International Journal of Rock Mechanics & Mining Sciences 96 (2017) 1–10

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Evolution of permeability and Biot coefficient at high mean stresses in high porosity sandstone

Mathew D. Ingraham[a,*], Stephen J. Bauer[a], Kathleen A. Issen[b], Thomas A. Dewers[a]

[a] Sandia National Laboratories, Geomechanics Department, PO Box 5800, Albuquerque, NM 87185, USA
[b] Mechanical and Aeronautical Engineering, Clarkson University, PO Box 5725, Potsdam, NY 13699, USA

ARTICLE INFO

Keywords:
Biot coefficient
Permeability
Sandstone
Ductile failure
Yield

ABSTRACT

A series of constant mean stress (CMS) and constant shear stress (CSS) tests were performed to investigate the evolution of permeability and Biot coefficient at high mean stresses in a high porosity reservoir analog (Castlegate sandstone). Permeability decreases as expected with increasing mean stress, from about 20 Darcy at the beginning of the tests to between 1.5 and 0.3 Darcy at the end of the tests (mean stresses up to 275 MPa). The application of shear stress causes permeability to drop below that of a hydrostatic test at the same mean stress. Results show a nearly constant rate decrease in the Biot coefficient as the mean stress increases during hydrostatic loading, and as the shear stress increases during CMS loading. CSS tests show a stabilization of the Biot coefficient after the application of shear stress.

1. Introduction

Understanding the effect of pore pressure on the deformation of reservoir rocks and reservoir analogs is of great importance for many applications: stability of underground structures, wastewater injection, and carbon sequestration to list a few. Classically, the effect of pore pressure on deformation (linear elastic) is described through a pair of parameters, the Biot coefficient (α)[1,2] which describes the deformation in drained conditions (i.e., the pore fluid is free to leave the rock volume in question), and Skempton's coefficient (B)[3] which is used to describe the reaction of the rock when the pore fluid is not free to flow out of the rock. Skempton's coefficient will not be addressed in this paper as all of the tests were performed under drained conditions. The Biot coefficient is calculated by

$$\alpha = 1 - (K/K_m) \quad (1)$$

where K represents the bulk modulus measured during testing of a jacketed specimen, and K_m is the bulk modulus determined from an unjacketed test at the same stress conditions.

While there is no direct relation between the poroelastic parameters, α and B, and permeability, the data collected to determine the Biot coefficient is much of what is needed to determine permeability. Thus, presenting the data together is natural. Permeability, or the ability of a rock to allow fluid to flow through it, is another important parameter for understanding the effect of pore pressure on rock deformation. Permeability provides an indicator of how long it will take for systems to equilibrate to changes in pore pressure. High permeability (or high diffusivity) systems will allow rapid equilibration (on the order of minutes or seconds) while low permeability systems may take years to come to equilibrium.

Both of these subjects, poroelastic parameters and permeability, are well explored in the literature. In this paper, previous works will be separated into low mean stress and high mean stress studies, where low mean stress indicates brittle failure occurring before the peak in the yield surface, and high mean stress refers to ductile failure (cataclastic flow) occurring on the cap of the yield surface. This delineation will simplify the discussion of previous works, and allow for ease of reference to the current work, which was performed at high mean stress.

2. Background

2.1. Low mean stress

Much of the work performed at low mean stress focuses on the effect of a localized band of deformation (dilating shear, compacting shear, or pure compaction) on the permeability of the specimen as a whole. Investigation of the Biot coefficient evolution in this case has little meaning after formation of a band, as the material can no longer be considered a single linear elastic element. However, the evolution of the Biot coefficient prior to localization is an important factor to consider in reservoir modeling.

* Correspondence to: Sandia National Laboratories, PO Box 5800, Mail Stop 1033, Albuquerque, NM 87185-1033, USA.
E-mail addresses: mdingr@sandia.gov (M.D. Ingraham), sjbauer@sandia.gov (S.J. Bauer), issenka@clarkson.edu (K.A. Issen), tadewers@sandia.gov (T.A. Dewers).

http://dx.doi.org/10.1016/j.ijrmms.2017.04.004
Received 12 September 2016; Received in revised form 5 April 2017; Accepted 16 April 2017

A number of researchers have examined either Biot coefficient evolution or permeability evolution in high porosity rock at low mean stress, e.g., [4–11]. Some of these authors noted that as shear stress increases, permeability decreases until the specimen begins to dilate, at which point permeability begins to increase (provided confining pressure is low enough). However, even with dilatant failure modes, the permeability of the rock remains below its original permeability level (i.e., the rock is most permeable at the start of testing). Hart and Wang [10] performed a very thorough investigation of the evolution of poroelastic moduli on Berea sandstone and Indiana limestone at low effective mean stresses (10–35 MPa). They performed sufficient tests to determine poroelastic parameters (of specific interest to this work were the values of K and K_m, needed to calculate the Biot coefficient) via different methods, thereby over constraining the solutions for their parameters, and using the difference between methods to determine the accuracy of each method. Overall, they determined that the effective stress law, determined from theory, provides a good estimate of effective stresses validated by measuring effective stress multiple ways during testing. This indicates that the effective stress law is a good metric for relating matrix and pore fluid compressibility for isotropic media, [12] i.e., the Biot coefficient is a good measure of the effect pore pressure has on rock response under drained conditions.

There have also been a number of investigations which have examined the anisotropic effects of the Biot coefficient. Cheng [13] formalized the micromechanical theoretical implications of an anisotropic Biot coefficient and suggested a model based on the 21 drained elastic moduli, a grain bulk modulus and a Biot modulus. Zimmerman [14] also investigated the theoretical implications surrounding the Biot coefficient and found that when coupling poroelasticity and thermoelasticity, the latter is much less important, i.e., stresses and strains do not appreciably change the temperature field. It was also found that the poroelastic coupling parameter is the product of the Biot coefficient and Skempton coefficient [14]. Lockner and Beeler [15] investigated the anisotropic aspects of the Biot coefficient and Skempton coefficient. They limited the applied differential stress to 50% of failure stress in an effort to minimize permanent damage due to micro-cracking. This allowed investigation into the reversibility of stress-induced anisotropy; it was found that under these test conditions, for Berea sandstone, the stress induced anisotropies of the Biot coefficient and Skempton coefficient were reversible. This indicates that the Biot coefficient and Skempton coefficient are elastic in nature during elastic loading. Thus, inelastic behavior of the poroelastic coefficients could be used as a proxy for plastic deformation/damage.

Hu et al. [16] investigated the anisotropy of porous media and examined anisotropy due to preferential microcrack closure and growth of induced microcracks, under triaxial compression (confining pressures to 30 MPa) conditions on Zhejiang Red sandstone. It was noted that the permeability of the rock was only significantly affected by damage when microcracks coalesced; diffuse microcracking had a minimal effect on permeability. Hu et al. [16] also noted that since microcracks are preferentially oriented in the maximum principal stress direction, the largest effect on permeability from microcracking will occur in the maximum principal stress direction. Due to the configuration of most testing systems (including the one used in this work), the maximum principal stress direction is also the direction in which permeability is measured, that is, the measured permeability direction should have the largest change in permeability. The work of Holcomb and Olsson [4] bridges the gap between the low and high mean stress tests. Their work examines compaction localization specifically; they note that the localized region of deformation has a significant effect on the overall specimen strain, as well as the permeability change in the specimen. They report that the formation of a compaction band is initiated by a propagating compaction front, often reducing permeability up to two orders of magnitude.

2.2. High mean stress

Results at high mean stress conditions are scarcer than those at low mean stress, although a large body of work was performed by Wong et al., e.g., [17–20]. They investigated changes in permeability and porosity in a number of different sandstones at a wide range of mean stress levels. However, Wong et al. did not calculate Biot parameters in their work because of a lack of an unjacketed test. David et al. [18] determined the evolution of permeability for five different sandstones to assist in determining fluid pressure generation in the crust. They found that, depending on the active compaction mechanism within the rock, sensitivity of the permeability to changes in pressure and porosity were significantly different. Zhu and Wong[19] studied the permeability and porosity evolution in five different sandstones at a wide range of mean stresses (0–540 MPa). They noted that in the cataclastic region (high mean stress), permeability and porosity decrease with increasing mean stress, and that there were sharp decreases in both permeability and porosity around the compactive yield stress, C^*. This decrease in permeability and porosity was later found to be caused by the formation of compaction bands at the onset of shear enhanced compaction, i.e., the formation of a compacting shear/compaction band.[21,22]

Baud et al.[20] performed an in depth study of Bleurswiller sandstone, and the effect of pore fluid on mechanical response of the sandstone. Baud et al.[20] reported two values for the effective stress coefficient that governs failure, and found values of 0.945 for brittle failure, and 0.96 for ductile failure. Their results were found through linear regression to determine the effective stress coefficient, assuming a linear failure envelope for both brittle and ductile failure. Note that the effective stress coefficient for failure is not the same as the Biot effective stress coefficient that governs elastic behavior, which is investigated herein.[12]

Blöcher et al.[23] recently investigated the effect of high mean stress on the evolution of the Biot coefficient and other poroelastic properties for a pair of sandstones (Bentheimer, 23.6% porosity, and Flechtinger, 12.5% porosity). They noted that at high effective mean stresses, the Biot coefficient, along with other poroelastic parameters, tended to decrease almost linearly with increasing effective mean stress. At lower effective mean stresses, the decrease in the poroelastic parameters was non-linear, starting with a steep decrease that leveled off as the effective pressure increased; eventually the decrease became linear at high effective pressure.

3. Materials and methods

Specimens for this study were cored from a block of Castlegate sandstone. This material was selected for two reasons. First, Castlegate is a commonly used reservoir analog; as such, its high porosity and extensively interconnected pore space make it ideal for tests of this type. Second, the team working on this project has extensive experience working with Castlegate[4,24–32] and has recently published a thorough investigation of the mechanical properties of the dry rock under general stress states.[28–32]

A fluvial rock from Utah, Castlegate is primarily quartz (90%) with lithics, weathered feldspars, loosely cemented calcite and a small amount of clay. Average grain size is 0.2 mm[27] and the porosity of the specimens used in this work was 26 ± 0.3%. Specimens were nominally 100 mm in length and 50 mm in diameter, cored parallel to bedding; cores were taken in this orientation to prevent premature formation of failure features such as compaction bands due to weak bedding planes. After coring, the specimen ends were ground on a surface grinder to ensure that the ends were parallel to each other and perpendicular to the coring axis. After drying in a 60 °C oven for at least 24 h, the specimens were weighed and the bulk density was determined assuming a perfect right circular cylinder. Actual specimen dimensions, weights and densities are given in Table 1.