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Chemoporoelastic characterization of Ghom shale

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A B S T R A C T

Swelling and deterioration of shales are the main causes of wellbore instability and associated problems in the drilling of hydrocarbon exploration and production wells. Shales have some unique characteristics that impact the wellbore stability. A few physiochemical theories are proposed for describing drilling fluid–shale interactions. The main problem in using these theoretical developments for evaluating potential borehole instability problems and developing realistic predictive models is the lack of experimental data on the shale properties. This paper presents results of study to characterize the chemo-poroelastic parameters of the illite rich Ghom shale in the laboratory. These parameters include a wide range of mechanical properties, porosity, permeability, solute diffusion coefficient, swelling coefficient and reflection coefficient. The required samples are prepared from an undisturbed outcrop block of Ghom formation.

The nitrogen gas injection method was utilized to measure the porosity of the shale sample. The pore volume was determined using the Boyles law technique. The permeability of the sample was calculated from transient analysis of the water injection pressure data. Consolidated drained and undrained triaxial tests were carried out to evaluate the required mechanical properties of Ghom shale. A diffusion cell was designed to measure the diffusion coefficient based on the concept of solute flow due to chemical potential gradient. A free swelling test was also conducted to investigate the swelling behavior of the rock samples in fresh water. Finally, a pore pressure transmission test was performed to quantify the osmotic properties of the shale in contact with a water-based fluid through calculation of the reflection coefficient.

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1. Introduction

Borehole instability in shale formations is a costly problem in drilling of oil and gas wells. A wide range of problems encountered in the field when shales experience failure are presented elsewhere (Yu et al., 2001; van Oort, 2003). These problems are mainly caused by redistribution of stress and pore pressure inside the shales when exposed to water-based drilling fluids. In addition to mud weight, the physio-chemical interactions between drilling mud and swelling shale greatly influence the resulting stress and pore pressure fields (van Oort et al., 1996; Wu et al., 1997; Zhou and Ghassemi, 2009). Swelling phenomena in shales result from the change in crystal dimension or grain boundary width that arises when water is incorporated into the crystal structure or adsorbed onto grain boundaries (Heidug and Wong, 1996).

Despite numerous developed models and numerical attempts to investigate the behavior of swelling shales in contact with water-based drilling fluids (e.g., Sherwood, 1993; Heidug and Wong, 1996; Ghassemi and Diek, 2003; Sarout and Detournay, 2011), experimental studies on the full range of chemo-poromechanical properties of shales are not commonly available. Experiments are necessary not only to obtain data for some of the parameters used in the constitutive models but also to check the validity of the assumptions used to develop these models (Heidug and Wong, 1996).

However, in recent years comprehensive laboratory studies are conducted to characterize shale gas and oil shales in terms of alternative energy resources (Josh et al., 2012; Sedman et al., 2012). Characterization of pore structure, mineralogy, saturation, organic matter abundance, rock physics and geomechanical properties of gas and oil shales are the necessary parameters for exploration and development of these energy resources. Furthermore, clay rich sedimentary rocks are characterized as potential host formations for geologic radioactive waste repository. Assessment of the suitability of the shales as host rocks for the disposal of radioactive wastes includes the quantification of solute transport retardation in these rocks. Therefore, laboratory programs investigating the shales from waste repository perspective mainly

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concern data acquisition on transport parameters such as porosity, permeability, sorption characteristics and diffusion coefficient (Vilks and Milller, 2007; Cave et al., 2010; Van Loon, 2010).

On the other hand, the subject of wellbore instability in shale formations is a complicated physico-chemical process and requires experimental data on mineralogy, mechanical properties, transport parameters and physicochemical interactions between the rock and the water based mud. The objective of this study is to measure the full range of chemo-poromechanical parameters for a swelling shale. First, a comprehensive constitutive model is introduced to identify the required parameters. Then the techniques and procedures for testing shales, analysing the results and calculating the parameters are included.

2. Chemo-poroelastic theory

Based on arguments from non-equilibrium thermodynamics, Heidug and Wong (1996) developed the first fully coupled chemo-poroelastic model of hydration swelling for water sensitive rocks. This continuum model is based on the extension of poroelasticity equations (Biot, 1941), Darcy's flow law and a diffusion equation for the transport of solute. Here we briefly explain the linear version of the governing equations. Details of the theory can be found elsewhere (Heidug and Wong, 1996; Ghassemi and Diek, 2003). In contrast to many models in the literature, this model is based on irreversible thermodynamics and hence has a solid basis. The original theory is non-linear and requires numerical methods for stress analysis (Zhou and Ghassemi, 2009). A linearized version of the model was developed by Ghassemi and Diek (2003) to facilitate analytical solutions and has been to perform wellbore stability analysis using closed-form solutions (Ghassemi et al., 2009).

2.1. Constitutive equations

The foundation of the constitutive equations is based upon the balance equation for Helmholtz free energy of a fluid infiltrated rock. There exist two types of water in shale–fluid system namely, pore water and bound water. Bound water is defined as the water that resides in the narrow space between individual clay platelets. This water is subjected to intermolecular surface forces (e.g., van der Waals, hydration, and electric double layer forces) and possesses physical properties that deviate from those of the bulk (Ghassemi and Diek, 2003; Zhou and Ghassemi, 2009). On the other hand, the pore water which freely diffuses in the pore space is not subjected to these intermolecular forces. Therefore, the quantity of Helmholtz free energy for fluid infiltrated shale is obtained by subtracting the free energy density of the pore fluid from that of the combined shale–fluid system. Under isothermal conditions this quantity becomes identical to the rock's strain energy and consequently holds the key to formulate the constitutive behavior of water-absorbing rocks (Heidug and Wong, 1996). The linear version of the constitutive equations, specifying the variations of solid stress and pore volume fraction in response to chemical and mechanical loading, is as follows (Ghassemi and Diek, 2003; Ghassemi et al., 2009):

$$\dot{\sigma}_{ij} = \left(K - \frac{2G}{3}\right)\dot{\varepsilon}_{kk}\delta_{ij} + 2G\dot{\varepsilon}_{ij} - \alpha'\dot{P}\delta_{ij} + \dot{\chi}\dot{C}^S\delta_{ij} \tag{1}$$

$$\dot{\xi} = \alpha\dot{\varepsilon}_{ii} + \beta\dot{P} + \chi'\dot{C}^S \tag{2}$$

where K and G denote the bulk and shear moduli, respectively. σ_{ij} is the total stress tensor, ε_{ij} is the strain tensor, P is the pore pressure, ξ is the variation of pore volume and C^S is the solute mass fraction. The coefficients in the constitutive Eqs. (1) and (2) are defined as

$$\alpha' = \left(\alpha - \frac{M^S\omega_0}{\overline{\rho}_f RT C_{mean}^D}\right),$$

$$\beta = \frac{\alpha - \phi}{K_s} + \frac{\phi}{K_f} + \frac{M^S\omega_0(\alpha - 1)}{\overline{\rho}_f RKTC_{mean}^D},$$

$$\chi = \frac{\omega_0}{C_{mean}^S}\left(1 - \frac{C_{mean}^S}{C_{mean}^D}\right)$$

$$\chi' = \frac{\alpha - 1}{K}\chi \tag{3}$$

where C_{mean}^S and C_{mean}^D denote the mean value of solute and diluent mass fractions over the range of interest, respectively; α is the Biot's coefficient; ϕ is the porosity; $\overline{\rho}_f$ is the fluid mass density; T is the absolute temperature; R is the universal gas constant; M^S is the molar mass of the solute; K_s and K_f are the bulk modulus of solid matrix and fluid, respectively. The linear version of the constitutive equations are derived using the approximation $\ln\left(C^S\right) \approx (C^S/C_{mean}^S) - b$, in which b is a reference value. In addition, the chemo-mechanical parameter ω can be defined as

$$\omega^S = \omega^D = \omega_0\frac{M^S}{RT} \tag{4}$$

where ω_0 can be viewed as a swelling or chemical stress coefficient which is fully explained in Section 4.4. Note that the total stresses are now defined by

$$\sigma_{ij} = \left(K - \frac{2G}{3}\right)\varepsilon_{kk}\delta_{ij} + 2G\varepsilon_{ij} - \alpha'P\delta_{ij} + \chi(C^S - bC_{mean}^S)\delta_{ij}. \tag{5}$$

2.2. Transport equations

The equations expressing the fluxes of water and solute in terms of their driving forces are derived from the concept of Rayleigh's dissipation function in the framework of non-equilibrium thermodynamics (Katachalsky and Curran, 1965). Assuming that the friction generated at the solid/fluid phase boundary in the porous skeleton is the only operative dissipation mechanism, Heidug and Wong (1996) established transport equations as follows:

$$J^f = -\overline{\rho}_f\frac{k}{\eta}\left(\nabla P - r\frac{\overline{\rho}_f RT}{M^S C^S C^D}\nabla C^S\right) \tag{6}$$

$$J^S = -\overline{\rho}_f D\nabla C^S \tag{7}$$

where k denotes the permeability, η is the fluid viscosity, r is the reflection coefficient and D is the solute diffusion coefficient. Permeability, solute diffusion and reflection coefficients for shales will be discussed in detail in Sections 4.1, 4.3 and 4.5, respectively.

2.3. Field equations

Combining the presented constitutive and transport equations with mechanical equilibrium, fluid and solute mass conservation equations, the general field equations may be written in terms of solid displacement **u**, pore pressure **p** and solute mass fraction **C^S** as

$$\left(K + \frac{G}{3}\right)\nabla(\nabla.\mathbf{u}) + G\nabla^2\mathbf{u} - \alpha'\nabla p + \chi\nabla C^S = 0 \tag{8}$$

$$\alpha(\nabla.\dot{\mathbf{u}}) + \beta\dot{p} + \chi'\dot{C}^S - \frac{k}{\eta}\left(\nabla^2 p - \frac{r\overline{\rho}_f RT}{M^S C^S C^D}\nabla^2 C^S\right) = 0 \tag{9}$$

$$\phi\dot{C}^S - D\nabla^2 C^S = 0 \tag{10}$$

Eqs. (8)–(10) present the Navier equations for displacement, pressure diffusion and solute diffusion equations, respectively. Solving the above equations, subject to appropriate initial and