Experimental measurements of pore volume compressibility of sandstones and carbonates.

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This paper was prepared for presentation during the 13th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 26-29, 2013.

Abstract

Several efforts are being put in place on researches about the interactions between rock and fluids and also on the physical laws that describe the fluid behavior in porous media, in order to optimize the production of hydrocarbons in an economic and effective way. Pore volume compressibility is one of the main properties on reservoir simulations and can be determined from correlations found in current scientific work that uses logging and seismic data, however for more accurate results additional lab measurements are crucial. Fluid production occurs due to a reduction on pore pressure while the overburden pressure is steady, which cause pore volume changes in the rock. This study comprises a Helium Gas Expansion Porosimetry that provides pore compressibility data for each applied confining pressure, a low cost method for very important experimental data. Such technique is based on an exponential relationship between pore volume measurements and the confining pressure. It was applied to four sandstone and three limestone samples at nine different confining pressures ranging from 400 to 2000 psi. Although the sandstone samples had a good correlation, limestone tests did not show an efficient correlation, probably due to their dual porosity behavior.

Introduction

The study of mechanical properties of rocks involves many knowledge fields and attracts a lot of interest from a variety of activities related to the hydrocarbon industry. Also, Petroleum Engineers use these properties on several steps of oil and gas recovering process, such as drilling, completion, wellbore production and avoiding unexpected interventions. Although reservoir characterization is based on its formation process, continuous update of the reservoir model using every data acquired during development phases of the reservoir is required. Rock characterization during formation productive life allows evaluation of different production scenarios, bringing relevant information for improvement of reserves' estimation reliability. Anyway, the energy that drives hydrocarbons production that is going to be discussed on this paper is consequence of external pressure created by overburden pressure acting on the reservoir rock. It is well known that the overburden force is transmitted through inter-grain contact, named external pressure, and that internal pressure is exerted on the grain by the confined fluid. The equilibrium of these pressures is kept until the production is started, when internal pressure is decreased and effective pressure increased (difference between the external pressure and the internal pressure) because the reservoir fluids become less effective in opposing the weight of the overburden and pores are compressed by additional formation compaction. Therefore, this behavior needs to be taken into account into reservoirs characterization because they commonly affect rock porosity and if neglected can result in mistaken analysis of reservoir behavior, recoverable volume and driving mechanism. Pore compressibility can also be utilized to calculate produced oil volume, gas and/or water during each production stage.
Many researchers conducted a series of theories and analysis attempting to obtain approximate values of pore compressibility. Geertsma (1957) did a remarkable work on the comprehension of pressure-volume relationship in porous reservoir rocks, developing equations for a better understanding of the bulk and pore volume. He introduced the concept of three kinds of compressibility: bulk (C_b), matrix (C_m) and pore (C_p). The determination of C_b and C_m uses relatively simple techniques of rock volumetric deformation.

The experimental determination of C_p as a porous pressure function, "simulating" the production process of a reservoir, in which as the depletion occurs, the pore volume is reduced, and is complicated by the presence of some factors such as the degree of saturation of the fluid, the connectivity and geometry of the pores. However, the compressibility of pores in function of the confining pressure is more easily to be obtained when it is assumed that the variation of the pore volume is equal to the bulk volume reduction of rock to undergo compression. Hall (1953) established equations for the pore compressibility correlating with porosity from analysis of measurements in the laboratory, and estimated the change in pore space with declining pressure. Knaap (1959) defined pore compressibility (C_p) by the variation of effective stress when the pore pressure (P_p) is kept constant. Newman (1973) on laboratory tests, applied effective stress to 256 samples for studying the pore compressibility in consolidated, friable and unconsolidated reservoir rocks. The results showed that correlation of pore compressibility with porosity for consolidated sandstones differed greatly from limestones, friable and unconsolidated sandstones. Horne (1990) extended Newman`s and correlated pore compressibility for consolidated and unconsolidated sandstones and well consolidated limestones. Jallah (2006) promoted new generalized correlations for pores compressibility in function of porosity that can be used for most oil and gas reservoirs. Aloki (2011) studied the influence of pore types of carbonate reservoir rocks on pore volume compressibility and porosity at different stress values. Zimmerman (1986) re-derived the relationships between different compressibilities and in terms of the confining and pore pressure. The three types of compressibility often cited in the characterization of a porous medium vary with the applied pressure. The pore compressibility in confining pressure function is defined as:

$$C_{pc} = \frac{-1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{P_p} \quad (1)$$

The negative term is used to compensate for the downward action of external pressure.

This work aims to analyze measurements of pore compressibility reservoir rocks subjected to different confining pressures. Laboratory experiments are commonly found in publications produced by hydrostatic compression due to its ease and convenience, this type of test results in the volumetric strain of the rock as a whole along its three axes. However, in the subsurface conditions lateral deformation of the reservoir is prevented by the surrounding rocks varying only in their vertical axis, therefore responses uniaxial deformation tests have a better approximation to reality. Measurements from hydrostatic testing can be converted to uniaxial deformation conditions using correlations in the literature.

Method

The compressibilities measurements for this study were based on the method developed by Unalmiser and Swalwell (1993). Such relevant technique demonstrates the development of exponential relationships between measurements of pore volume and simulated overburden pressure. It differs from the other conventional procedures for maintaining pore pressure constant near to the atmospheric pressure when the overburden pressure is increased, resulting in a similar tension in the matrix of rock. The tests were performed on dry rock samples, so that the sample did not suffer the influence of the pressure developed by the action of the saturating fluid but only by the pressure transmitted through the rock grain matrix. So, in order to this method be effective, the authors seized the following considerations:
(i) The pore compressibility of the reservoir depends only on the effective stress based on the theory poroelasticity;
(ii) The grain expansion due to pore pressure reduction is neglected and therefore the reduction in the pore volume reduction is equal to the reduction in bulk volume;
(iii) Measurements of hydrostatic pore compressibility can be converted to uniaxial condition based on Poisson's ratio for all conditions of loading.

An exponential relationship was developed to relate the pore volume measurements and the applied confining pressure, which corresponds to equation (2):

$$V_p = bP^{-m} \quad (2)$$

Where V_p is the pore volume P is the overburden pressure, b refers to intercept between V_p *and* P, and m is the slope of the exponential regression of the V_p *versus* P.

The derivation of the equation as a function of pressure is expressed by the equation (3):

$$\frac{dV_p}{dP} = -mbP^{-(m+1)} \quad (3)$$

Substituting equation 2 and 3, one obtains an equation for C_p:

$$C_p = -\frac{m}{P} \quad (4)$$

The method has been found to be effective in achieving good correlation (R^2> 95%) for most of the cases. The slope of the line allows the exponential value to be found in order to determine the pore volume compressibility also allows finding corresponding values of porosity at each pressure applied.

Measuring the Pore compressibility.

Among the various existing procedures to determine the pore compressibility, hydrostatic and uniaxial testing, are the most used. The first consists in obtain the pore compressibility through the variation of pore pressure (C_{pp}) or through the variation of the confining pressure (C_{pc}), while the second consists in the variation of pore pressure under zero lateral deformation condition, however, uniaxial strain test is the best to represent the existing conditions during depletion in a petroleum reservoir. The laboratory experiments for this work were carried out simulating a uniaxial test, using a Helium porosimeter (Ultra Pore 300 Helium Pycnometer System), as shown in Figure 1.

Figure 1: Ultra Pore 300 Helium Pycnometer System.

This equipment allows the measurement of porosity, pore volume, grain volume and grain density of a rock sample. The pore compressibility can be obtained from the gradual application of the confining pressure in the sample causing the variation of the pore volume.

The confining pressure is applied to the sample through a pressure vessel filled with a fluid, typically hydraulic oil. The fluid is pressurized by a line, which connects the pressure vessel to a hydraulic piston. The fluid pressure acts as a confining pressure and is measured using pressure transducers. The pressure vessel also has a core holder where the sample is accommodated for the test to be performed. A representative model is illustrated in Figure 2. The samples used in the experiments have cylindrical shapes with a diameter of 1 ½ inch and a length ranging from 1 to 2 inches.

The porosimeter also has a reference cell (matrix cup) used for calibration of the equipment, which has six disks of different volumes to fill the entire space of the cell. The discs are removed one by one while the cell is filled with helium gas triggered by software, this way it is possible to get a calibration curve for the machine to be used. After this procedure the sample is stored in the core holder, which enables the compression of the rock to the same time as prevents contact with the confinement fluid. The core is holding on a rubber waterproof jacket, preventing any influx of the hydraulic fluid to the rock pores.

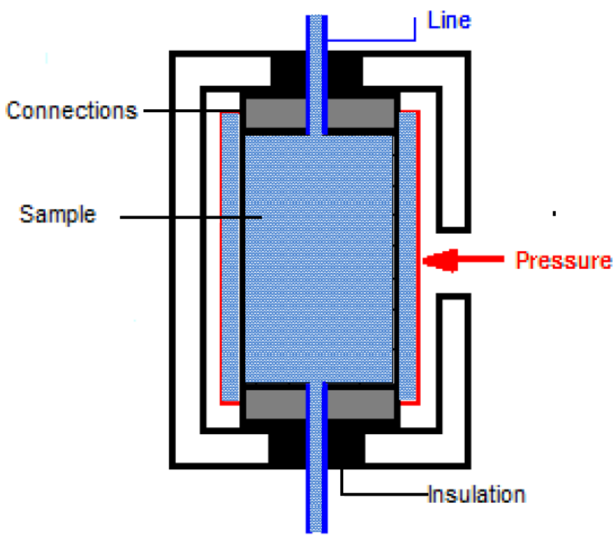

Figure 2: Illustration representing the "core holder" of the pressure vessel.

This kind of technique is based on the gas expansion method. The helium gas is initially contained in a pressure chamber with pressure and volume (V_1 *e* P_1) known. This chamber is connected to a secondary chamber through a gauge that when it is opened, allows the helium gas to expand into this secondary chambre, typically a matrix cup, which holds the sample, making the pressure to drop down to a new value (P_2). The whole process is controled by a microcomputer and the grain volume (GV) of sample (V_2), can be calculated. If the matrix cup holds a non-porous material with a known volume and the sample is placed in a Hassler core holder, it was also possible to determine the pore volume (PV), instead of the grain volume. This type of test allows measurements of pore volume for a given applied pressure, which represents the effect of overburden on the layers while the pore pressure remains approximately atmospheric pressure at room temperature. Fatt (1953) and Hall (1958) indicated that the temperature does not affect the pore compressibility. Figure 3 outlines all the apparatus needed for the operation of the equipment, Ultra Pore 300 Helium Pycnometer System.
Considering that the grain volume did not change when the confining pressure is applied, porosity (ϕ) can be determined after evaluate the bulk volume from grain and pore volumes, as shown in equation (5).

$$f = \frac{PV}{PV + GV} \quad (5)$$

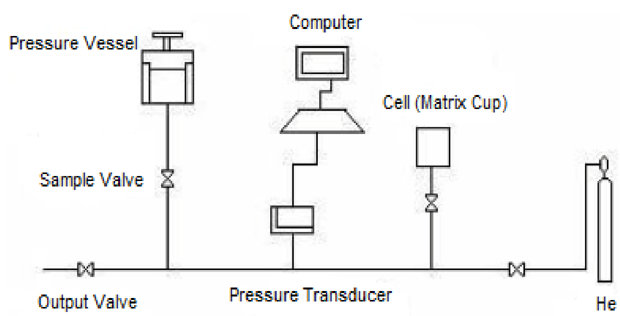

Figure 3: Outline the operation of Ultra Pore 300 Helium.

Samples Description

A total of seven samples were subjected to the uniaxial simulated experiment with helium gas porosimeter. The samples were obtained in siliciclastic and carbonate outcrops in Brazil and in the USA. The sandstones were represented by: Botucatu, Berea, Pirambóia and Rio Bonito, and carbonates were: Edward Yellow, Pink Desert and Indiana Limestone. The mineralogical compositions of the samples were obtained by X-ray diffraction (XRD) and fluorescence spectrometry (XRF) and may be checked in table 1 and 2:

	Desert Pink	Edward Yellow	Indiana Limestone
Calcite	99,60	99,80	99,456
Dolomite	0,12274	0	0
Quartz	0,17806	0	0,51153
Sylvite	0,09436	0	0,3272
Fluorite	0	0,20801	0

Table 1 - Limestones Mineralogical composition obtained by X-ray diffraction.

	Berea	Botucatu	Piramboia	Rio Bonito
Na2O	0,777	0	0	3,28
MgO	0,760	0,616	4,60	1,16
Al2O3	3,83	5,30	13,8	13,4
SiO3	90,9	92,9	58,0	77,7
SO3	0	0,192	2,18	0
Cl	0,179	0,130	0	0,145
K2O	1,02	0	1,94	2,69
CaO	0,582	0,234	16,0	0,332
TiO2	0,299	0	0,325	0,271
Fe2O3	1,35	0,453	2,82	0,839

Table 2 - Sandstones Mineralogical composition obtained by X-ray fluorescence spectrometry.

Applying confining pressure

The tests were carried under overburden pressure (confining) increasing in stages of the same interval and variations of the pore volume of the samples were measured. All samples were submitted to an initial pressure of 400 psi with a gradual increase of 200 psi until reaching a maximum pressure of 2000 psi, while the pore pressure remained constant.

Results and Discussion

The exponential relationship was effective for the experimental data with a determination coefficient of R^2> 95% for most samples. The correlation (R^2) for the sample of sandstones varied between 98.6% and 91.5%. The responses of Pirambóia and Botucatu samples were better, reporting R^2> 98%.

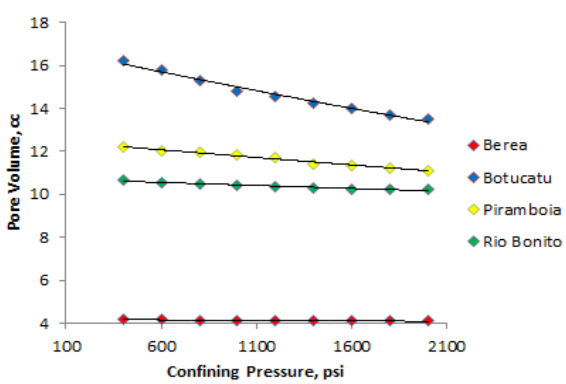

Figure 4: Sandstone samples pore volume vs confining pressure.

For carbonates samples, the highest accuracy for the exponential relationship was for the Edward Yellow sample resulting R^2> 95%, while the Indiana Limestone sample resulted in a determination coefficient of about 85%, a bit higher than the Desert Pink which reached 83.5%. These differences are due to the lithology, packing and the geometric arrangement of the grains and possibly the presence of fractures and different types of porosity for carbonate rocks. Figures 4 and 5 show the results obtained in the laboratory in terms of pore volume variation to confining pressure.

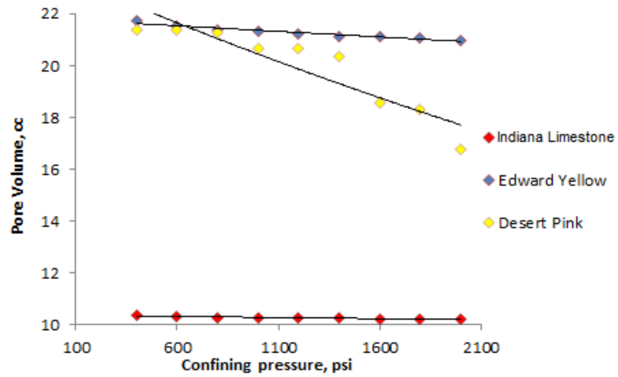

Figure 5: Carbonate samples pore volume vs confining pressure.

In the figures, it can also be observed the pore volume reduction as confining pressure increases. However, for the Desert Pink sample, this correlation, which is normally expected, has not occurred. For instance, when applying 1200 psi of confining pressure, the pore volume increased rather than decreased and came back to reduce when subjected to a pressure of 1400 psi indicating a fluctuation. This sample also showed a high variation for the pore volume, these occurrences explain the fact that its exponential correlation was not as reliable as in the other samples. An analysis of the pore configuration may explain the reason for his quite irregular behavior.

The proposed method was concluded using Equation 4, in order to obtain values for pore compressibility from the exponential relationship found between the pore volumes and confining pressure. Figure 6 showed that pore compressibility decreases as pressure increases for sandstone samples. The data presented for Botucatu sample indicates that this rock has pores more compressible than the other sandstones. On the other way, Berea sample results show a little compressible pore system.

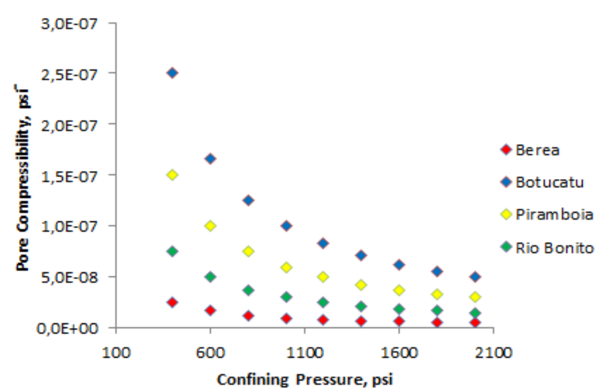

Figure 6: Carbonate samples pore volume compressibility versus confining pressure.

In Figure 7, it is possible to visualize the behavior of the pore compressibility when the carbonate rocks were subjected to a gradual increase of confining pressure. The data indicates that the Desert Pink sample has pores more compressible, but this supposition is not reliable due to the fact that their exponential correlation was not as high as most of the other samples.

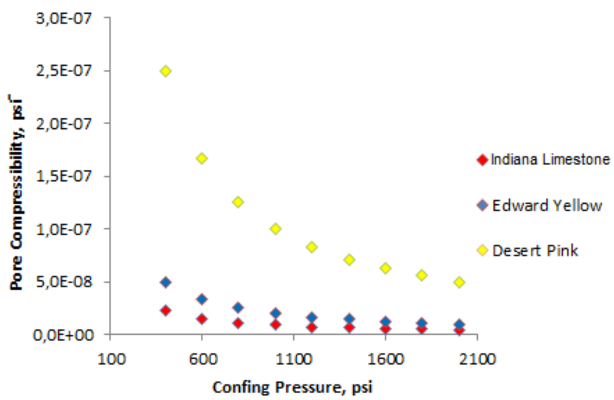

Figure 7: Sandstone samples pore volume compressibility versus confining pressure.

The pore volume variation of the sandstones sample follows a consistent trend, which did not occur in carbonates, the answer to this difference may be due to the fact that those rocks have different textures, while sandstones are formed entirely by depositional porosity, and the grain can be well selected, rounded, and sphere shaped, providing a more uniform geometric rearrangement to suffer compression, however, the carbonates have asymmetric pores due to their post depositional porosity, causing an irregular variation of the pore volume.

The comparison between the compressibility of the pore volume and the porosity (Figs. 8 and 9) showed that rocks with low porosity (12%) have less compressible pores compared to rocks with porosity above 20%. The overall behavior shows that the pore compressibility decreases as porosity reduces.

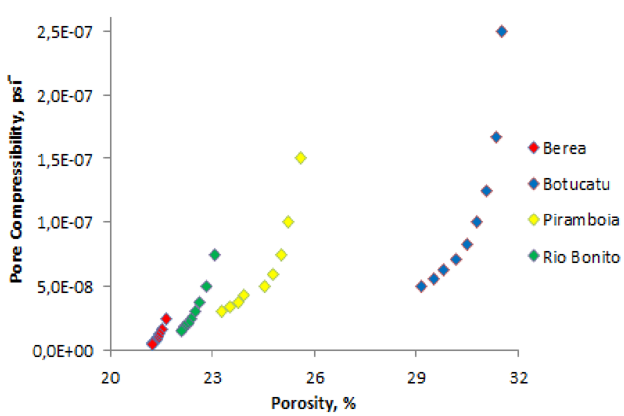

Figure 8: Sandstone samples pore volume compressibility versus porosity.

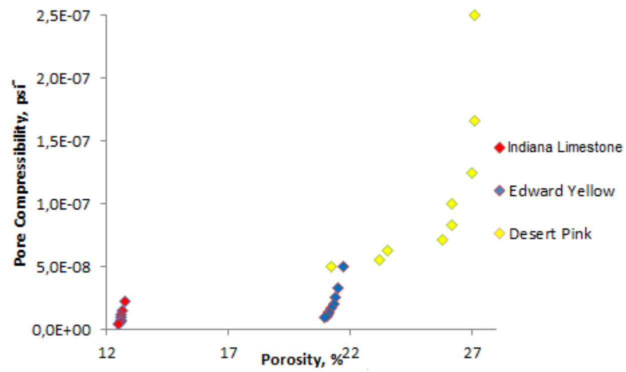

Figure 9: Carbonate samples pore volume compressibility versus porosity.

Conclusions

Due to the great accuracy of the exponential correlation, R^2> 95%, the method is considered effective for most of the samples, however, a more detailed knowledge about the pore system should be useful to understand the low accuracy for carbonate samples, and aid to obtain a more efficient relationship to correlate pore volume and confining pressure on that kind of rocks.

Pore compressibility may vary according to the type of rock, and ambient (atmospheric pressure) porosity, but in general, it tends to decrease as the confining pressures increases, as a result of porosity reduction the and enhancement of rock stiffness.

The method itself is low cost, very accurate, insensitive to mineralogy, since it is a non-invasive test and the sample can be available for new petrophysical tests. Sample preparation procedures are easy and responses are rapid and automatic. The values obtained by the proposed static method can be converted from uniaxial to hydrostatic for comparing to results derived from dynamic methods as seismic and sonic well logs.

Acknowledgments

The authors acknowledge LENEP/UENF and ANP/PRH-20 for the facilities that made this world possible. GLPO thanks CAPES for her M.Sc. scholarship. RMM thanks FAPERJ for Jovem Cientista research grant. We also thank Luiz G. Abreu and Nathaly Archilha for their support during this work and Alexandre S. Vaz Jr. and Hélio S. Ribeiro for providing some of the samples.

References

ALOKI, B. H., 2011, The effect of rock types on pore volume compressibility of limestone and dolomite samples: JGeope 1, 37-46.

FATT, I., 1958, Pore volume compressibilities of sandstone reservoir rocks.Journal of Petroleum Technology: Society of Petroleum Engineers, 10, 64–66.

GEERTSMA, J., 1957, The effect of fluid pressure decline on volumetric changes of porous rocks: Petroleum Transactions, AIME , 210, 331–340.

HALL, H., 1953, Compressibility of reservoir rocks. Petroleum Transactions, AIME, 198, 309-311.

HORNE, N.R., 1990, Modern Well Test Analysis: A Computer-Aided Approac: Petroway, Inc, 257.

JALALH, A., 2006, Compressibility of porous rocks: Part i. measurements of Hungarian reservoir rock samples: Acta Geophysica, 54, 319–332.

KNAAP, W. Van der, 1959, Nonlinear behavior of elastic porous media: SPE Annual Fall Meeting, 216, 179-187.

NEWMAN, G., 1973, Pore-volume compressibility of consolidated, friable, and unconsolidated reservoir rocks under hydrostatic loading: SPE Journal of Petroleum Technology, 25, 129–134.

TEEUW, D., 1971, Prediction of formation compaction from laboratory compressibility data, Old SPE Journal, , 11, 263–271.

UNALMISER, S and SWALWELL, J. T. 1993, Routine determination of pore compressibility at any pressure based on two point measurements: Society of Core Analysts.

ZIMMERMAN, R. W., SOMERTON, W. H., and KING, M. S., 1986, Compressibility of porous rocks: Journal of Geophysical Research, 91, 12765–12777.