



The role of moisture adsorption in wellbore stability of shale formations: Mechanism and modeling



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ABSTRACT

Understanding the interaction of drilling fluid with a shale formation is a critical step to properly describe pore pressure distribution, which directly affects wellbore stability. In this study, the moisture adsorption to shale surfaces is investigated to identify the proper isotherm type curve. It is shown that the moisture content of shale is correlated with water activity using a multilayer adsorption theory. It is found that the GAB model (developed by Guggenheim, Anderson and De Boer) fairly well describes the adsorption process for the selected shale types. Accordingly, the moisture content is correlated with water activity through the GAB model, which is incorporated into the transport equations. The adsorption parameter signifies the characteristic of a specific shale that interacts with aqueous fluids and can be introduced as an index to characterize different shale formations.

In this study, the constitutive equations are generalized to consider the case of non-ideal solutions. The coupled transport equations are solved using a finite difference method and numerical computations are conducted to predict the stability of the wellbore. Having developed a transient model that predicts the instantaneous moisture content around the wellbore, it is possible to update the rock compressive strength as a function of its moisture content using available empirical correlations in the literature. The results of this analysis indicate that the range of safe mud weight reduces substantially due to moisture adsorption. Comparisons of several compressive failure criteria indicate that stability reduction of the wellbore due to moisture transport is a common pattern based on the selected criteria. The results of this investigation assist in drilling fluid optimization and address wellbore stability issues in troublesome shale formations.

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1. Introduction

The adsorption of water to argillaceous rock is known to change some of the physical properties of the rock. Specifically, the increase in moisture content of the rock due to weathering or interaction with aqueous fluids has been shown to have a negative effect on the compressive strength of the rock (Chenvert, 1970; van Oort et al., 1996; and Lal, 1999). Lama and Vutukuri (1978) investigated the effects of moisture on rock properties for several rock types. Colback and Wiid (1965) conducted extensive experiments under a controlled moisture environment and concluded that the compressive strength of quartzitic shale under saturated condition

is reduced to 50% of its strength under dry conditions. Lashkaripour and Passaris (1995) investigated the effects of moisture content on the module of elasticity and uniaxial compressive strength of shales. They indicated that moisture content can be used as a suitable index for the determination of compressive strength and other mechanical properties of shale. Al-Bazali (2013) offered empirical correlations to estimate the uniaxial compressive strength of some shale cores in the Middle East. He postulated that the uniaxial compressive strength of the rock can be represented as a function of the uniaxial compressive strength of dry rock (σ_c^{dry}) and its moisture content (w). Hsu and Nelson (2002) presented a negative correlation between the moisture content and the uniaxial compressive strength of Eagle Ford Shale. Altogether, these correlations share a common theme in which uniaxial compressive strength reduces exponentially as the moisture content of the rock increases (Table 1).

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Table 1
Models for prediction of uniaxial compressive strength of shales.

Reference	Equation
Colback and Wiid (1965)	$\sigma_c = \sigma_c^{dry} e^{-0.034w}$
Hsu and Nelson (2002)	$\sigma_c = \sigma_c^{dry} e^{-0.083w}$
Al-Bazali (2013)	$\sigma_c = \sigma_c^{dry} e^{-0.44w}$

The effective stress is an important parameter to evaluate wellbore stability. The key to determination of effective stress is to evaluate the true pore pressure around the borehole. It is known that ion and water transport between the drilling fluid and shale formation can lead into an abnormal pore pressure in the vicinity of the wellbore (Ewy and Stankovich, 2002; Yu et al., 2003; and Chen et al., 2010). The magnitude of chemical potential of water within shale is usually approximated in terms of the solute concentration of the pore fluid (Sherwood, 1995; Lomba et al., 2000; and Ghasemi and Diek, 2003). However, this assumption does not include interaction between the pore fluid and the rock matrix and is not practical for non-ideal solutions. Experimental results have shown that the magnitude of water activity measured from a simulated pore fluid is not consistent with values measured over the shale rock sample (Simpson et al., 2001). Such observations indicate that the matrix and pore fluid interaction is essentially reflected in the measured values of shale water activity. In addition, it is known that shale–fluid interactions change some of the physical properties of the rock and this fact is often neglected in mathematical models. Furthermore, presence of natural fractures within shale formations or induced cracks due to drilling operations extends the instability zone. Case studies in the literature have shown that smearing effect due to casing drilling is an effective method to seal fractures and hence improve borehole stability (Karimi et al., 2011; Dokhani et al., 2013). However, van Oort and Razavi (2014) argued that wellbore strengthening has not been always successful in shale formations.

Therefore, one of the motivations of this paper is to develop a mathematical model that considers the interaction between a shale matrix and pore fluid through a thermodynamic framework. The formulation also aims to remove the ideal solution assumption. It is expected that these efforts help to improve pore pressure prediction near the wellbore and provide an estimate of the rock strength upon contact with water-based muds. Such analysis ultimately enhances rock failure prediction for field application.

1.1. Adsorption isotherms

One of the important interaction processes between a rock matrix and pore fluid is the hydration of clay minerals. An adsorption isotherm is a useful way to describe the hydration process of clay minerals (Chenevert, 1970). Tien (1994) presented five general type curves of adsorption isotherms that identify the adsorption mechanisms based on porous structure of the surface and the extended multilayer sorption phenomena (Fig. 1). To describe the adsorption process between aqueous fluids and shale rocks, reviewing the adsorption mechanism in clay minerals is helpful. Such a background helps to develop a theoretical explanation for the determination of adsorption isotherms in shale rocks.

1.2. Adsorption isotherms of clay minerals

Keenan et al. (1951) showed that the adsorption isotherm of sodium kaolinite follows BET (Brunauer–Emmett–Teller) isotherms (Type curves II and III in Fig. 1). Mooney et al. (1952)

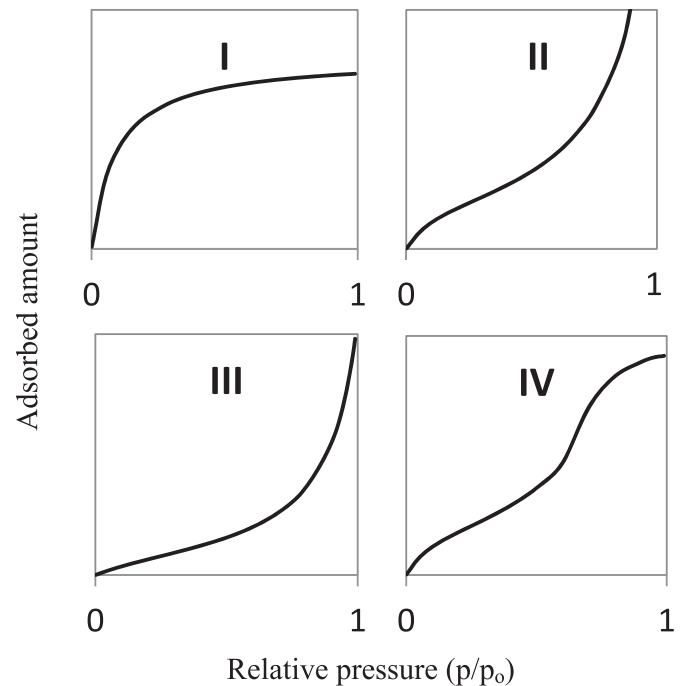


Fig. 1. Gas adsorption isotherms; (I) small pore size and uni-molecular adsorption, (II, III) wide range of pore size and multilayer adsorption, and (IV) two surface layer adsorption [After Tien, 1994].

examined water adsorption on natural montmorillonite and sodium montmorillonite. The authors reported that the adsorption and desorption isotherms follow different paths, indicating a clear hysteresis in the sorption process. Keren and Shainberg (1975) identified hysteresis between adsorption and desorption curves of Na- and Ca-montmorillonite and reported that the amount of water uptake by the Ca-clay is higher than by the Na-clay. The authors realized that the BET theory yields a good prediction of adsorption isotherm data. A similar pattern of isotherm type curve is reported by Cases et al. (1997) to describe the adsorption of water by Na-montmorillonite. The authors explained that the adsorption mechanism at low water activity ($0 < a_w < 0.25$) can be different from that at higher water activity.

1.3. Adsorption isotherms of shale rocks

The adsorptive tendency of shale rock toward aqueous solutions due to chemical imbalance between the two media was first quantified by Chenevert (1969) by applying thermodynamic relationships.

The author explained that the measurement of the relative humidity that is in equilibrium with the rock enables the calculation of adsorptive pore pressure. It is also shown that the uniaxial compressive strength of shale decreases with an increase in the moisture content of the rock through a nonlinear relationship. An experimental investigation by Chenevert (1970) indicates that the adsorption and desorption isotherms of shale rocks can exhibit hysteresis. This observation is analogous to the one reported for clay minerals in Section 1.1. The author examined the relationship between the moisture content and the relative humidity in equilibrium with ground samples for several shale types from different geological environments. Comparing the experimental results of Chenevert (1970) with the isotherm type curves in Fig. 1 reveals that the adsorption isotherm of selected shales can be represented by a multilayer sorption processes (i.e., Type II or III). Tandanand

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