Marine and Petroleum Geology 77 (2016) 640–652

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Laboratory measurement of deformation-induced hydro-mechanical properties of reservoir rock in deep saline aquifers: An experimental study of Hawkesbury formation

M.S.A. Perera [a], T.D. Rathnaweera [a], P.G. Ranjith [a, *], W.A.M. Wanniarachchi [a], M.C.A. Nasvi [b], I.M. Abdulagatov [c], A. Haque [a]

[a] Deep Earth Energy Laboratory, Department of Civil Engineering, Monash University, Building 60, Victoria 3800, Australia
[b] Department of Civil Engineering, Faculty of Engineering, University of Peradeniya, Sri Lanka
[c] Institute Geothermal Research Institute of the Russian Academy of Sciences, Machachkala, Dagestan, Russia

ARTICLE INFO

Article history:
Received 5 August 2015
Received in revised form
10 July 2016
Accepted 12 July 2016
Available online 14 July 2016

Keywords:
CO_2 sequestration
Brine
Critical stress
Permeability
Saline aquifers
CCS
Reservoir

ABSTRACT

The long-term integrity of CO_2 storage in deep saline aquifers has become uncertain due to the unsteady character of surrounding factors, and the time-dependent nature of the aquifer's overburden load (the vertical stress imposed on the aquifer by the weight of overlying materials (rock/soil layers), which may vary over time as a result of natural incidents such landslides and earthquakes) is critical. The aim of this study is to identify the influence of overburden load variations on the long-term integrity of the CO_2 storage process in deep saline aquifers. High-pressure tri-axial strength and permeability tests, along with acoustic emission (AE) and scanning electron microscopy (SEM) analyses, were conducted on Hawkesbury sandstone obtained from the Gosford basin.

According to the results, the injection of CO_2 into the Hawkesbury formation may dissolve aquifer rock minerals, enhancing aquifer flow performance and reducing aquifer strength. Increasing the stress applied on the aquifer causes aquifer flow ability to reduce to some extent due to pore matrix compaction. Further increase of the overburden pressure may accelerate the aquifer's flow performance due to dilation-induced pore opening. This permeability transition point occurs earlier at greater CO_2 injection pressures and overlaps with the crack formation point of the aquifer rock mass. Therefore, weakening of the rock mass after the transition point can be expected. Importantly, this permeability transition point occurs at lower overburden loads after longer interaction of CO_2 with the saline aquifer. This exhibits the long-term risk associated with CO_2 sequestration in saline aquifers. Permeability enhancement after the transition point may also produce environmental disasters, such as sudden leakages of injected CO_2 from the reservoir to surrounding fresh water aquifers (Evans et al. 2004; Little and Robert 2010), exceeding the specific rates proposed by many regulatory frameworks. Therefore, it is essential to study the long-term integrity of the sequestration process in order to develop a regulatory structure to meet the demands of deep saline sequestration projects.

1. Introduction

An understanding of the hydro-mechanical response of geological materials like rocks to natural loading is imperative in many geo-engineering and petroleum industry-based applications, where extensive loading may create harmful impacts on natural formations, including micro-cracking due to local stress concentrations, frictional sliding on pre-existing micro-cracks, and even failure due to newly-formed micro- and macro-cracks. The evaluation of deformation-induced changes in hydro-mechanical properties in deep saline aquifers caused by CO_2 geo-sequestration is very important, because unexpected permeability enhancements and formation strength reductions may cause many issues, including back-migration of the injected CO_2 into the atmosphere, contamination of freshwater aquifers (Brasier and Kobelski, 1996, Evans et al., 2004; Little and Robert, 2010), surface uplifting, unpredictable leakages, and seismic activities (Wilson

---

* Corresponding author.
E-mail address: ranjith.pg@monash.edu (P.G. Ranjith).

http://dx.doi.org/10.1016/j.marpetgeo.2016.07.012
0264-8172/

et al., 2003; Ranjith et al., 2013). Some of these issues (e.g. contamination of freshwater aquifers and back-migration of the injected CO_2 into the atmosphere) may even create devastating catastrophes when they exceed critical limits, such as leakage of CO_2 into the atmosphere and surrounding aquifers at significantly high rates with the creation of major cracks in the formation caused by the injecting CO_2 (Bruant et al., 2002; Wilson et al., 2003).

A number of studies have been carried out to date on the deformation-induced fracturing process and its impacts for various underground reservoir materials, including rock salt, shale, siltstone and mudstone (Kachanov 1982; Steif, 1984; Stormont and Daemen, 1992; David et al., 1994; Schulze et al., 2001; Cappa and Rutqvist, 2011; De Silva and Ranjith, 2012; Wang et al., 2013). However, the deformation-induced hydro-mechanical behaviour of reservoir rocks in deep saline aquifers resulting from CO_2 sequestration has not been studied, and the chemico-mineralogical interactions between the injected CO_2, brine and reservoir rock make the problem extremely complex. It is now well accepted that CO_2/brine/rock interaction-induced mineralogical changes (Marbler et al., 2013; Rathnaweera et al., 2015, 2016) can alter the flow-mechanical properties in reservoir rocks. The coupling between these changes and existing overburden pressures will therefore create more complicated situations during the sequestration process. Moreover, in a developed reservoir, differential depletion of lithostatic layers with various permeabilities and the movement of fluid contacts can change the overburden pressure profile. Failure to manage and control these overburden pressure effects can cause serious equipment damage and injury or loss of life. It is therefore necessary to conduct comprehensive research studies to fully understand the hydro-mechanical behaviour of reservoir rock under different overburden pressure conditions during the CO_2 sequestration process.

To date, a number of studies have been conducted to identify the flow pattern alterations and fracture formations in reservoir rocks with deformation. For example, Stormont and Daemen (1992) carried out gas permeability and porosity measurements to characterise deformation-induced permeability and damage in rock salt. According to these researchers, the gas permeability of rock salt can increase by more than five orders of magnitude from its natural state with increasing deviatoric load applied on it. They also proposed a flow model based on the equivalent channel concept, and the model results were found to be consistent with the laboratory data. Similar trends in rock salt behaviour upon the application of deviatoric loading during conventional tri-axial compression testing have been shown by Lai (1971), Donath et al. (1987), Peach et al. (1987), David et al. (1994) and Peach and Spiers (1996). The experiment performed by Peach et al. (1987) under 5 MPa confining pressure revealed that gas permeability can be increased by more than four orders of magnitude by increasing axial strain by 10%. Donath et al. (1987) observed more than two orders of magnitude increment in brine permeability in Domal rock salt upon 5% axial strain increment under 6 MPa confining pressure. The permeability alterations of Domal rock salt upon axial deformation shown by Lai (1971) are higher than those in the above studies, and the discrepancy is believed to be due to the different pore arrangements. The development of damage and permeability in deforming rock salt has been studied by Schulze et al. (2001), who performed strength and creep tests using a Karman-type pressure apparatus coupled with ultrasonic wave velocities. This study further discussed the behaviour of rock salt under both non-dilatancy and dilatancy domains based on the analysis of acoustic emission (AE) counts, volumetric strain, permeability, and ultrasonic wave velocities. Peach and Spiers (1996) performed dilatometric tri-axial tests to investigate the influence of crystal plastic deformation on the dilatancy and permeability of synthetic rock salt and observed a rapid permeability increment (from 10^{-21} to 10^{-16} m^2) at 0.1–0.2 vol% dilatancy. This shows that even a minor dilatancy (<0.2 vol%) occurring during plastic deformation of rock salt may lead to huge permeability enhancements and extreme formation instability.

Flow and crack linkage models are able to articulate such rapid permeability developments in reservoir rocks upon deformation (Peach, 1991; Stormont and Daemen, 1992). The flow model developed by Stormont and Daemen (1992), based on the equivalent channel concept (the channels represent the pore structure of the rock mass), aimed to evaluate the deformation-induced permeability characteristics of rock salt. The concept was originally proposed by Wyllie and Rose (1950) and was subsequently re-derived and analysed by Paterson (1983) and Walsh and Brace (1984). The equivalent channel model describes the permeability characteristics as a function of the tortuosity (t^2), porosity ($\varnothing$) and hydraulic radius of the equivalent channel (m) (see Eq. (8)). Stormont and Daemen (1992) used a frictional sliding crack model to understand the variations of permeability characteristics which occur as a result of micro-cracking initiation and propagation. This frictional sliding crack model considers the loading history of the sample to predict the stresses during the initial and secondary cracking stages, and to evaluate the secondary crack length during load application. A different crack model for sliding cracks initially oriented at an angle of $1/2\tan^{-1}(1/\mu)$ with respect to the maximum principal stress has been proposed by Jaeger and Cook (1979):

$$\sigma_1 = \frac{2S + \sigma_3\left[\sqrt{(\mu^2+1)} + \mu\right]}{\sqrt{\mu^2+1} - \mu} \tag{1}$$

where, S is the intrinsic shear strength, σ_1 is the axial stress, σ_3 is the confining stress and μ is the coefficient of static friction.

After the initial crack formation, secondary cracks generally initiate when the induced tensile stress (hoop stress) through compression exceeds the strength of the rock near the micro-flow tip (Stormont and Daemen, 1992). The angles of secondary cracks (β) with respect to the maximum principal stress, that slide along a particular stress direction can be given as follows (Brady, 1969):

$$\beta = \frac{1}{2}\left[\tan^{-1}\left(\frac{1}{\mu}\right) \pm \cos^{-1}\left(\frac{2S + \mu(\sigma_1+\sigma_3)}{\sqrt{(1+\mu^2)}\,(\sigma_1-\sigma_3)}\right)\right] \tag{2}$$

Kachanov (1982) modified Eq. (1) by replacing $2S$ by $2K_{IC}/\varphi(\sqrt{2/\pi l}) + 2S$ to capture the secondary crack initiation in the model (Eq. (3)), and the length of this secondary crack can be estimated based on Steif's (1984) findings. The deformation-induced flow paths predicted by this model are initially developed along the weaker grain boundaries and then along the secondary cracks upon continuous loading until the failure of the rock mass (Stormont and Daemen, 1992).

$$\sigma_1 = \frac{2K_{IC}/_{\varphi}\left(\sqrt{2/\pi l}\right) + 2S + \sigma_3\left[\sqrt{(\mu^2+1)} + \mu\right]}{\sqrt{\mu^2+1} - \mu} \tag{3}$$

where φ is a constant, K_{IC} is the mode I critical stress intensity factor and l is the secondary sliding crack length. Fig. 1 gives the schematic illustration of the Eq. (3), and shows how a secondary crack originates from a primary crack (original crack) in an axial loading environment.

Peach and Spiers (1996) studied the influence of crystal plastic deformation on dilatancy and permeability developments in synthetic rock salt under low pressure and temperature conditions by