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Determination of effective stress parameters for effective CO_2 permeability in deep saline aquifers: An experimental study

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ABSTRACT

Global warming has been a major threat to the world for many decades, and CO_2 geo-sequestration in deep saline aquifers has recently been identified as an effective solution due to its ability to greatly mitigate anthropogenic CO_2 emissions to the atmosphere. However, CO_2 sequestration-induced chemical and mineralogical reactions affect the hydro-mechanical characteristics of natural formations, resulting in limited injectability to aquifers. A detailed knowledge of the hydro-mechanical behaviour of natural formations is therefore important to enhance the safety and effectiveness of the CO_2 storage process. Such understanding can only be gained on the basis of in-depth knowledge of the applied effective stresses on the formations. The aim of this study was therefore to understand the effect of reservoir salinity level on the effective stress parameters of deep saline aquifer rock under various in-situ conditions, including salinity levels ranging from 0 to 30% (NaCl concentration by weight) and confining pressures ranging 20–35 MPa. Tri-axial permeability tests were conducted for a range of injection pressures (1–12 MPa) under different confining pressures (20, 25, 30 and 35 MPa) at 35 °C constant temperature. Comprehensive SEM (scanning electron microscopy) and acoustic emission analyses were also conducted to clarify the observed results.

According to the results, the effective stress coefficient (α) for CO_2 permeability decreases with increasing aquifer salinity level, and increasing salinity level from 0 to 30% causes the effective stress coefficient to be reduced by 31%. Moreover, the Skempton coefficient (B) increases with increasing salinity level from 0 to 30% and the increment is about 18%. Interestingly, the poro-elastic coupling parameter (αB) decreases from 0.89 to 0.72 as the salinity level increases from 0 to 30% and the reduction is about 19%. The SEM analysis conducted on tested samples confirmed the deposition of NaCl crystals in rock pore space during the saturation period of one year, and these observed variations in effective stress parameters are probably due to the NaCl crystal deposition in the rock pore space. This significantly alters the rock porosity and pore geometry, causing the simple effective stress law for CO_2 permeability to be inapplicable to saline aquifers.

1. Introduction

The evaluation of rock permeability and its variation with varying effective stress is important in many engineering applications, including mining engineering, petroleum engineering and CO_2 storage projects in deep sub-surface geological reservoirs, as it greatly affects the effectiveness and safety of these projects. For example, reduced pore pressure causes the permeability of oil/gas fields to be reduced, resulting in reduced production rates (Ghabezloo et al., 2009; Rempel and Rice, 2006; Sulem et al., 2007). Therefore, this implies the importance of having a clear understanding of the effect of effective stress laws on permeability for many geo-physics and geo-engineering applications. The CO_2 geo-sequestration process in deep saline aquifers is one such application, which has been recently identified as one of the most promising means of reducing anthropogenic CO_2 emissions in the world (Bruant et al., 2002). Generally, the preferable aquifers for this purpose are 800–2000 m deep sedimentary rocks, mainly sandstone, most of which are highly saline (salinity percentages may vary from 5% to more than 25% (NaCl by weight) depending on the depth (Shukla et al., 2012)). However, to date, little consideration

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has been given to understanding the influence of effective stress on reservoir rock properties of deep saline aquifers, especially under in situ conditions. Evaluation of the effective stress coefficients for CO_2/water/rock and CO_2/brine/rock systems plays a vital role in offering accurate input parameters for long-term numerical models, which are used to simulate the sequestration process in deep saline aquifers. It is therefore important to conduct an appropriate evaluation of the hydro-mechanical responses of saline aquifers to CO_2 injection under various effective stress environments.

The aim of this study was therefore to conduct a comprehensive set of experiments to evaluate the effective stress parameters for reservoir rock permeability in deep saline aquifers and to identify the influence of reservoir salinity level on them. A series of undrained tri-axial permeability tests was therefore performed on water- and brine-saturated reservoir rock samples under different confining and pore pressures, and a series of scanning electron microscopy (SEM) analyses was also carried out to clarify the corresponding chemico-physico microstructural variation of the reservoir rock.

1.1. The concept of effective stress law for permeability of reservoir rock

The concept of "effective stress" has long been used in rock mechanics. The concept was first introduced by Terzaghi (1936), who defined it as the difference between the confining pressure and the pore pressure, based on a simple force-balance argument (Eq. (1)):

$$P_d = P_c - P_p \tag{1}$$

This proposed concept reveals that the pore pressure and confining pressure tend to have opposite effects on the volume and therefore on many petro-physical properties, including permeability, storage capacity, electrical resistivity, and mechanical properties, such as pore volume compression, bulk volume compression, acoustic wave propagation, and failure. Terzaghi (1936) proposed this equation (Eq. (1)) based on an experimental study conducted to evaluate the application of effective stress on the permeability of reservoir rock in deep saline aquifers. Permeability, or any material property of rock, follows an effective stress law if it can be defined as a linear combination of total stress and the pore pressure. However, since different material properties depend on total stress and pore pressure in different ways, there is no unique effective stress to represent all the material properties of rocks (Ghabezloo et al., 2009). This implies the requirement of different effective stress relationships for different material properties. According to past studies (Zimmerman, 1991; Berryman, 1992; Keaney et al., 2004; Ghabezloo et al., 2009), effective stress can be simply used as a single variable to express the stress dependency of many material properties, and the stress dependency of reservoir rock permeability, k, can be defined as follows:

$$k = k(P_c, P_p) = k(P_d) \tag{2}$$

As can be seen from Eq. (2), the development of such a relationship reduces the number of independent variables from two to one. If the incremental variation of the permeability (k) is considered (derivation of $k(P_c, P_p)$):

$$dk = \frac{\partial k}{\partial P_c} dP_c + \frac{\partial k}{\partial P_p} dP_p \tag{3}$$

Eq. (3) can then be re-arranged as follows:

$$dk = \frac{\partial k}{\partial P_c}\left[dP_c - \left(-\frac{\partial k/\partial P_p}{\partial k/\partial P_c}\right)dP_p\right] \tag{4}$$

The stress dependency behaviour of k can then be defined as a function of the incremental variation of effective pressure (dP_d):

$$dk = \frac{\partial k}{\partial P_c} dP_d \tag{5}$$

$$dP_d = dP_c - \alpha dP_p \tag{6}$$

Comparison of Eq. (4) with Eq. (5) shows the relationship between k and the differential pressure (effective stress), and can be correlated using coefficient α (Eq. (6)), which is the effective stress coefficient corresponding to the permeability of the reservoir rock, and can be presented as follows:

$$\alpha = -\frac{\partial k/\partial P_p}{\partial k/\partial P_c} \tag{7}$$

Thus, the iso-lines of permeability can be obtained by integrating the differential equation of $P_d = 0$, which gives the expression for effective stress for the permeability of reservoir rock. The linear relationship presented in Eq. (8) is the most commonly used expression for effective stress evaluation in rocks, which can be obtained by evaluating the iso-lines of k (P_c, P_p). Furthermore, the α coefficient in the effective stress law can be determined using the gradient of the iso-permeability curves in the (P_c, P_p) plane.

$$P_d = P_c - \alpha P_p \tag{8}$$

2. Relevant literature

To date, many approaches have been taken to identify the applicability of effective stress law to the permeability of many materials, including sedimentary (sandstone) and crystalline rocks (limestone, granite) (Zoback, 1975; Zoback and Byerlee, 1975; Walls and Nur, 1979; Nur et al., 1980; Walls, 1982; Zimmerman, 1991; Berryman, 1992; Al-Wardy, 2003; Keaney et al., 2004; Ghabezloo et al., 2009). However, there are still limited experimental data available on this aspect for permeability of reservoir rocks in deep saline aquifers, especially during the CO_2 geo-sequestration process. This results in a poor understanding of the effect of CO_2 geo-sequestration in deep saline aquifers (fully brine-saturated sandstones) on their stress-dependent behaviour.

Keaney et al. (2004) conducted hydrostatic compression experiments to investigate the influence of effective pressure on both the permeability and specific storage capacity of water-saturated Tennessee sandstone and observed reduction trends of both with increasing effective pressure. They determined the effective stress coefficient, α, for both properties by developing iso-permeability and iso-specific storage lines in the (P_c, P_p) plane. According to the plots, the α values for both permeability and specific storage were not constant over the considered effective pressure range, and the α for permeability varied from 1.1 to 0.5 and for specific storage from 1.1 to 0.8 at low and high effective pressures, respectively. These observed changes in effective stress coefficient α with the effective pressure were then interpreted to examine how the volume and shape of flow paths change with effective pressure. A similar experiment was performed by Bernabe (1987) on Chelmsford and Barre granites to determine the effect of the effective