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Effect of CO_2-Clay Interaction on Swelling Stress Generation Capacity and Porosity of Clay-rich Medium Exposed to CO_2

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ABSTRACT

Among clay minerals, smectite adsorbs a considerable amount of CO_2 at geological sequestration conditions resulting in volumetric expansion or swelling-stress generation in free or constant volume conditions. The adsorption-induced volumetric strain can cause a reduction in the porosity and permeability of smectite at constant volume conditions, which in turn will influence the migration of CO_2 in a media. Simultaneously, in constant volume conditions generation of swelling stress will affect the stress regime of the medium surrounding the smectite. The present study illustrates the effect of CO_2 adsorption-induced strain on the porosity and state of stress of the smectite-rich medium. A coupled hydromechanical model that incorporates the adsorption-induced strain due to the interaction between clay minerals and CO_2 is employed to investigate the behavior of smectite-rich medium. The model uses a generalized porosity change equation that captures the contribution from the effective stress, adsorption-induced strain, and compressibility of the solid grains. The effects of overburden stress, saturation pressure, and gas injection pressure on the swelling stress and porosity of the medium are investigated. The higher the overburden stress and gas injection pressure higher the swelling stress while the higher the initial pore pressure lower is the swelling stress. Whereas, there is a declining trend in the porosity at higher overburden stress, saturation gas pressure, and injection gas pressure. Overall, this study demonstrates that the porosity and state of stress of smectite-rich medium post-CO_2 injection will be governed by overburden stress, gas injection pressure, and reservoir saturation pressure.

Keywords: Carbon dioxide, sequestration, adsorption-induced strain, smectite, porosity, swelling stress

1. INTRODUCTION

In carbon geosequestration, carbon dioxide (CO_2) is captured from a stationary source of emission and transported into deep geological aquifers for long-term storage (Shukla et al., 2011). The CO_2 in storage aquifers saturated with formation fluid rises buoyantly from the bottom of aquifers and reaches the bottom of a caprock due to its lower density than the density of the formation fluid. The further migration of CO_2 from the bottom of caprocks into regions near the ground surface is obstructed by the impermeable property of a caprock (Rutqvist, 2012). However, when a caprock consists of features like faults or fractures, the stored CO_2 is prone to leak out into the ground surface through faults depending on the fault's hydraulic properties (Nicol et al., 2017). Generally, when a normal fault is formed in a caprock made of sandstone or shale with a tiny clay seam, clay smears are entrained within the fault zone and redistributed between the footwall and hanging walls of the caprock (Smith 1966). Given this, to determine the fate of CO_2 stored in geological aquifers overlaid by a non-intact caprock made of shale, the hydraulic properties of a clay-rich medium/ clay smears which determine the flow of CO_2 through the caprock and the generation of stress that can alter the stability of the caprock needs investigation.

Numerous studies have reported the impact of the swelling and shrinkage of clay minerals due to hydration and dehydration on the permeability of a clay-rich porous media, which determines the flow ability of aqueous fluids through porous media (Rojas et al., 2017; Zeng et al., 2020). The clogging of pores owing to the expansion of the clay platelets upon adsorption of water molecules reduces the unsaturated hydraulic conductivity of the media (Wang et al., 2013; Pradhan et al., 2015). Romero (2013) demonstrated the evolution of the hydraulic property of the compacted clay upon macroscopic shrinkage due to the change in microvoid volume owing to the variation in moisture content. Similarly, the permeability of the compacted montmorillonite increases with the shrinkage of the mineral due to dehydration upon CO_2 interaction (Aksu et al., 2015; Pal and Ghosh, 2014). Overall, the change in permeability of clay caused by swelling and shrinking of clay minerals reported so far occurs due to hydration and loss of moisture by evaporation or absorption of moisture by CO_2. On the other hand, De Jong et al. (2014), Busch et al. (2016) and Zhang et al. (2018) quantified the influence of interaction between clay minerals, containing only one to two layers of water molecules and supercritical fluid CO_2 on the sealing capacity of the caprock at the mineralogical scale. Understanding the effect of clay mineral swelling on the macro properties of a medium containing clay is beneficial in scenarios where processes like fluid injection and extraction in the medium are involved. Very few studies have reported the effect of clay mineral swelling due to CO_2 adsorption on the permeability of the medium containing the clay. The CO_2 adsorption-induced strain of clay minerals altered the permeability of a smectite-rich medium at uniaxial, confined, and free in-situ stress conditions (War et al., 2022). Besides influencing the hydraulic property of smectite-rich medium, CO_2 adsorption-induced strain can cause the state of stress of the medium to change. Hence, there is a need to investigate the change in the state of stress of a smectite-rich medium post CO_2 injection and the change in hydraulic properties of smectite-rich medium at conditions existing in the field that have not been considered in the previous study.

Saturation pressure or pore pressure is the pressure of the fluid in the pore space of soils or rocks and is termed hydrostatic pressure when it is simply equal to the weight of the overlying fluid. Generally, pore pressure in a porous medium is not hydrostatic at great depth due to various natural phenomena. For instance, the pore pressure increases due to under-compaction caused by the rapid burial of low-permeability sediments, lateral compression, expansion of fluids because of heating, fluid density contrasts, and fluid injection. While pore pressure decreases due to fluid shrinkage, unloading, rock dilation, and reservoir depletion (Bernard et al., 2017). Examining these phenomena, they are prevalent in subsurface reservoirs where fluid injection and extraction occur. Therefore to understand the effect of the fluctuation of saturation pore pressure in subsurface regions, saturation pore pressure is considered one factor.

The non-linearly variation of lateral stress coefficient (K) with depth indicates that the horizontal in-situ stress changes with depth (Wang et al., 2009). Apart from the variation in K, the different tectonic regimes identified below the ground surface based on in-situ stress infers the changes in horizontal stress with depth. The measured in-situ stress in Bjorko geothermal project, Sweden, at depths < 400-500 m, indicates a reverse faulting stress state, and at deeper depth, it suggests that the stress arrangement changes to a strike-slip faulting regime (Taherynia et al., 2016). A variation in the tectonic regime with depth was observed in Michigan Basin, where the hydraulic fracturing test at depths up to 5 km was performed. Variations in tectonic regimes, which indicate alterations in in-situ stresses with depth, can occur due to various natural or man-made activities and are unavoidable. Considering different in-situ stresses when analyzing the effect of subsurface injection can account for different field scenarios. Hence, the influence of varying overburden stress along with other specified conditions on the behavior of a smectite-rich medium demands systematic investigation.

The objective of the present study is to investigate the behavior of a smectite-rich medium exposed to CO_2 at reservoir conditions. The study considers the effect of overburden stress, saturation pressure, and injection pressure on the swelling stress generated from a smectite-rich medium and the change in the porosity of the medium, which has not been addressed in the author's previous study. The values for overburden stress, saturation pressure, and injection pressure are considered based on observed field data (Zhang, 2019; Lyu et al., 2018). The loading conditions and material properties ensure only elastic deformation occurs within the smectite-rich medium. A coupled hydromechanical model solved using the finite element method is employed for the behavior analysis of smectite-rich medium post CO_2 injection.

2. MATHEMATICAL MODEL

An isothermal coupled hydromechanical model developed and validated in the authors' previous work (War et al., 2022) to analyze the permeability evolution of smectite-rich medium undergoing deformation upon CO_2 adsorption is employed in this study. To comprehend the list of governing equations and strategies to estimate the model's parameter value, it is recommended to refer to the author's previous work (War et al., 2022). Only the model's final derived equations, which include fluid flow and poroelasticity equations describing the geomechanical response of a porous medium due to the flow of injected fluid, are presented below:

The mass balance equation for gas flow through a porous medium that accounts for the storage of gas in the porous media as a free and adsorbed phase is defined as the following relation.

$$\frac{\partial\left(S_g\rho_g\phi+(1-\phi)\frac{\rho_g\rho_c V_L p}{p+P_L}\right)}{\partial t}+\nabla.\left(-\rho_g\frac{k}{\mu}\Delta p\right)=Q_s \tag{1}$$

where $\partial/\partial t$ is the partial time derivative, $\nabla.(\ )$ is the divergence operator, S_g is the saturation of gas, ρ_g is the gas density, ϕ is the porosity, ρ_c is the density of a porous medium (compacted clay), V_L is the Langmuir volume constant, P_L is the Langmuir pressure constant, p is the pore gas pressure and unknown variable, k is the permeability, μ is the gas viscosity, Q_s is the gas source or sink and t is the time. According to the ideal gas law, the gas density ρ_g is described as

$$\rho_g=\frac{M_g}{RT}p=\frac{p}{p_a}\rho_{ga} \tag{2}$$

where M_g is the molecular mass of the gas, R is the universal gas constant, T is the absolute temperature, p_a is the atmospheric gas pressure (101.325 kPa), and ρ_{ga} is the gas density at STP conditions.

The stress equilibrium equation after the incorporation of fluid pore pressure p is transformed into the Navier-type equation and is defined below.

$$Gu_{i,kk}+\frac{G}{(1-2\nu)}u_{k,ki}-\alpha p_{,i}-K\frac{\varepsilon_L p_{,i}}{(p_{,i}+P_L)}+f_i=0 \tag{3}$$

where,

$$G=\frac{E}{2(1+\upsilon)}=\frac{3K(1-2\upsilon)}{2(1+\upsilon)} \tag{4}$$

where G is the shear modulus, E is Young's modulus, ν is Poisson's ratio, K is the bulk modulus, ε_L is a constant representing the volumetric strain at large pore pressure, α is Biots coefficient defined as $\alpha=1-K/K_s$ where K_s is the bulk modulus of solid. To coalesce the effect of mechanical loading, pore fluid pressure, and adsorption-induced swelling on the porosity, the model proposed by Zhang et al. (2008) is considered as follows:

$$\phi=\frac{1}{1+\varepsilon_\phi}\left[(1+\varepsilon_{\phi o})\phi_o+\alpha(\varepsilon_\phi-\varepsilon_{\phi o})\right] \tag{5}$$

where ε_ϕ is the overall strain, including poroelastic and adsorption-induced phenomena and

$$\varepsilon_{\phi} = \left(\varepsilon_{v} + \frac{p}{K_{s}} \right) - \varepsilon_{s} \tag{6}$$

$$\varepsilon_{\phi o} = \left(\varepsilon_{vo} + \frac{p_{o}}{K_{s}} \right) - \varepsilon_{s0} \tag{7}$$

where S_o, ε_{v0}, $\varepsilon_{so,}$ and p_o refer to the initial values. If we consider S<<1 and S_0<<1, the simplified expression for porosity can be derived, and hence Eq. 5 becomes,

$$\phi = \phi_{o} \left(1 + \frac{\alpha}{\phi_{o}} \left(\varepsilon_{v} + \frac{p - p_{o}}{K_{s}} + \frac{\varepsilon_{L} P_{L} (p_{o} - p)}{(p_{o} + P_{L})(p + P_{L})} \right) \right) \tag{8}$$

As per Eq.8, the porosity of the porous medium is controlled by the volumetric strain associated with effective stress (Eq. 8), incorporating the gas adsorption-induced strain and grain volumetric strain. Storing the captured CO_2 in aquifers at depths of 0.8-1 km is beneficial due to the ease of gas injection and high storage capacity. Few studies have reported the porosity of the media at these depths to be in the range of 0.15- 0.25, where the permeability of the porous medium can be estimated precisely by knowing its porosity using a cubic power law (Nogues et al., 2013). The power law (Eq. 9) relates the gas permeability of the porous medium and its porosity as follows.

$$\frac{k}{k_{o}} = \left(\frac{\phi}{\phi_{o}} \right)^{3} \tag{9}$$

where k_o is the initial intrinsic permeability, and ϕ_o is the initial porosity of the porous medium.

3. MODEL GEOMETRY

Figure 1(a) illustrates a typical geological formation consisting of an aquifer to store CO_2, an impermeable caprock to prevent the stored CO_2 from leaking out into the ground surface, and combined layers of geo-material contributing to overburden load labeled as overburden formation in the figure. In geological formations where caprocks contain features such as faults or cracks, there is a possibility for CO_2 stored in aquifers to escape through these permeable features. Figure 1(b) illustrates the smectite-rich media typically encountered in faults or cracks of a caprock, where leaked CO_2 may flow through. To simulate the behavior of a smectite rich media present in faults when exposed to CO_2 injection, a 2-D model measuring 0.1 m x 0.1 m was created with the following boundary conditions: the top boundary of the model was subjected to overburden stress, while the sides and bottom boundaries were set to roller mechanical conditions. CO_2 was permitted to flow into the media through the model's top boundary, while no flow was assigned to the sides and bottom boundaries of the model. Although the actual flow direction of gas into the smectite-rich media is from the bottom towards the top, gas was injected from the top boundary for consistency with the focus of the study on analyzing quantities such as swelling stress and porosity at equilibrium, which are not dependent on flow direction. In addition, the study did not consider gravitational effects, further supporting the choice to inject gas from the top boundary. The model's parameters value obtained using statistical method and material properties considered in War et al. (2022) are employed.

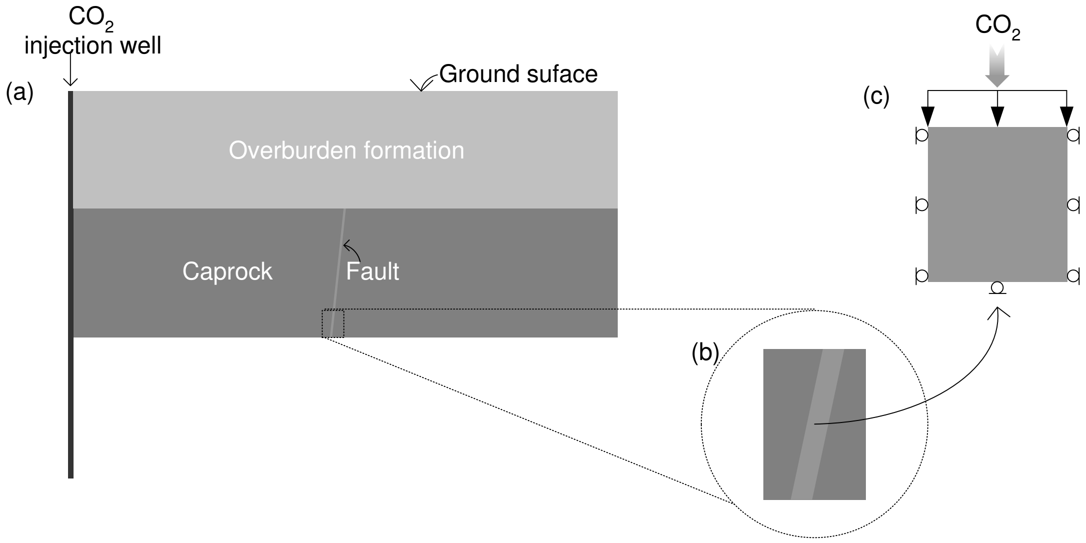

Figure 1. *(a) Schematic representation of CO_2 storage aquifer overlaid with a faulted caprock and (b) fault media (c) model geometry of a fault media with boundary conditions.*

4. RESULTS AND DISCUSSIONS

4.1. Effect of saturation pressure on porosity and swelling stress

Before injecting CO_2 into the smectite-rich medium, the clay minerals in the porous medium underwent swelling due to the initially saturated CO_2 leading to a reduction in porosity and generation of initial swelling stress. The swelling of clay minerals due to initially saturated fluid produces swelling strain in the medium proportional to the saturation pressure, and the developed model follows Langmuir's equations. As per the developed model, the amount of swelling of clay minerals and saturation pressure are directly related; hence, a medium saturated with high pore pressure undergoes larger swelling, resulting in a higher reduction in effective porosity (macropores) as well as the generation of higher swelling stress. Hence, the medium saturated with high pore pressure has already undergone significant swelling before the injection of gas and, as a result, has a low capacity to swell during and after gas injection.

Figures 2(a)&(b) demonstrate the effect of initial saturation pore pressure on the porosity of the smectite-rich medium and swelling stress generated by the smectite-rich medium after CO_2 injection. The findings suggest that when a medium is initially saturated at a low pore pressure, its porosity is lower compared to when the medium is initially saturated at higher pore pressures. The reported lower porosity in medium saturated with low pore pressure before gas injection is attributed to the significant swelling of clay minerals in the medium occurring due to the medium's higher swelling capacity. Also, results indicate that mediums saturated with high pore pressure generate low swelling stress which can also be attributed to the medium's low swelling capacity.

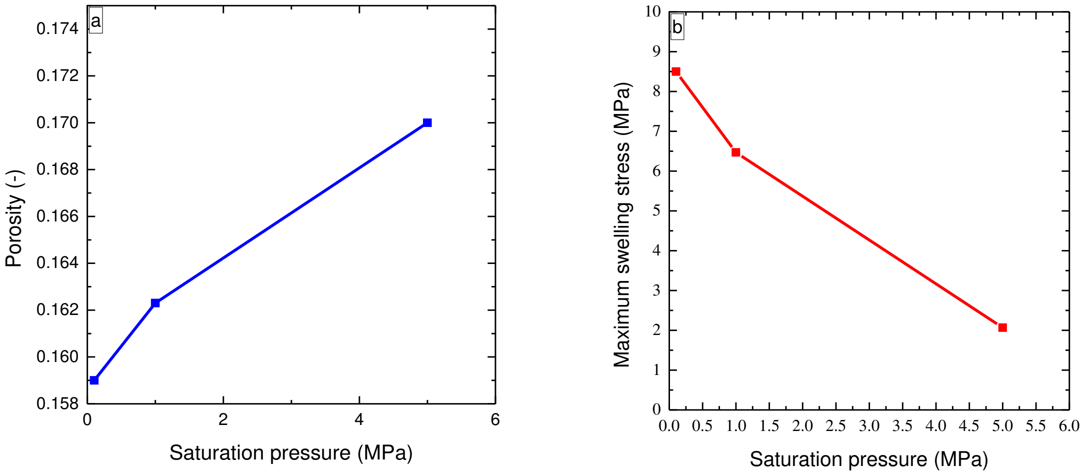

Figure 2. *(a) Porosity and (b) swelling stress of a smectite-rich medium saturated at different initial pore pressure post CO_2 injection.*

4.2. Effect of overburden stress

Figure 3 illustrates the variation of the vertical displacement of a point at the top boundary of a smectite-rich medium before and after CO_2 injection. The negative vertical displacement at the initial time, t=0, indicates that the pores of the medium are compressed due to overburden stress which reduces the medium's thickness. In other words, the pore space of the smectite-rich medium becomes smaller, reducing the total volume of the medium. The negative sign in vertical displacement represents compression. The downward vertical displacement of the top boundary increases with overburden stresses 20 MPa, 25 MPa, and 30 MPa, as shown in Figure 3.

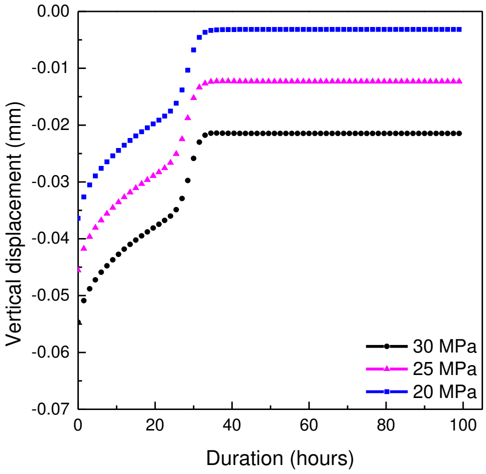

Figure 3. *The vertical displacement in the medium before and after CO_2 injection.*

The injection of CO_2 has caused the medium's thickness to increase, which is represented in terms of the reduction in the magnitude of the vertical displacement, as shown in Figure 3. The increase in the thickness of the medium is due to the physical expansion of the CO_2 that takes up space and pushes the medium outwards. However, CO_2 injection has caused the porosity of the medium to reduce due to an increase in the volume of clay minerals which reduces the pore volume. The reduction in porosity of the medium increases with overburden stress, as shown in Figure 4(a). With the increase in overburden stress, the medium undergoes more compression, resulting in higher pore volume reduction and low porosity. Conversely, as overburden stress increases, swelling stress generated by the medium increases, as shown in Figure 4(b), due to an increase in confinement provided by the overburden stress.

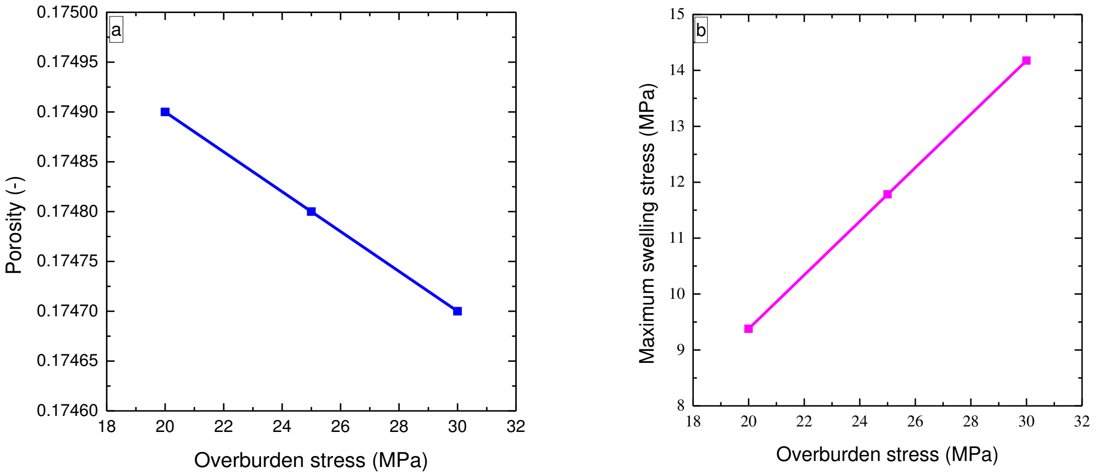

Figure 4. *(a)Porosity and (b)swelling stress of a smectite-rich medium after injection of CO_2.*

4.3. Effect of injection pressure

During CO_2 injection, the pore gas pressure within the medium increases from the initial pore pressure up to the injection pressure and remains constant. As a result, injection pressure governs the final pore gas pressure within the medium. As the amount of CO_2 uptake by clay minerals depends on the gas pressure, the medium injected with a higher injection pressure will adsorb more CO_2 than the medium injected with lower injection pressure. During the uptake of CO_2 by the medium, swelling of clay minerals in the medium takes place and is proportional to the CO_2 uptake by the medium. The swelling of clay minerals due to CO_2 injection has led to a reduction in the porosity of the medium. The porosity of the medium injected with high injection pressure is lower than that of the medium injected with low injection pressure since the swelling of clay minerals which causes porosity reduction is significant in medium with high injection pressure. Figure 5 illustrates the variation of porosity with CO_2 injection pressure. In confined conditions, the swelling of clay minerals due to CO_2 injection generates swelling stress. Swelling stress increases with injection pressure due to increased CO_2 uptake by clay minerals resulting in a significant swelling of clay minerals.

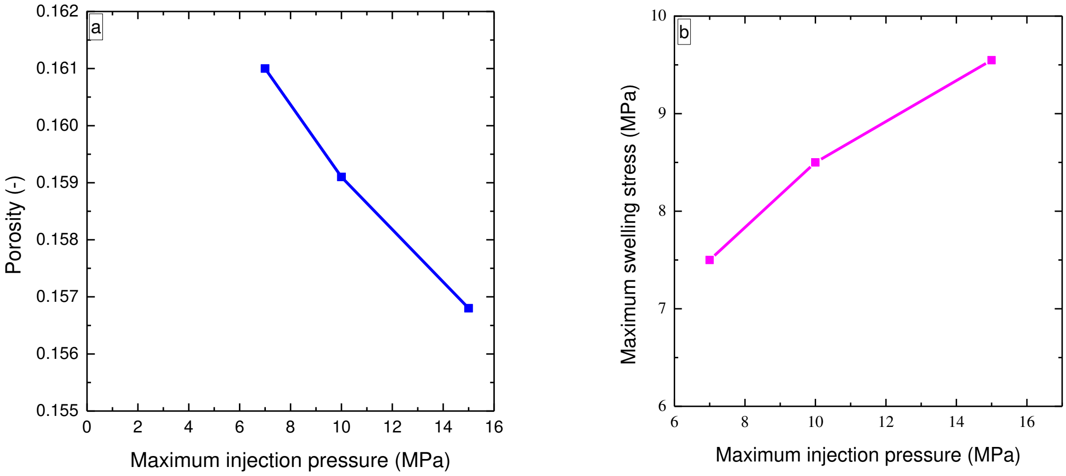

Figure 5. *(a) Porosity and (b) swelling stress within smectite-rich medium after CO_2 injection.*

5. SUMMARY AND CONCLUSIONS

Caprock comprises silicate clays such as muscovite, smectite, kaolinite, and illite, and non-silicate clay such as quartz. The interaction between CO_2 and clay minerals found in caprocks resulted in the adsorption of CO_2 onto the clay mineral's surfaces. With their distinct characteristics, smectite clay minerals have the highest adsorption capacity and swell upon adsorption of CO_2 due to the intercalation of CO_2 in the interlayer space of clay minerals. When the smectite medium under a confined and no volume change condition is exposed to CO_2, the medium generates swelling stress against the restricted volume change. In the field, the generation of swelling stress by a smectite-rich medium can alter the state of stress of the surrounding rock. Also, during such a condition, the porosity of the smectite-rich medium changes due to the swelling of clay minerals which can alter the flow of CO_2 through the medium. The swelling stress of a smectite-rich medium located at different depths in a CO_2 injection site is determined by considering different overburden stress, saturation pressure, and injection pressure conditions for analysis. Similarly, the change in the porosity of the smectite-rich medium due to the swelling of clay minerals is also observed at these conditions. A coupled hydromechanical model solved by a finite element method is used to analyze the scenario, and the following conclusions were drawn:

1. The swelling stress of a smectite-rich medium generated due to CO_2 injection increases with overburden stress, implying that the swelling stress increases with depth. This finding suggests that the potential benefit of injecting CO_2 into deeper depths may be compromised by generating higher swelling stress that can destabilize the caprock in the presence of a smectite-rich media. However, the advantages and disadvantages of injecting CO_2 at deeper depths must be investigated through proper study.

2. The smectite-rich medium saturated with higher pore fluid pressure generates lower swelling stress than a medium saturated with low pore fluid pressure. Analysis results indicate that in the presence

of high content of smectite-rich media, the generation of high swelling stress due to the CO_2 injection can be prevented by selecting an injection site with high saturation pore pressure.

3. The overburden stress influences the effect of CO_2 adsorption-induced strain on the porosity of the smectite-rich medium. The smectite-rich medium subjected to higher overburden stress has lower porosity than the medium with lower overburden stress. Thus, in agreement with the overburden stress increasing with depth below the ground surface, the porosity reduction of the smectite-rich medium due to CO_2 injection at deeper depths is relatively higher than that at lower depths. With the reduction in the porosity of the smectite-rich medium due to CO_2 injection with depth, the sealing efficiency determined in terms of porosity or permeability, which governs the flow of CO_2, is enhanced relatively at deeper depths due to CO_2 injection.

4. The CO_2 adsorption-induced strain of the smectite-rich medium reduces with the increase in saturation pore pressure due to a reduction in the CO_2 adsorption capacity. This results in decreased porosity reduction caused by CO_2 adsorption-induced strain. Thus, the higher the saturation pore pressure lower the reduction in the porosity of the smectite-rich medium due to CO_2 injection.

Application of the developed model to shallow depths where the clay-rich medium is anticipated to have more than two layers of water molecules may result in overestimating the swelling stress caused by gas injection and misinterpreting the porosity change. Overall, the study contributes to a comprehensive approach for evaluating the efficacy of the potential geological reservoirs with faults for long-term storage of CO_2 by considering the integrity of caprocks.

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