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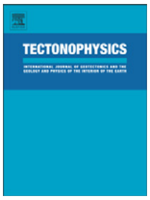

Numerical study of variation in Biot's coefficient with respect to microstructure of rocks

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ABSTRACT

Biot's coefficient, which is the key parameter of poroelasticity, strongly depends on the microstructure of the porous medium. Due to the complexity to conduct effective experiments at the microscale, there are very limited experimental data available, which document the influence of microstructure on Biot's coefficient. Therefore, numerical method was used in this paper to specify the influences of microstructural parameters on Biot's coefficient. Two-dimensional discrete element models with simplified microstructural geometries have been constructed with the purpose of obtaining a quantitative description of the influences of internal cavities (pores, fractures etc.) on the macroscopic deformability. Based on the numerical results some observations were revealed: 1) the Biot's coefficient is strongly dependent on the internal microstructure of the rock, and different porous media with the same composition of constituents may exhibit quite different poroelastic behavior due to their different microstructures; 2) the cracks, rather than the pores seem to have the dominant effect on Biot's coefficient; 3) the distribution of cracks and pores influences the Biot's coefficient and creates anisotropy. Two phenomenological equations were established by using the generalized mixture rule to describe the relationship between Biot's coefficient and rock microstructures, which give more accuracy results than the existing empirical equations.

1. Introduction

Rocks of the earth's upper crust (down to 10–15 km depth) are typically porous to some extent and often contain cracks and fractures at different scales. Number, shape and orientation of these cavities depend on the rock type and the damage it suffered. For example, sedimentary rocks may have porosities up to 40% with pore sizes in the range of 10 nm to 100 μm, whereas the porosity of igneous rocks is low, e.g. granite has a porosity usually less than 5%, and the main cavities are micro-cracks (Fig. 1). Most rocks are saturated and the cavities are filled with fluid (liquid and gas). Therefore, an important area of geophysical research is based on elastic property variations in rocks due to fluid content/microstructure coupling (Adelinet et al., 2011).

The theoretical basis for the hydro-mechanical coupling is the Biot's coupling theory which is also named theory of poroelasticity. Terzaghi (1943) developed the one-dimensional consolidation theory based on the concept of "effective stress". Rendulic (1936) extended Terzaghi's theory to three dimensions. Between 1955 and 1973 Biot presented the governing equations for coupled three dimensional fluid flow and deformation field for linear elastic porous media (Biot, 1955, 1956a, 1956b, 1956c, 1962, 1972, 1973). The Biot's effective stress is given as

$$\sigma'_{ij} = \sigma_{ij} + \alpha_{ij} p \tag{1}$$

where, the Biot's coefficient α represents the influence of pore fluid pressure to the elastic solid matrix. It is the key parameter of poroelastic theory and is essential in any hydro-mechanical coupled calculations. Many geotechnical problems, like dam and slope stability, ground settlements, oil and gas production, and underground storage of nuclear and toxic waste involve coupling mechanisms (Zhang et al., 2010).

The phenomenological theory of Biot considers the rock material (multi-phase media) as a single phase medium to solve deformation and strength problems based on a continuum mechanical basis (Huth and Laloui, 2008; Khalili et al., 2004; Lei and Chen, 2011). Therefore, Biot's coefficient has to be considered as a macroparameter of the representative element volume (REV), which is the smallest volume over which a measurement can be made. For volumes smaller than the REV, a representative geophysical property cannot be defined and the continuum description of the material breaks down. Otherwise, rock deformation under loading is governed by the combined deformation of grain skeleton and pores. Especially for rocks with stiff mineral grains, the deformation of microstructure is the main contributor to rock deformation. Therefore, the specification of Biot's coefficient should base on the microscopic characteristics, and the study considering the influence of rock microstructures below REV is necessary.

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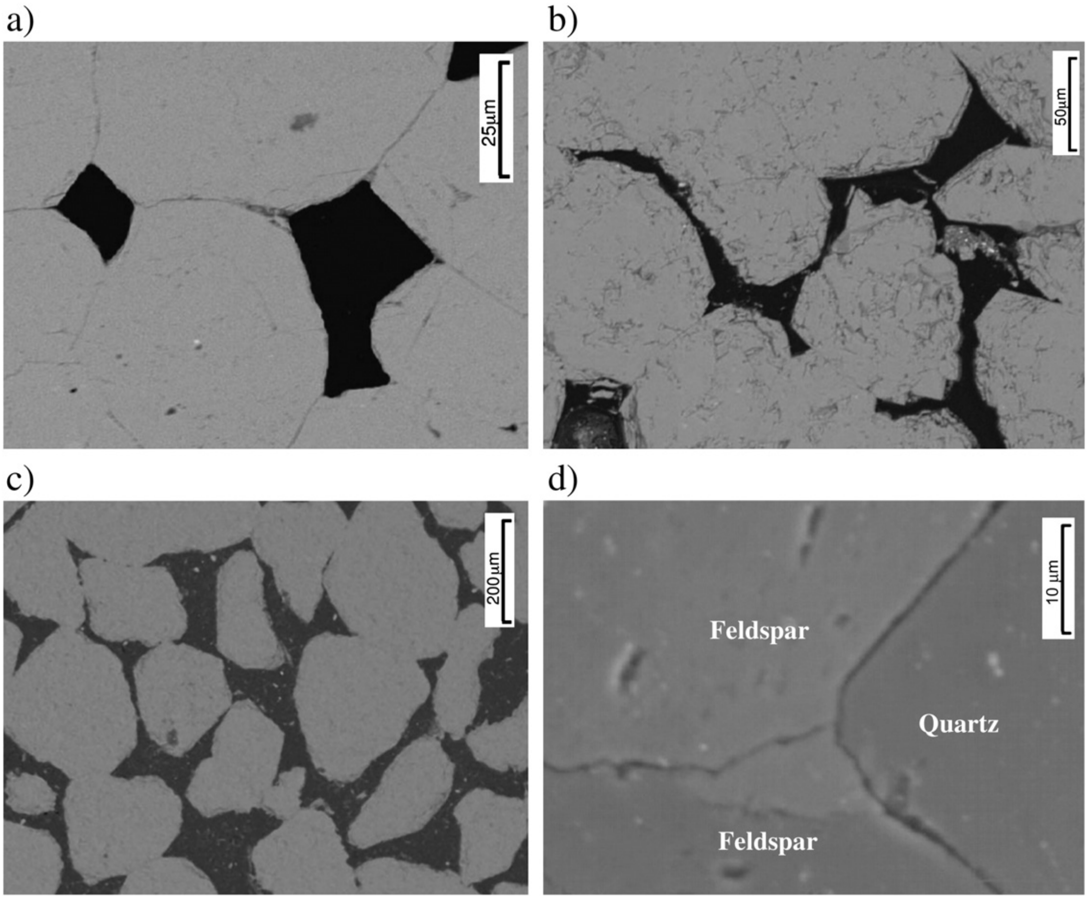

Fig. 1. a) SEM image of pores, Fontainebleau sandstone with 17% porosity; b) interconnected pores in Fontainebleau sandstone (SEM) with 25% porosity; c) SEM image of cracks and pores in deformed Fontainebleau sandstone with 17% porosity; d) cracked boundary and intragranular crack (SEM), Westerly granite (Leroy and Lehner, 2012).

We have to consider rock as a multi-phase medium. Therefore, the effect of cracks and pores on the effective bulk properties can be calculated by applying effective medium theories, which include the classical theory of Voigt (1928), Reuss (1929) and Hashin and Shtrikman (1962, 1963), self-consistent methods (Berryman, 1980; Berryman et al., 2002; Budiansky, 1965; Hill, 1965), differential effective medium methods (Avellaneda, 1987; Norris, 1985) and the generalized mixture rule (GMR) (Ji et al., 2006). Extensive literature (Dattke, 2003; Kachanov, 1987; Kachanov et al., 1994; Nemat-Nasser and Hori, 1999) is available about results of studying cracked elastic and poroelastic dry, saturated and partially saturated media, respectively. So far, most studies of the effective properties have focused on elastic moduli and strength parameters, but has not considered Biot's coefficient. Recent comprehensive review on the analysis of cracked elastic materials is given by Berryman et al. (2002).

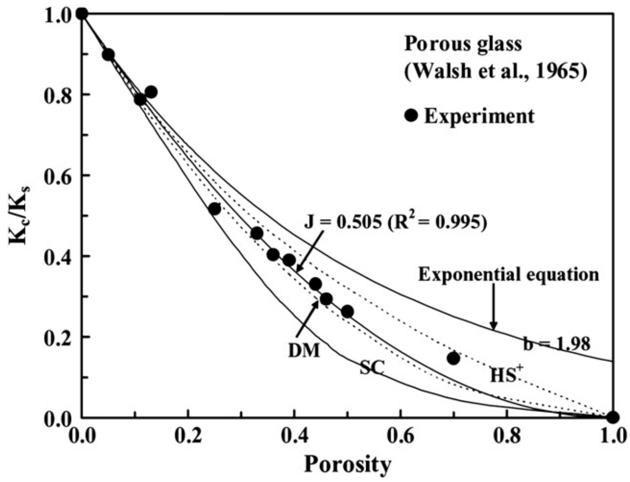

Fig. 2. Comparison between experimental and theoretical results for relative bulk modulus for glass foams (Ji et al., 2006).

Song and Renner (2008) investigated the hydro-mechanical properties of Fontainebleau sandstone and point that their experiments show that the Biot's coefficient depends on porosity. Hu et al. (2010) performed laboratory experiments on the evolution of Biot's coefficient induced by deviatoric stresses in cracked cylindrical marble sample and later also experiments on saturated sandstone samples (Hu et al., 2009) to study the evolution of Biot's coefficient with induced damage. It was found that: 1.) the Biot's coefficients are anisotropic, because the cracks in the specimen are growing along the direction of maximum normal stress; 2.) the axial and lateral Biot's coefficients are increasing with increase in axial strain, because increasing axial strain leads to the propagation of cracks; and 3.) the values of axial and lateral Biot's coefficients under low confining stress are greater than that under high confining stress, because failure pattern are different for different confining pressure. Ramos da Silva et al. (2010) presented fitting relations between Biot's coefficient and porosity of saturated limestone based on the empirical equations, which shows that the Biot's coefficients increase with increasing porosity. Further experimental observations on Biot's coefficient are documented by Sayers and Kachanov (1995) for sandstones and by Schubnel and GuéGuen (2003) for granite. Both research articles confirm the observations described above, especially in respect to the evolution of anisotropic crack densities prior to macroscopic failure. But most of the researchers measured the Biot's coefficient