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# The Elastic Moduli and Velocities of Artificial Carbonate rocks with Known Pore Structure at Different Saturation Conditions

*Zizhen Wang*[*]
*School of Petroleum Engineering, China University of Petroleum (Huadong)*
*Institute for Geophysical Research, Department of Physics, University of Alberta*
[*]*wzzhprince@gmail.com*
*Ruihe Wang*
*School of Petroleum Engineering, China University of Petroleum (Huadong), China*
*Douglas R. Schmitt*
*Institute for Geophysical Research, Department of Physics, University of Alberta*

## Summary

We designed and prepared eight carbonate artificial cores with known pore structures, and measured the velocities of these cores at different saturations. We use natural carbonate cuttings and epoxy to form the matrix. Further, predesigned aluminum foils or NaCl grains were embedded into the matrix and these were then leached out to form crack-like or vuggy porosity, respectively. This method can provide low-cost cores with known pore structure for carbonate rock physics experiments. Our ultrasonic measurements indicate that pore structure is an important inner factor responsible for the velocity variation in carbonate rocks, and that the combined effects of pore structure and pore fluids are responsible for the dynamic moduli, especially the shear modulus changes with saturation. The maximum velocity variation of our artificial cores is 503 m/s (relatively 13.7%) for P-wave, and 394m/s (relatively 18.4%) for S-wave at approximately 22% porosity. From dry to brine saturation, cores with cracks show shear stiffening mainly because of the viscous coupling effects, and cores with vuggy pores show shear weakening due to the reduction in free surface energy. From dry to kerosene saturation, cores show shear stiffening regardless of the secondary pore types. But cores with cracks display stronger shear stiffening effects than cores with vuggy pores at kerosene saturation because of more active viscous coupling. The dynamic moduli changes with saturation increase as the secondary porosity increases.

## Introduction

Carbonate reservoirs contain nearly 60% of world's total hydrocarbon reserves (Chopra et al., 2005) and account for approximately 50% of world's total hydrocarbon production (Xu and Payne, 2009). However, carbonate rocks have complex pore structures: a variety of pore types and a wide range of pore sizes, and show very strong heterogeneity, which make it difficult for researchers to reach consensus reliable relationships between petrophysical and geophysical properties for carbonate rocks.

It is worthwhile to notice that Gassmann's equation predicts no shear modulus changes due to fluid saturation. However, many experiment observations of carbonate rocks at high frequencies (~1MHz) (Wang at al., 1991; Assefa et al., 2003; Baechle et al., 2009; Bakhorji, 2010; Fabricius et al., 2010; Verwer et al., 2010) show changes in shear modulus from dry to brine or oil saturation.The velocity variations of carbonate rocks are closely related to their pore structures at the same porosity (Anselmetti and Eberli, 1993; Eberli et al., 2003; Weger et al., 2009). The changes in elastic moduli and velocities with saturation of carbonate rocks, to some extent, are also related to their pore structures (Verwer et al., 2010). However, it is difficult to gain representative carbonate samples and to quantify their pore structures due to the complex pore system and high heterogeneity. So carbonate rocks have not been intensely investigated from the rock physics perspective. Building rock physical models with known pore structure is the basis for quantitatively studying the pore structure effects on velocities through experiments. Here, we are trying to study the changes of elastic properties and velocities of porous rocks due to fluid substitutions using artificial carbonate cores with known pore structures.

## Method

*(1) Artificial carbonate cores*

We use natural carbonate cuttings and epoxy to form a base matrix. Pieces of predesigned aluminum foils or NaCl grains are embedded into the matrix in sufficient quantitity to allow for a connected permeable network. These materials are then leached out to form void cracks or vuggy pores. We use a 4% NaOH alkali solution to remove the aluminum foils. The NaCl grains are extracted using hot water. The secondary porosity (cracks and vuggy pores) are directly quantified by the pre-set volume fraction of aluminum foils or NaCl grains. Once this is completed, the total posority is measured by a helium porosimeter. We made four cores with different crack porosities and four cores with differrent vuggy porosities, respectively. Figure 1 shows these eight cores and their typical digital images.

*(2) Ultrasonic measurements at different saturation conditions*

We made three runs of ultrasonic measurements using pulse-transmission method with different pore fluid saturants (air, brine, and kerosene successively) for all the cores. We saturated the cores with brine and kerosene respectively under vacuum condition for 12 hour to insure full saturation. In order to keep the cracks open during the ultrasonic measurements, we maintain a low confining pressure of 0.5MPa. The pore fluid pressure is 0.1MPa (about 1 atmosphere of pressure) for all the measurements.

The central frequency of the transducers is 0.5MHz for P-wave and 0.25MHz for S-wave. The emitting transducer is excited by a rectangular pulse electronic wave. After transmitting through the core, the received signals are processed using a high-pass filter (>0.1MHz for P-wave, and >0.05MHz for S-wave). The corresponding wavelengths are around 17~42mm, which is larger than the size of secondary pores (cracks and vuggy pores). For each measurement, the received signal is recorded at a sampling rate of 15 MHz with a length of 2000~5000 points. The travel time is picked at the first peak of the receiving signal, and then used to calculate velocity. The maximum error is about 0.5% for Vp, and less than 1% for Vs.

## Results and Analysis

*(1) Effects of Porosity and Pore Type on Velocities*

It is not surprising that the P- and S-wave velocities of our synthetic carbonate cores generally decrease as the increase of total porosity with great velocity variations (Figure 2). The maximum velocity variation is 503m/s (relatively 13.7%) for P-wave, and 394m/s (relatively 18.4%) for S-wave at approximately 22% porosity. The velocities of cores containing cracks are much lower than those of cores containing vuggy pores at similar total porosity. This is because the pore stiffness of cracks is much lower than that of vuggy pores. So the softening effecting of cracks is stronger than vuggy pores when the porosity and matrix composition are the same, which is consistent with the modeling results of effective medium theories (Kumar and Han, 2005; Xu and Payne, 2009; Sun et al., 2012). Therefore, pore structure is an important inner factor responsible for the velocity variation in carbonate rocks, which confirms the findings of Eberli et al. (2003) based on velocities and digital core images of real carbonate rocks.

*(2) Changes in Dynamic Moduli with Saturation*

We calculated the dynamic bulk moduli and shear moduli (equation 1-2) for cores under dry, brine-saturated, and kerosene-saturated conditions based on the corresponding density and velocities, respectively, and compared the dynamic moduli changes at different saturations (Figure 3).

$$\mu = \rho v_s^2 \tag{1}$$

$$K = \rho\left(v_p^2 - 4v_s^2/3\right) \tag{2}$$

The bulk moduli all increase after fluid saturation, and the increase in bulk moduli after brine saturation is larger than that after kerosene saturation (Figure 3(a)). This is because fluids usually have lower compressibility than air, and brine has lower compressibility than kerosene. Pore fluids with lower compressibility contribute more to the core's saturated bulk modulus.

The change in the shear moduli with fluid saturation is more complex (Figure 3(b)).From dry to brine saturation, cores with cracks show shear stiffening, which is mainly caused by the viscous coupling effects (Khazanehdari and Sothcott, 2003); cores with vuggy pores show shear weakening due to the reduction in free surface energy (Khazanehdari and Sothcott, 2003). From dry to kerosene saturation, cores show shear stiffening regardless of secondary pore types. But cores with cracks display stronger shear stiffening effects than cores with vuggy pores at kerosene saturation because of more active viscous coupling.The dynamic moduli changes with saturation seemingly do not correlate with total porosity, which is consistent to the finding of Verwer et al. (2010). But our measurements also indicate that the dynamic moduli changes with saturation increase as the secondary porosity increases.

## Conclusions

We made eight artificial carbonate cores with known racks or (and) vuggy pores, and measured the velocities of these cores at different saturations. Our experimental results indicate that pore structure is an important inner factor responsible for the velocity variation in carbonate rocks, and that the combined effects of pore structure and pore fluids are responsible for the dynamic moduli, especially the shear modulus changes with saturation. From dry to brine saturation, cores with cracks show shear stiffening mainly because of the viscous coupling effects, and cores with vuggy pores show shear weakening due to the reduction in free surface energy. From dry to kerosene saturation, cores show shear stiffening regardless of secondary pore types. But cores with cracks display stronger shear stiffening effects than cores with vuggy pores at kerosene saturation because of more active viscous coupling. The dynamic moduli changes with saturation increase as the secondary porosity increases. Many amplitude-versus-offset and time-lapse seismic analyses are based on the Gassmann's prediction of constant shear moduli which is discrepancy to our experiment findings. It is very important to consider the influence of pore structure when interpret reflection seismic data of carbonate reservoirs with complex pore system.

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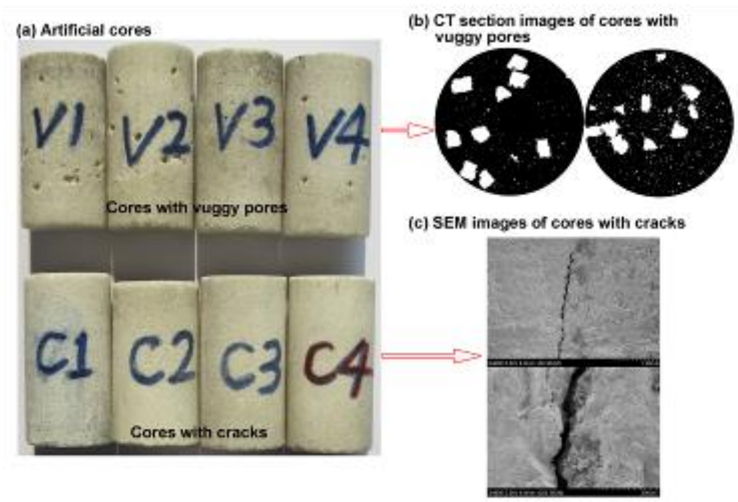


Figure 1. Images of artificial carbonate cores

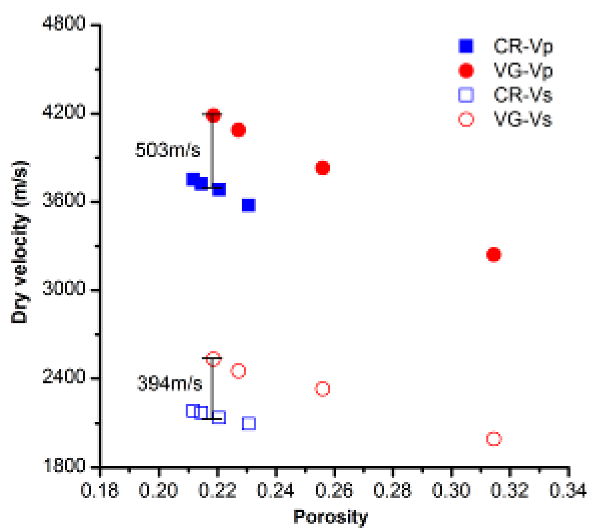


Figure 2. The P- and S-wave velocities of dry synthetic carbonate cores with different pore structure. CR represents cores with cracks, and VG represents cores with vuggy pores.

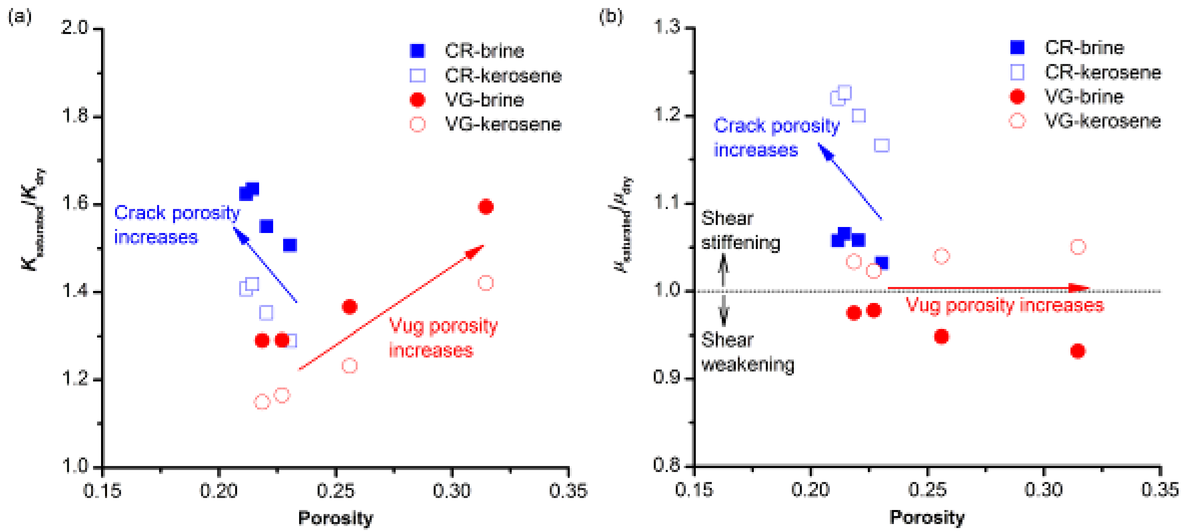


Figure 3. Dynamic moduli changes due to different saturations. (a) Bulk modulus change; (b) Shear modulus change. CR represents cores with cracks, and VG represents cores with vuggy pores.