects are negligible – to derive a set of equations that explain the impact of spherical and spheroidal inclusions on elastic properties of rock. Following equations (23) and (24) in Berryman (1980), which are the generalization of equations derived by Kuster and Toksöz (1974), we have,

\[ (K_m - K^*) K_m + \frac{4}{3} \mu_m = \sum_{i=1}^{N} c_i (K_m - K_i) P_{mi} \]

\[ (\mu_m - \mu^*) \frac{\mu_m + F_m}{\mu^* + F_m} = \sum_{i=1}^{N} c_i (\mu_m - \mu_i) Q_{mi} \]

\[ F_m = \left( \frac{\mu_m}{6} \right) \frac{9K_m + 8\mu_m}{K_m + 2\mu_m} \]

where the summation is over inclusion types with \( c_i \) the volume concentration, \( \mu_m \) is the shear modulus of the mineral matrix, \( K_m \) is the bulk modulus of the mineral matrix, \( K^* \) is the effective shear modulus, \( \mu^* \) is the effective bulk modulus, \( K_i \) is the bulk modulus of inclusion material i, \( \mu_i \) is the shear modulus of inclusion material i, and \( P_{mi} \) and \( Q_{mi} \) are coefficients that explain the impact of the inclusion of material i in a background medium. \( P_{mi} \) and \( Q_{mi} \) for spherical inclusions are defined as (Kuster and Toksöz, 1974; Berryman, 1980),

\[ P_{mi} = \frac{K_m + \frac{4}{3} \mu_m}{K_i + \frac{4}{3} \mu_m} \]

82nd EAGE Conference & Exhibition 2020
8–11 June 2020, Amsterdam, The Netherlands
\[ Q^{ii} = \frac{\mu_m + \mu_i}{\mu_i + \mu_m} \quad (5) \]

Berryman (1980) derived \( P \) and \( Q \) for spheroidal inclusions as follow,

\[ P = \frac{1}{3} T_{iij} \quad (6) \]

\[ Q = \frac{1}{3} (T_{ijij} - \frac{1}{3} T_{iij}) \quad (7) \]

where \( T \) is Wu's tensor (Wu, 1966). Berryman (1980) defined \( T_{iij} \) and \( T_{ijij} \) for spheroidal, penny shaped pores. We now have a tool to study the impact of pore shape on the elastic properties of the medium, which we will compare with our experimental results.

**Physical Models**

In order to study the impact of pore shape on elastic properties, we utilize 3d printing technology that allows us to print almost any desired models. The 3D printer that we used to print our models is an sPro 60 that uses 3D Selective Laser Sintering (SLS) technique to print. This process takes a Nylon powder and spread it in layers and then selectively sinters the layer with the laser, spreads another layer of powder on top and then repeating the process over and over again. This printing process, building materials layer by layer, simulates a sedimentary process. The powder we used was an ALM brand powder called PA-650 which is a Nylon 12.

In this study, we printed one solid cubic model with dimension of 10 \( \times \) 10 \( \times \) 5 cm (Figure 1a) to use as a reference model and to extract the density, the bulk modulus \( (K_m) \) and the shear modulus \( (\mu_m) \) of the sintered powder. We measured the density of sintered powder as \( \rho_m = 0.98 \text{ g/cm}^3 \), the P-wave and S-wave velocities as \( V_P = 2288 \text{ m/s} \) and \( V_S = 931 \text{ m/s} \), respectively. Then, we calculate the dynamic shear and bulk modulus as \( K_m = 4000 \text{ MPa} \) and \( \mu_m = 850 \text{ MPa} \), respectively.

In addition to the solid model, we printed three cubic models with prolate ellipsoidal inclusions. (Figures 1b-1d) depict the internal structure of inclusion models in XY plane cross section. Figure 1b shows the internal structure of the model with spherical inclusion which is the representative of ellipsoidal inclusion with pore aspect ratio equal to 1 (Model I). Figures 1c and 1d show the internal structure of ellipsoidal inclusion with aspect ratios of 0.33 (Model II) and 0.16 (Model III), respectively. In order to understand the impact of pore aspect ratio on elastic properties, we keep the pore volume (Porosity) of all inclusion models equal to 20\% which also implies that their densities are the same and equal to \( \rho = 0.78 \text{ g/cm}^3 \).

**Ultrasonic Velocity Measurement**

For velocity measurements we used the ultrasonic pulse transmission technique. The ultrasonic transducer that is connected to the waveform generator sends a 200 KHz Sine pulse through the sample and the pulse is recorded on the other side of the sample using another ultrasonic transducer that is connected to the oscilloscope. The transducer used in our experiments are piezoelectric transducers (Olympus Pulser-Receiver 5077PR) with 1 MHz central frequency and calibrated each time before measurement to correct the delay time. We also utilized an averaging function of the oscilloscope to increase signal to noise ratio by stacking 4096 waveforms to increase the precision of picking P- and S- waves arrival times. It is worth mentioning that we measured the velocity of printed models along the Z axis in Figure 1 that is parallel to the minor axis of the inclusions. The reported velocities are the average of seven measurements for each model.

**Results**

Figure 2 shows the measured velocity for all three inclusion models along the minor axis of the pores along with the predicted velocities using the KT model (Equations 1 - 3). Both the KT model and...
Figure 1  (a) The printed solid model using Nylon 12 powder with $10 \times 10 \times 5$ cm dimensions.  (b) The internal structure of inclusion model I with spherical inclusions that is representative of ellipsoidal inclusions with the pore aspect ratio equal to 1.  (c) The internal structure of inclusion model II with ellipsoidal inclusions with aspect ratio equal to 0.33.  (d) The internal structure of inclusion model III with ellipsoidal inclusions with aspect ratio equal to 0.16.

measured velocities show that the pore aspect ratio significantly impacts the velocity of medium. Figure 2a shows that P-wave velocity is reduced by 10 percent by decreasing the pore aspect ratio, which supports the idea of flat pores making the frame of medium weaker compared with rounded ones. The discrepancy between measured and predicted P-wave velocities could be the result of large pore volume concentration. One of the assumptions made by Kuster and Toksöz (1974) was non-interacting pores, which means that the pore volume concentration should be small. Figure 2b depicts the impact of pore aspect ratio on S-wave velocity. Based on Figure 2b, we can conclude that S-waves are less sensitive to the pore shape compared with P-wave velocities.

**Conclusion**

In this study, we used 3D printing technology to design inclusion models to study the impact of pore aspect ratio on P- and S-wave velocities. We printed 4 models, one model without any inclusion called the solid model and three models with embedded ellipsoidal inclusions with aspect ratios equal to 1 (Model I), 0.33 (Model II) and 0.16 (Model III). The laboratory measurement using the ultrasonic transmission technique shows that pore aspect ratio can significantly impact the velocity of the medium. In our experiment we measured 10% velocity differences for models that have the same pore volume but different pore aspect ratios. We observed that the flatter pores (smaller pore aspect ratio) make the rock frame weaker compared with more rounded pores and that is the reason we record lower velocities for Model III compared with Models I and II. These observations show how important the pore aspect ratio is and that it should be considered when we want to link obtained elastic properties (P- and S-wave velocities in particular) with reservoir properties.
Figure 2 The measured velocities of the inclusion models using the ultrasonic transmission technique and predicted velocities using Equations 1 - 3 for (a) P-wave, (b) S-wave. The S-wave is less sensitive to the pore aspect ratio compared with the P-wave. However, both P- and S-wave velocities decrease as we move toward flatter pores (Model III).

Acknowledgements

This work is supported by Chevron and with grants from the Natural Sciences and Engineering Research Council of Canada Industrial Research Chair Program (IRCPJ 491051-14), and InnovateNL and by the Hibernia Management and Development Corporation.

References


