On Poroelastic Homogeneity: Experimental Measurements of C_ϕ

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Introduction

The work of Brown and Korringa (1975) (BK75) effectively defines the concept of poroelastic inhomogeneity as a distance from Gassmann's equation (GE). GE is the typical algorithm used to predict the saturated bulk modulus of rocks. GE is also the limiting case of a broader theory of poroelasticity. Undrained bulk modulus prediction starts from the assumptions that the porous medium is a homogeneous solid on a macroscopic scale, and composed of a microhomogeneous and microisotropic matrix out of which pore space is carved. Since sedimentary rocks do not satisfy GE assumptions, the work of BK75 investigated how to relax the homogeneity constrain. The important result of BK75 is that the homogeneity assumption can be dropped by adding a set of coefficients linked by one poroelastic relationship:

$$C_s = \phi C_\phi + \psi C_m \qquad (1)$$

All the compressibilities in (1) are unjacketed, thus obtained under constant differential stress P_d. $C_s = -\frac{1}{V_b}\frac{dV_b}{dP_p}\Big|_{P_d}$ is the unjacketed bulk volume compressibility, $C_\phi = -\frac{1}{V_p}\frac{dV_p}{dP_p}\Big|_{P_d}$ is the unjacketed pore space compressibility, and $C_m = -\frac{1}{V_m}\frac{dV_m}{dP_p}\Big|_{P_d}$ is the unjacketed mineral compressibility. Porosity is ϕ and the solid fraction is $\psi = 1-\phi$. These concepts were already present in the work of Biot (1972), however their relevance is less explicit, and their significance more obscured. One of the major contributions of BK75 is to highlight the relevance of unjacketed compressibilities and to connect them to the concept of homogeneity, which in in poroelastic composites is defined as:

$$\frac{d\phi}{dP}\Big|_{P_d} = 0 \qquad (2)$$

Equation (2) means that for a given differential stress porosity of a homogenous rock does not change with stress. BK75 evolved to this result from the idea that a homogeneous solid matrix must be made of a single mineral. The monomineralic condition determines equation (2). It also sets $C_s = C_\phi = C_m$ in equation (1). Since sedimentary composites are rarely monomineralic, the logical conclusion would be that all realistic poroelastic media are inhomogeneous. Thus the real interest is in evaluating the degree of inhomogeneity.

BK75 make available to the experimentalist the theoretical framework to test the degree of inhomogeneity of a poroelastic composite using unjacketed compressibilities. However, these poroelastic parameters have been historically difficult to measure. They require tracking simultaneous variations of confining and pore pressures under conditions of constant differential stress. In particular, C_ϕ requires the ability to track very small amounts of fluid moving in and out of the pore space. Historically, experimental research on this topic can be defined as episodic, and unfortunately not entirely successful. Hart and Wang (1995) measured a large number of poroelastic coefficients with the exception of C_ϕ on a set of sandstones and limestones. The redundant poroelastic set of parameters allowed them to estimate C_ϕ using poroelasticity and optimization. Berge (1998) concluded that C_ϕ could have significant relevance in the estimate of the undrained bulk modulus. The primary objective of this study is to report on the attempt to measure C_ϕ directly.

Methods

Sandstone samples were exposed to stress cycles under constant differential stress. For each cycle a volume accumulator acts as a temporary storage and measuring device of the fluid expelled and going into the sample. Measurements of pore volume changes at constant differential stress are difficult to isolate because as confining and pore pressures are changed, the whole system will exhibit some variations of pore volume, irrespectively of the presence of the sample. Thus the basic idea for a successful measurement relies on the ability to measure the system response. The system compressibility is then subtracted out from measurements on rock samples. The calibration process eliminates systematic errors from pore volume measurements, thus increasing the accuracy of the pore volume accumulator.

Results

Figure 1 shows results for a sandstone exposed to a number of cycles at constant differential stress. In this particular case $K_\phi = 1/C_\phi$ is constant with respect to stress. Other cases showed a more classical asymptotic behavior, with non-linearity in the low stress regime.

Conclusions

Measurements of unjacketed pore space compressibility have been done on several sandstone samples. With exception of a few cases, the values of C_ϕ recovered show that inhomogeneity is the rule as opposed to the exception. While the implications of these findings are still evolving, it is time for this technique to be exposed and receive feedback on its validity.

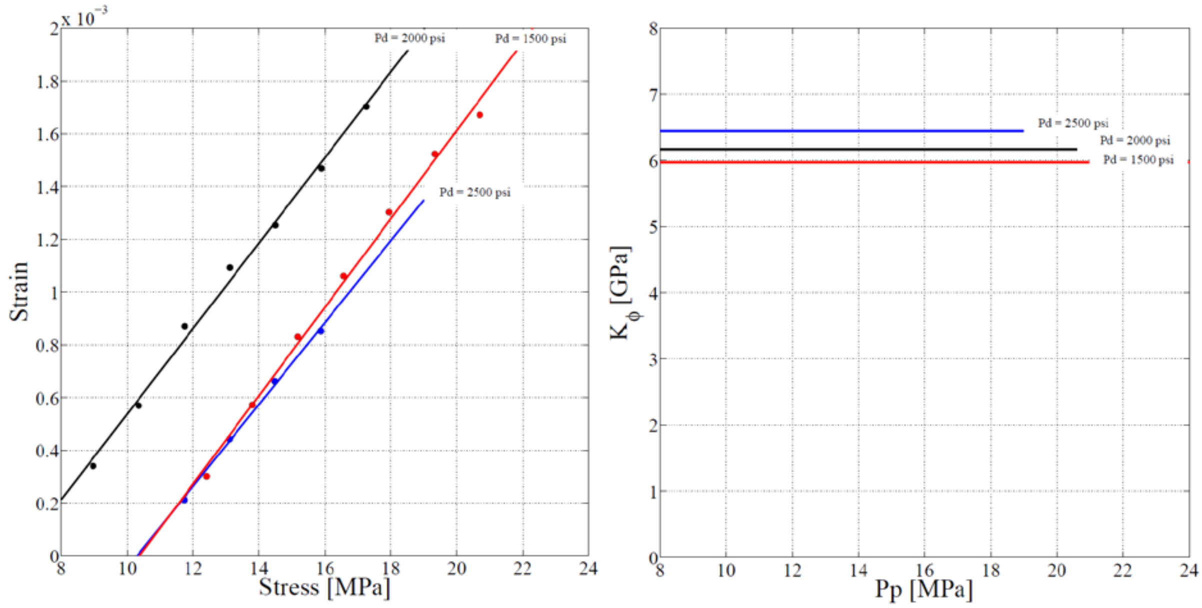

Figure 1: Pore strain and bulk modulus of a sandstone after multiple cycles at various levels of constant differential stress.

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