DRAINED AND UNDRAINED PLANE STRAIN COMPRESSION OF POROUS ROCK

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Summary Multiaxial compression experiments were conducted on water-saturated Berea sandstone, such that drained and undrained poroelastic response was measured under biaixal deformation. Assuming saturation of the rock by application of 7 MPa back-pressure, the unjacketed pore bulk modulus was estimated to be an order of magnitude smaller than the unjacketed bulk modulus of the rock. The former one appears to be close to the bulk modulus of the pore fluid – pure water (2.7 GPa and 2.2 GPa respectively) at low effective stress (5 MPa). Also, application of acoustic emission technique showed the tendency of rock to dilatantly harden under undrained loading.

INTRODUCTION

The presence of pore fluid plays an important role in a wide variety of geomechanical problems. Both elastic and inelastic material parameters differ under drained (long-time response) and undrained (rapid deformation) conditions. Laboratory measurements that provide estimates of poroelastic parameters and consider rate dependent effects of coupling of deformation with pore fluid diffusion are needed to describe these effects.

This paper presents the results of water saturated, plane strain compression tests on Berea sandstone. The University of Minnesota Plane-Strain Apparatus was used for this purpose. The device allows application of three different principal stresses and measurement of principal strains, as well as the ability to apply and measure pore pressure within the rock. All specimens were cut from the same block of sandstone in the same direction. The obtained drained and undrained bulk moduli and Skempton coefficient were used to calculate unjacketed bulk and pore bulk moduli. Also, acoustic emission (AE) rates were compared for drained and undrained compression tests.

EXPERIMENTAL METHODS

The University of Minnesota Plane-Strain Apparatus is based on a passive stiff-frame concept [1]. Prismatic specimen covered with polyurethane and wedged inside the biaxial frame within the apparatus is subjected to confining pressure and compressed axially (Figure 1). Minor and major principal stresses (σ_3 and σ_1) are obtained from a pressure transducer and load cell respectively. Strains in these directions are calculated from displacement (LVDT) measurements. Deformation in the plane strain direction ε_2 is measured by strain gages and σ_2 is calculated from generalized Hooke's law. In addition, the apparaus allows back-pressure saturation of the rock and measurement of upstream and downstream fluid pressures. Eight acoustic emission sensors glued to the sides of the specimen detect microseismic events.

The experimental procedure included water saturation of the specimen with the back-pressure saturation technique. After equilibration of the pore pressure within the rock, *B*-checks at constant Terzaghi's effective stress were performed. Saturation of the rock specimen was assumed when the Skempton coefficient $B = du/dP$ became constant. The specimen was then axially loaded to failure.

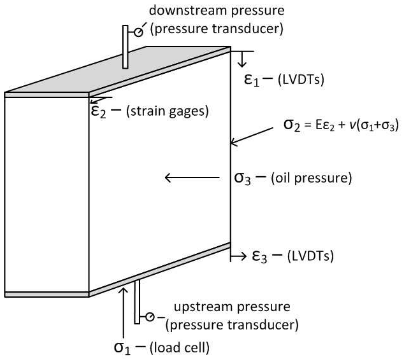

Figure 1. Biaxial specimen.

Young's modulus E and Poisson's ratio ν were calculated with generalized Hooke's law for the incremental behavior of an isotropic solid under plane strain ($\varepsilon_2=0$) and constant σ_3, using the sign convention of compression positive:

$$E = \Delta\sigma_1 \frac{\Delta\varepsilon_1 - 2\Delta\varepsilon_3}{\left(\Delta\varepsilon_1 - \Delta\varepsilon_3\right)^2} \qquad \nu = \frac{-\Delta\varepsilon_3}{\Delta\varepsilon_1 - \Delta\varepsilon_3} \tag{1}$$

Measuring bulk modulus of the material under drained (K) and undrained (K_u) conditions and knowing the porosity ϕ and pore fluid bulk modulus K_f, allows the calculation of the remaining poroelastic parameters [2]:

$$\alpha = 1 - \frac{K}{K_s'} \qquad B = \frac{K_u - K}{\alpha K_u} \qquad K_u = K + \frac{\alpha^2 K}{(1-\alpha)\alpha + \phi K\left(\dfrac{1}{K_f} - \dfrac{1}{K_s''}\right)} \tag{2}$$

where α is the Biot coefficient, K_s' and K_s'' are the unjacketed bulk and pore bulk moduli respectively.

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RESULTS

Poroelastic response

The tested Berea sandstone exhibited slight (5%) anisotropy in P-wave velocity, and the porosity ϕ=0.23, permeability k=40 mD. The results of the undrained and drained compression experiments, which were conducted at 5 MPa effective confining pressure, are the following:

undrained: $E_u = 13.5GPa$ $\nu_u = 0.35$ $K_u = 13.8GPa$

drained: $E = 10.9GPa$ $\nu = 0.31$ $K = 9.6GPa$

Assuming full water saturation of the undrained specimens with K_f=2.2 GPa, and taking account of the system response in measuring pore pressure, the following values for Biot's and Skempton's coefficients, and unjacketed bulk moduli were calculated:

$$\alpha = 0.67 \qquad B = 0.54 \qquad K_s' = 28.9GPa \qquad K_s'' = 2.7GPa \,.$$

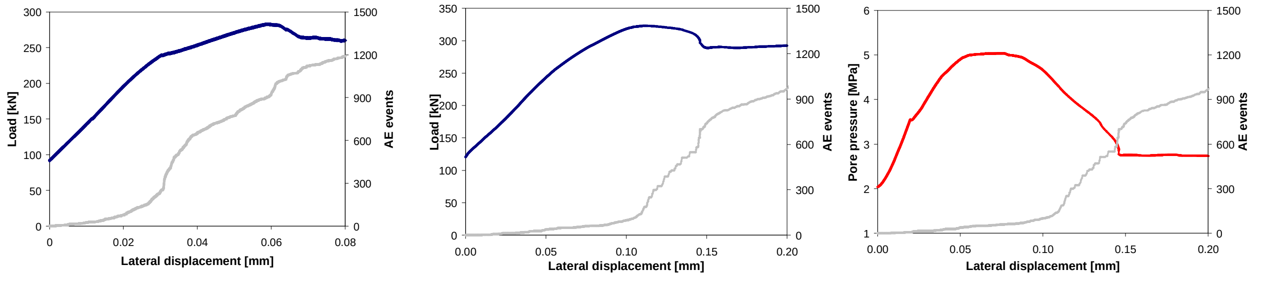
The undrained bulk modulus and Poisson's ratio were larger than their drained counterparts. Calculation of the unjacketed bulk modulus (28.9 GPa) showed that it is smaller than that usually taken for sandstones quartz grain bulk modulus (36 GPa). Also, it can be an order of magnitude larger than the unjacketed pore bulk modulus (2.7 GPa), which is close to the bulk modulus of the pore fluid (2.2 GPa). These results are in agreement with the experimental observation of Hart and Wang [3], who obtained the following values for poroelastic parameters from triaxial tests at 2.5-5.5 MPa effective confining pressure:

$$B = 0.61 - 0.75 \qquad K = 3.4 - 5.9GPa \qquad K_u = 11.1 - 14.3GPa \qquad K_s' = 27.0 - 34.5GPa \qquad K_s'' = 3.2 - 7.0GPa \,.$$

The difference between unjacketed bulk modulus and pore bulk modulus can be explained by the presence of highly compressible clay cement between quartz grains. Christensen and Wang [4] showed that the quartz grains are coated with clay, which also partially fills the pores in Berea sandstone. In this case, grain (or skeleton) bulk modulus can be significantly larger than pore bulk modulus under unjacketed condition, because an increase in pore pressure has a stronger impact on the change of pore volume than the equal increase in confining pressure.

AE behavior

A significant difference between drained and undrained compression in terms of AE rate with loading was observed. For the drained test where the pore pressure inside the rock was constant, the number of AE events per load step remarkably increased when the axial load on the specimen reached approximately 70% of peak load (Figure 2a). However, in an undrained test, only a few microseismic events were recorded prior to failure of the specimen (Figure 2b). The abrupt change in the slope of AE rate occurred only when the pore pressure in the rock dropped significantly due to localization of deformation and appearance of a macrocrack (Figure 2c). This effect could be explained by the delayed tendency to dilate for the rock under an undrained condition and the fact that an increase in specimen volume is usually accompanied by the intense microcracking, hence the AE rate should be increasing.



(a) (b) (c)

Figure 2. AE rates for a) drained and b)-c) undrained compression tests

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