Direct laboratory measurement on solid and fluid in heavy oil sands rock and its rock physics interpretation

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Summary

The elastic properties of heavy oil sands are influenced by multiphase of heavy oil and sands grain, as well as temperature, pressure, microstructure and sedimentary history. In order to quantitatively investigate the role of a single phase in integrated rock of heavy oil sands at a specific condition, special laboratory measurements on oil and sands of heavy oil sands rock are designed and performed for three artificial samples. By the improved laboratory approaches, we can gain an insight into the physical interaction between the solid and fluid components in heavy oil sands. The exact laboratory results reveal that the elastic properties of heavy oil is distinctively temperature dependent, which reflects the total variation of the multiphase on temperature, and in turn demonstrates that heavy oils dominate the elastic properties of the heavy oil sands. Furthermore, the extended Gassmann model indicates that heavy oil properties may be the major reason for the misfit of underestimating the both P- and S-wave velocities as temperature decreases.

Introduction

Developing ultrasonic measurements and rock physics models are both powerful tools to let us understand and reasonably predict the complex elastic properties of heavy oil sands reservoir (Han *et al*. 2006; 2007; 2008; Batzle *et al*., 2004; 2006). However, direct measurements of P- and S- wave velocities for heavy oil reservoir samples are still lacking, which are regarded as a very challenging task. Heavy oil sands samples are typically unconsolidated sands and held together by viscous heavy oils. These properties make the sample very soft and highly attenuated when the waves pass through. In consequence, to quantitatively investigate the role of a single phase in integrated heavy oil sands rock by specific laboratory measurement is necessary to understand the effects of each components on whole rock properties. We build three artificial heavy oil sands samples, two of which are glass beads-heavy oil mixture and another is extracted grains re-saturated with heavy oils. We obtain the modulus of the samples under different conditions (saturation, temperature, pressure), and insight into physical states of heavy oil reservoir in practical situations.

Heavy oil measurement

The velocity measurements of heavy oil are performed at Rock Physics Laboratory (RPL) of University of Houston. Based on measured sample length and travel time by ultrasonic pulse-receiver technique, the velocities are defined. It is then transferred to modulus by known densities. It is difficult to recognize transmitted shear signals because of strong attenuation in heavy oil. Therefore, the shear modulus of heavy oil can be estimated. According to this philosophy, Han's model (2007) is adopted to predict the shear modulus of heavy oil as a function of API and frequency. Specifically, we estimate S-wave velocity by using FLAG program, which is developed by RPL.

Heavy oil sands sample measurement

Three heavy oil sands samples are measured at RPL of University of Houston. Both sample #8 and #9 are artificial, which are made of glass beads-heavy oil mixtures. The sample V3 is extracted solid grains re-saturated with heavy oil. Their physical properties are listed in the table 1. The dominant frequency of P- and S-wave is 1 MHz and 0.5 MHz, respectively. The first arrival of either P- or S-wave can be picked up distinctively under low confining pressure, which ensures us to minimize the measured errors. During measurement, we assume that the sample lengths keep constant. In general, errors on P- and S-wave velocity data are 1% and 2-3%, respectively, even under very low differential pressure condition.

All three artificial samples are tested under both dry and saturated conditions in a single run. The test procedure contains two loading and unloading cycles at dry condition, and four loading and unloading cycles at saturated condition as temperature variations. For measuring the heavy oil-sands/glass beads artificial samples, the dry glass bead packs are also firstly measured at different confining pressure and horizontal pressure, P- and S-wave increase while, no surprise, sample length decreases (about 1.4%) as confining pressure increasing. Extracted heavy oil sands/glass beads then are saturated, so that any empty pore space is filled with heavy oil. During the fluids saturation of two glass beads-heavy oil samples, we set the fluids injection flow rate and sample temperature is 0.01 ml/cc and 25 ºC, respectively. It will ensure the sample is fully saturated under low injection flow rate. We inject the fluids from the bottom of the sample, the flow is observed in the upper pore channel outlets. The sample is then kept for 3 hours to make sure no air trapped inside the sample. In order to test the fluids type influence on the heavy oil sands sample, the sample #9 has been through the water saturation cycle before injecting the heavy oils.

Experimental results

The viscosity is extremely sensitive to temperature, especially when the measured temperature approaches both liquid point and glass point. Figure 1(a) shows that the

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shear viscosity gradually decreases with the increment of temperature. Usually, shear viscosity varies by orders of magnitude even at the same API gravity depending on the chemical composition of heavy oils (Hinkle *et al*., 2008). The high shear viscosity at low temperature enables heavy oils to act as part of solid frame, especially when the temperature is less than glass point. Certainly, heavy oils at high temperature could also be treated as movable liquid with no additional contribution to rock solid frame. In our case, the shear viscosity of heavy oils is about 10^{15} cp at glass point (-34.6 ºC) while it quickly decreases to 10^{3} cp when temperature goes up to liquid point (48.7 ºC). Undoubtedly, the elastic properties of heavy oil sands are inevitably affected by the viscosity of heavy oils.

As shown in figure 1(b), the bulk modulus increases steadily as pressure increasing at a given temperature point. More importantly, the temperature has a vital influence on bulk modulus. At a given pressure point, the lower is temperature, the higher is bulk modulus, which is because that the heavy oil is becoming stiffer as temperature deceases. The shear modulus in the figure 1(b) also shows the temperature-dependent and pressure-dependent. The shear modulus is almost zero when temperature rises upon 60 ºC, which has exceeded the liquid point. Once the temperature is greater than the temperature of liquid point, the shear modulus gradually decreases to 0. Generally, it displays the same trend as that of bulk modulus does.

The figure 2 displays modulus against confining pressure for sample #8 (a) and #9 (b) and V3 (c) at different temperature, respectively. The dry dynamic modulus are measured at a second pressure cycle, then sample #8 and V3 are directly saturated with heavy oils, while sample #9 is firstly fully saturated with water, then replaced with heavy oils. The dataset indicate that bulk modulus and shear modulus increase with the decrease of temperature. Due to the low viscosity of water, both bulk and shear modulus of fully water saturated sample #9 is lower than that of heavy oils saturated even over the liquid point temperature. Additionally, the whole modulus trend of sample #9 (Phi=35.90%) is higher than that of sample #8 (Phi=40.96%) because of the porosity effect.

After saturation, increasing temperature from 20 ºC to 60 ºC causes a 17% reduction in the saturated bulk modulus while the shear modulus almost keeps constant. This behavior can only be explained by the temperature-dependent bulk modulus of heavy oil. Another important phenomena is that it seems the water saturation has no giant impact on the elastic properties of heavy oil sands by comparing sample #8 and sample #9. For sample #9, we firstly inject water instead of directly injected heavy oil. The results show, firstly, the modulus of fully saturated water sample at room condition (temperature is 25 ºC) is even lower than that of fully heavy oil saturated sample at 60 ºC, which is because of low viscosity of water (1 cp). From this point of view, the temperature-dependent viscosity of heavy oil could make ignorable influence on elastic properties of heavy oil sands.

The figure 2(c) displays the modulus against confining pressure for sample V3 (Phi=37.1%) at different temperature. Then sample V3 is fully saturated with heavy oils and measured at the initial low temperature. It shows the same trends comparing with artificial sample #8 and #9. Namely, the bulk modulus and shear modulus increase as the temperature decreases. Additionally, the whole modulus trend of these three artificial samples satisfy: sample #9 (Phi=35.90%) ＞V3(Phi=37.1%)＞ #8 (Phi=40.96%) may because of the porosity effect.

Rock physics modeling

For all these three artificial samples, there is a good match between the predicted both P- and S-wave velocities and measured data well at high temperature, but shown an underestimation as temperature decreases (Figure 3). Heavy oil properties may be the major reason for this misfit. As temperature increasing, especially at quasi-solid stage, part of heavy oils could attach to the sand grains contact which will endure the overburden pressure rather than pore pressure and act as part of solid frame. Additionally, the pressure effect can be well predicted by the extended solid Gassmann model for these three artificial samples (Ciz *et al*., 2007).

Concluding remarks

The modulus of heavy oil is highly temperature dependent at the constant measured pressure. The modulus increases steadily as pressure increases and/or temperature decreases. Specifically, heavy oil (API=6.6), the estimated glass point is -34.6 ºC, and liquid point is 48.7 ºC.

The heavy oil sands properties is mainly determined by the heavy oil. After saturation, increasing temperature from 20 ºC to 60 ºC causes a 17% reduction in the bulk modulus while shear modulus almost keeps constant. Additionally, the whole moduli trend of these three artificial samples satisfied: #9 (Phi=35.90%) ＞ V3 (Phi=37.1%) ＞ #8 (Phi=40.96%) because of the porosity effect.

The extended Gassmann model indicates that heavy oil properties may be the major reason for the misfit of underestimating the both P- and S-wave velocities as temperature decreases.

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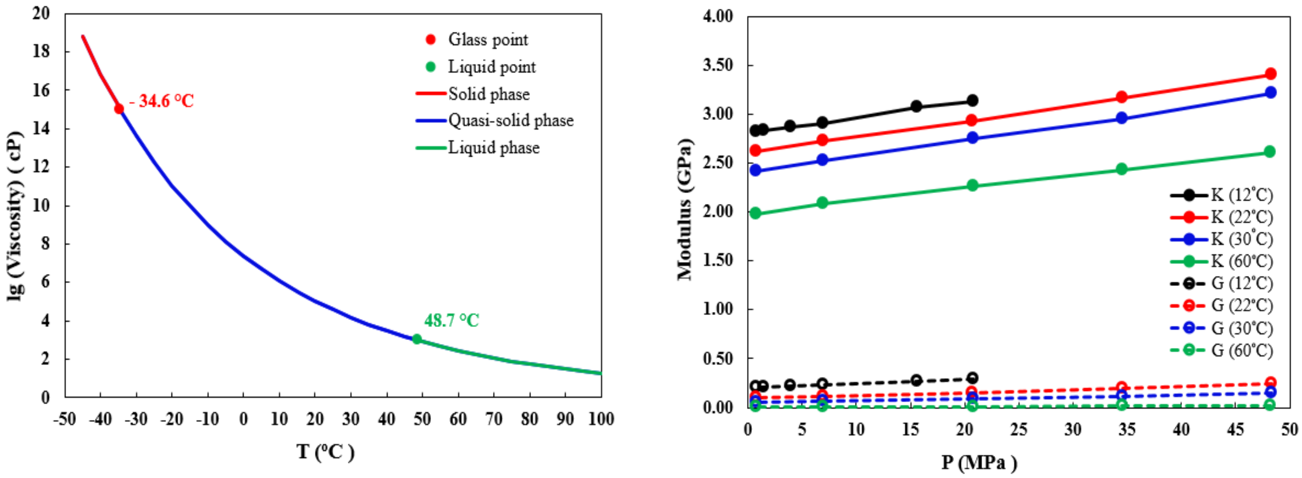
Table 1: Physical parameters distribution of oil sands samples

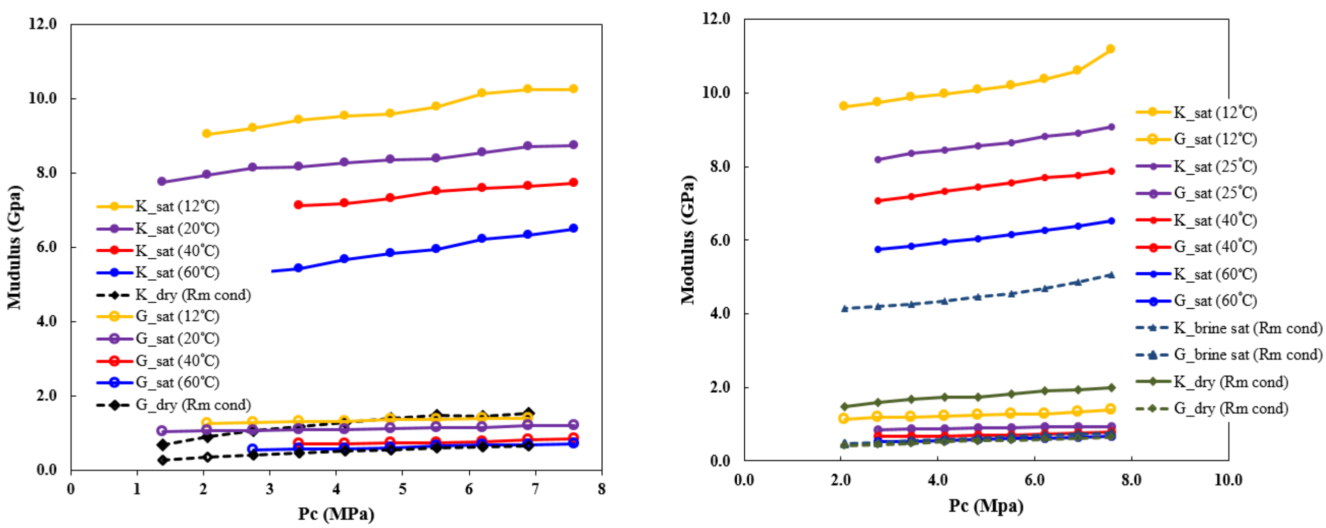
Sample ID	Type	Porosity %	Grain density (g/cm^3)	Bulk density (g/cm^3) Dry	Water saturation	Oil saturation
#8	GB-HO	40.96	2.49	1.47	-	1.89
#9	GB-HO	35.90	2.49	1.60	1.95	1.96
V3	ES-HO	37.10	2.66	1.54	-	1.97

Note: "GB-HO" represents glass bead packs saturated with heavy oils; "Field" represents the sample is from the same heavy oil reservoir; "ES-HO" represents the extracted heavy oil sands packs re-saturated with heavy oils.



(a) (b)

Figure 1. (a) The shear viscosity against the temperature of heavy oils (API=6.6); Glass point (red point) and liquid point (green point) is -34.6 ºC and 48.7 ºC, respectively. (b) Measured bulk modulus and estimated shear modulus of heavy oils (temperature: 12 ºC to 60 ºC, pressure: 0.81 MPa to 48.39 MPa).



(a) (c)

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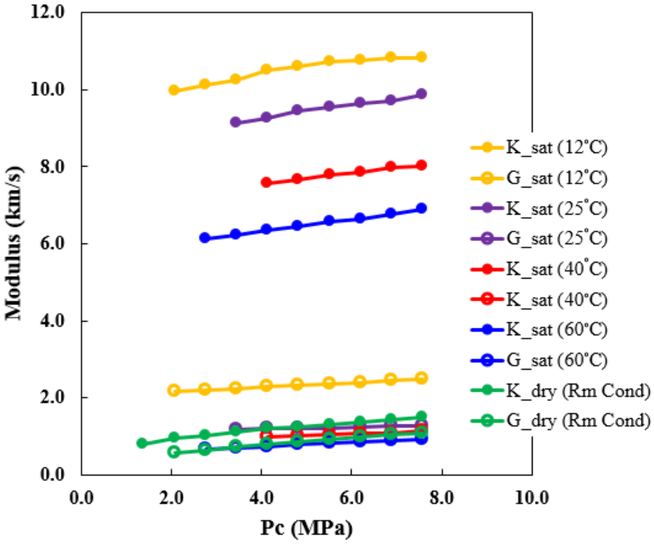
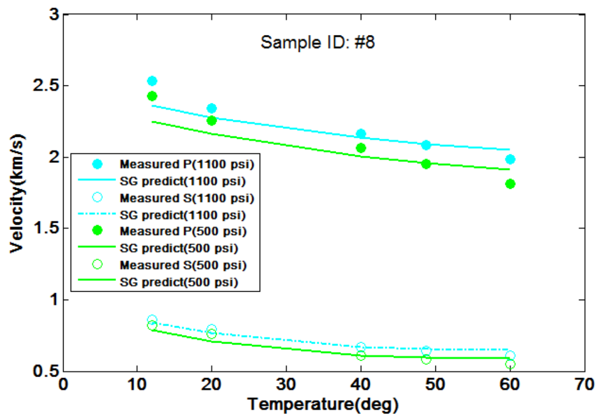
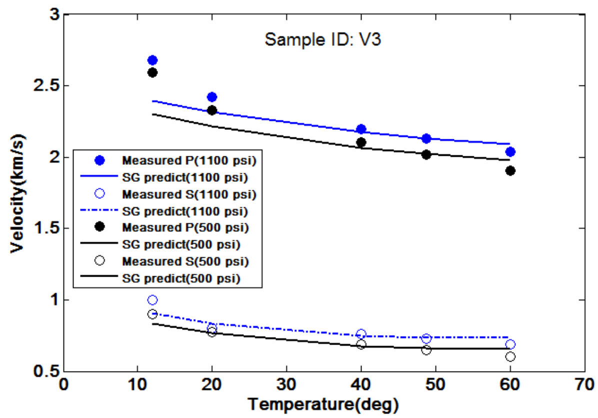


(b)

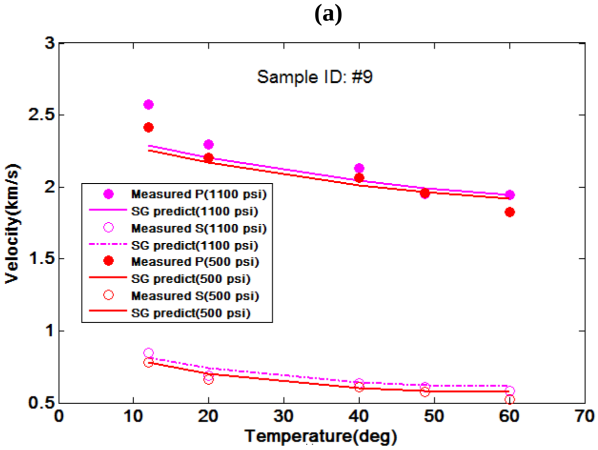
Figure 2. Modulus versus confining pressure for sample #8 (a) and #9 (b) and V3 (c) at different temperatures. Since the extracted heavy oil sands are not perfectly rounded, the sample V3 has a lower porosity after second pressure cycle. For both sample #8 and #9, the dry dynamic modulus are measured at second pressure cycle, then the sample #8 is directly saturated with heavy oils, meanwhile the sample #9 is firstly fully saturated with water solution, then replaced out by injecting the heavy oils. The both data indicate that bulk modulus and shear modulus increase as the temperature decreases. Due to the low viscosity of water, both bulk and shear modulus of fully water saturated sample #9 are lower than that of heavy oils saturated even at temperatures over the liquid point temperature. Additionally, the whole modulus trend of sample #9 (Phi=35.90%) is higher than that of sample #8 (Phi=40.96%) because of the porosity effect.



(a)



(c)



(b)

Figure 3. Velocity against temperature with measured data at high pressure (1100 Psi) and low pressure (500 Psi). Additionally, the extended solid Gassmann model predictions (solid line and dashed line for P- and S-wave velocities, respectively) are also displayed.

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EDITED REFERENCES

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REFERENCES

Batzle, M., R. Hofmann, and D.-H. Han, 2006, Heavy oils — Seismic properties: The Leading Edge, **25**, 750–756, http://dx.doi.org/10.1190/1.2210074.

Batzle, M., B. Zadler, R. Hofmann, and D.-H. Han, 2004, Heavy oils — Seismic properties: 74th Annual International Meeting, SEG, Expanded Abstracts, 1762–1765.

Ciz, R., and S. Shapiro, 2007, Generalization of Gassmann equations for porous media saturated with a solid material: Geophysics, **72**, no. 6, A75–A79, http://dx.doi.org/10.1190/1.2772400.

Han, D., J. Liu, and M. Batzle, 2006, Acoustic property of heavy oil — Measured data: 76th Annual International Meeting, SEG, Expanded Abstracts, 1903–1907.

Han, D. H., J. J. Liu, and M. Baztle, 2008, Seismic properties of heavy oils — Measured data: The Leading Edge, **27**, 1108–1115, http://dx.doi.org/10.1190/1.2978972.

Han, D. H., Q. Yao, and H. Z. Zhao, 2007, Challenges in heavy oil sand measurements: University of Houston/Colorado School of Mines (UH/CSM) Fluids/DHI Consortium Internal Report.

Hinkle, A., E.-J. Shin, M. W. Liberatore, A. M. Herring, and M. Batzle, 2008, Correlating the chemical and physical properties of a set of heavy oils from around the world: Fuel, **87**, no. 13-14, 3065–3070, http://dx.doi.org/10.1016/j.fuel.2008.04.018.