EXPERIMENTAL INVESTIGATION OF THE HYDROMECHANICAL RESPONSE OF LOW PERMEABLE ROCKS DURING INJECTION OF SUPERCRITICAL CARBON DIOXIDE

Ardy Arsyad[1], Lawalenna Samang[2]

[1,2]*Department of Civil Engineering, Faculty of Engineering, Hasanuddin University, P. Kemerdekaan Km.10 Makassar*
Email: ardy.arsyad@unhas.ac.id

ABSTRACT

In this paper, we developed an experimental design using a newly developed flow pump permeability test to measure the permeability and specific storage including the change of pore pressure and stress-strain on the Ainoura sandstone cores under the injection of supercritical CO_2. The experiment was set up to reproduce the similar condition of deep underground reservoir with 20 MPa confining pressure, 10 MPa pore pressure, 35°C temperature and 3 μl/min CO_2 injection rate. As CO_2 was injected to the specimen, the hydraulic pressure increased and generated a stress alteration. The hydraulic pressure and volumetric strain in the core were monitored. Based on the change of differential pressure generated by CO_2 injection, such three phase of CO_2 behavior in the specimens was also observed. First phase is the flow of the displaced water with the volumetric strain relatively stable. Second phase is the flow of CO_2 penetrated the specimen and the volumetric strain started increasing. The direction of the volumetric strain indicated a poroelastic expansion of the specimen. The third phase is the CO_2 flowing through the specimen to achieve steady state with irreducible water saturation remained. In the third phase, mechanical response of the specimen became more pronounced, affecting hydraulic response. This was indicated by the transient increase of the volumetric strain implying that the onset of dilatancy of the specimen has occurred. It was also found that mechanical response of the specimen would initiate if the pore pressure equaling to 60% of the confining pressure was exceeded. The results suggested that, while low permeable rocks has better specific storage for sequestering CO_2, the injection of supercritical CO_2 to the rocks has considerable effects on their integrity even at low flow rates.

Keywords: ***hydromechanical response*, *supercritical CO_2 injection*, *low permeable rocks***

INTRODUCTION

Over the past several hundred years, CO_2 emissions into the atmosphere has increased steadily and become a major contributing factor to global warming. To mitigate this effect, technologies for CO_2 sequestration have been introduced with limited applications. One of those technologies is carbon capture and geological storage (CCS), which can be defined as a process of separating CO_2 emission produced by large stationery sources such as industrial plants and power stations, then compressing it to be supercritical CO_2 and transporting via pipelines to suitable geological formations, such as unmineable coal beds, deep saline aquifers, and depleted oil and gas reservoirs (IPCC, 2005). So far, CCS in the depleted oil and gas reservoirs is the most readily applicable technique due to its similarity to enhanced oil recovery (EOR) commonly applied in petroleum industries. However, although oil and gas reservoirs remain a large deposit in a number of countries, they are unequally distributed around the world. Other constrains are that it will take a very long time for those reservoirs to be depleted and ready for CO_2 storage, and vast pipelines distributions are still needed due to the fact that the location of the sources of CO_2 emission is often times far away from the field for CO_2 Storage (Benson, 2008). For those reasons, deep saline aquifers have been recently considered as geological media to sequester CO_2.

The risk of CO_2 leakage on groundwater and surface still is under-investigation. Given by the proposed mechanism of CCS, CO_2 will be injected to a certain depth of rock formation. Supercritical CO_2, which has a lower density than the native brine residing in the formation, will move upward due to buoyancy, while flowing laterally driven by a differential pressure at the same time (Shi et al., 2011). A low permeability sedimentary rock or caprock will retain the flow of CO_2 so that it will take a very long time to reach upper groundwater and ground surface. However, an overpressured injection of CO_2 to the formation will likely occur resulting in an excessive compression, or possibly tension (Bachu S, 2000, Mackenzie et al. 2001). This situation may lead to an increasing stress, even initiating and propagating cracks in the formation and large deformation that can be sensed even in the ground surface (Rutqvist et al., 2010). In this paper, we conducted an experimental study of hydromechanical behavior on low permeable sedimentary rocks during supercritical CO_2 injection. Newly developed laboratory system of constant flow pump permeability test was employed to inject supercritical CO_2 to a core from the Ainoura sandstone formation in Japan. The confining pressure of 20 MPa and the initial pore pressure of 10 MPa within the temperature of 35 °C were generated on the specimen in order to create similar physical conditions of CO_2 storage expected in deep underground reservoirs. The specimen was then injected by supercritical CO_2 at a constant flow rate of 3 μl/min. It should be noted that a constant flow rate method was selected due to easiness of fixing the flow rate of injection rather than setting the constant differential pressure in the field scale application; while very low flow rate was employed in order to mimic very low hydraulic gradient occurred in deep underground.

LABORATORY EXPERIMENT

Physical characteristics of CO_2 are much influenced by its temperature and pressure. In a number of existing CO_2 injection project, it is observed that the temperatures and pressures of CO_2 injected to deep underground are beyond the critical point of 31.1°C and 7.39 MPa (Sasaki et al., 2008). At this state, CO_2 will behave as supercritical fluid in which its density like a liquid and compressibility like a gas. We developed newly laboratory system of flow pump permeable test in order to mimic physical condition of deep underground, which is characterized as geological formation with high temperature and high pressure, and very low hydraulic gradient.

Experimental Apparatus

Figure 1 shows the schematic diagram of newly developed flow pump permeability test including its specimen arrangement. The main problem of flow pump permeability test in creating reservoir condition for supercritical CO_2 injection is the vulnerability of the test system to the fluctuated temperature associated with seasonal weather and experiment apparatus heat. The volatile temperature will contribute to unstable physical property of CO_2 affecting its flow behavior. Therefore, we attempted to control the internal lab temperature by setting a greenhouse chamber with air temperature controlling, while we stabilised the apparatus temperatures by connecting pumps and pipes to hemathermal circulation tank and a bath temperature controller, respectively. Furthermore, specimen temperature was controlled by heater bars and temperature sensors while pressure vessel temperature was controlled by thermocoupler. To minimize lab temperature changes due to human interference, remote measurement with data acquisition system were established.

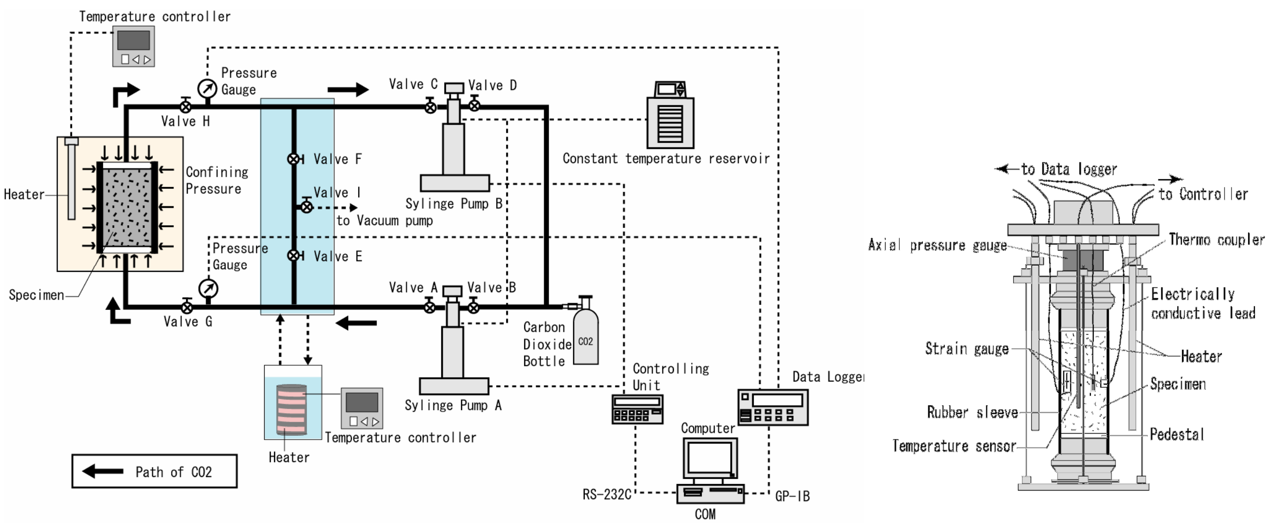

Figure 1. Schematic diagram of newly developed flow pump permeability test and specimen arrangement.

Rock Specimens

The rock specimen employed in this study is Ainoura sandstone obtained from Sasebo near Nagasaki Prefecture Japan. The specimen dimension is a cored cylinder with a 50 mm diameter and 100 mm height, following the ISRM standard that the height of rock specimen for core test is twice to its diameter. In order to examine the pore size characterisitic of the specimen, a mercury-porosimetry was carried out and its results are presented by Table 1 and Figure 2. Both the tested Ainoura 1 and the tested Ainoura 2 exhibited bi-modal pore size distribution, indicating slightly heteregenous porosity. In more detailed, the tested Ainoura 1 had high microporosity (pore fraction with diameter less than 1 µm), comprising 64.7%, over the total pores, whereas the tested Ainoura 2 has little bit lower, which was about 51.07%. On the other hand, the macroporosity (pore fraction with diameter more than 3 µm) of the tested Ainoura 1 was lower (13.1%) compared to the Ainoura 2 (19.6%). The results suggested that the tested Ainoura 1 contained finer grain matrix than the tested Ainoura 2, resulting in their different porosity. The porosity of tested Ainoura 1 and 2 were accounted for 0.126 and 0.154, respectively. In addition, The capillary pressure of the specimen was also measured by mercury injection test. The interfacial tension (IFT) of air-mercury for the tested Ainoura sandstone was quantified at 148 mN/m. The air-mercury capillary pressure data was converted to water-CO_2 capillary pressure data on the basis of the water-CO_2 IFT for the experimental condition were 25.5 mN/m (Bachu and Bennion, 2009). As shown in Figure 2, as it is expected, the capillary pressure of the tested Ainoura 1 is slightly higher than that of the tested Ainoura 2.

Table 1. Pore characteristics of the tested Ainoura sandstone.

Specimen	% Micro Porosity	% Meso Porosity	% Macro Porosity	Median Pore size (micron)	Average Porosity (%)	Interfacial Tension (mN/m)	Threshold Capillary Pressure (kPa)
Ainoura 1	64.7	22.1	13.1	1	12.6	148	60
Ainoura 2	51.06	29.4	19.6	1.2	15.46	148	62

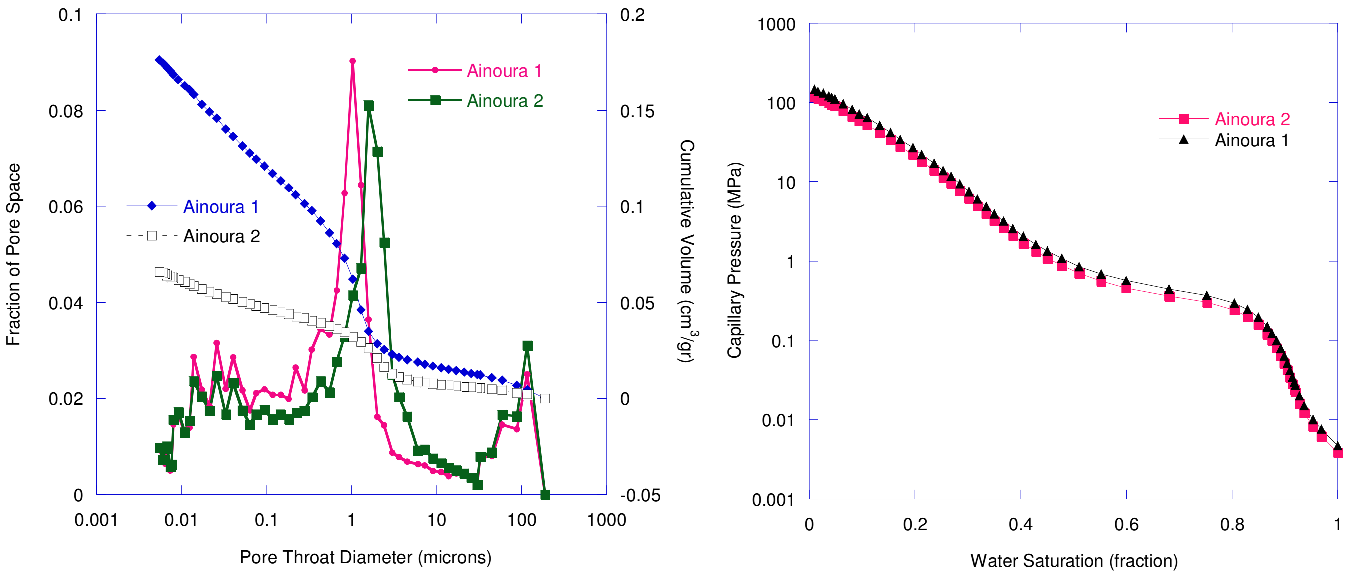

Figure 2. Pore throat-size distribution and capillary pressure curves of the tested Ainoura specimens.

Experimental Procedures

Initial conditions of pressures and temperature in experimental system for mimicking reservoir condition were generated prior to CO_2 injection. Therefore, the specimen were full saturated by water and then placed in a tri-axial chamber. The temperatures of the syringe pump, pipes and pressure vessels were loaded at 35°C, 36°C, and 38°C respectively. After the temperatures of these devices stabilized, a 20 MPa confining pressure and 10 MPa pore pressure were subjected on the specimen. Pure water with a constant flow rate of 3 µl/min was injected and the pressures in the upstream and downstream of the specimen were measured. This aimed to measure the intrinsic permeability (K) of the specimen at a steady state condition based on the Darcy Law. The intrinsic permeability of the tested Ainoura 1 and 2 were measured at 0.023 m D and 0.035 mD respectively. After that, supercritical CO_2 was injected to the specimen with the same flow rate of

3 µl/min. The pressures in the upstream and downstream, including the longitudinal and lateral strains of the specimen were measured during the injection.

3. RESULTS AND INTERPRETATION

During the injection of CO_2 to the specimen, the generated hydraulic pressures in the upstream and downstream including the longitudinal and lateral strains of the specimens were obtained. Overall, the injection of CO_2 into the specimen increased the hydraulic pressure in the downstream and upstream of the specimen (Figure 3). The differential pressure between the upstream and the downstream consistently exhibited such three patterns, suggesting a three phases of CO_2 flowing through the specimen (Figure 3). First phase, the differential pressure increased transiently and stabilized at a certain level. Given by the similarity of this curves to the curves generated by the water injection tests previously undertaken to measure intrinsic permeability of the specimen, it can be suggested that, this phase was just the period of the flow of displaced water in the specimen. Other measurement results shows that the longitudinal and lateral strains of the specimens were observed at relatively stable, confirming the absence of the compressible CO_2 flow in the specimen.

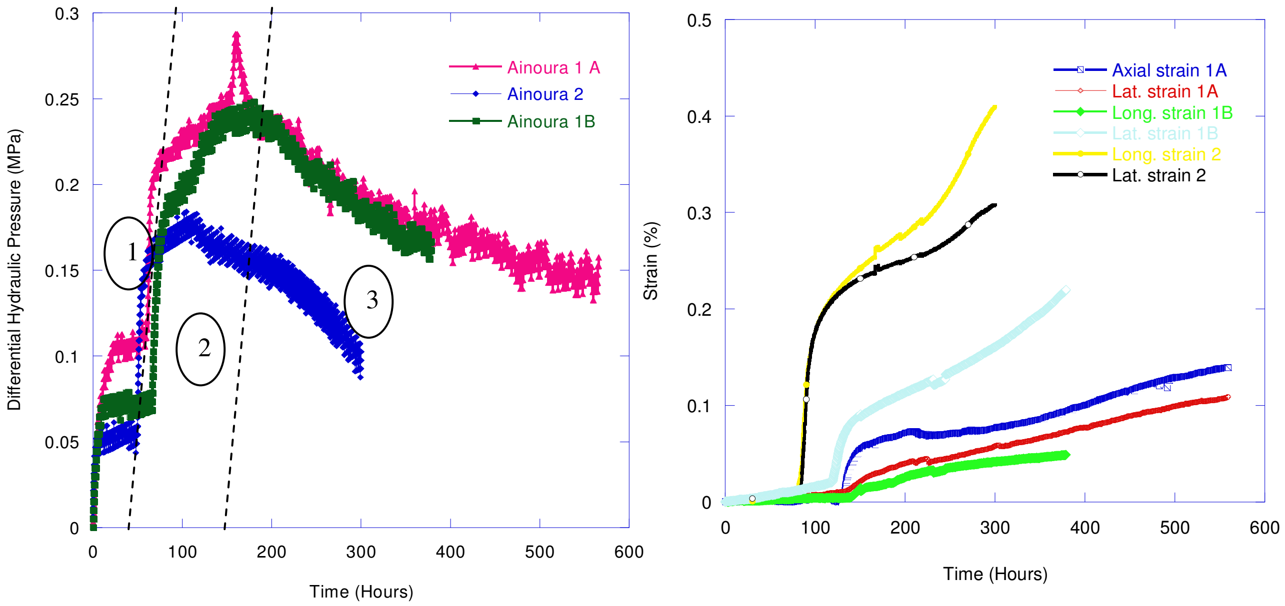

Figure 3. Differential pressures and strains generated by the injection of supercritical CO_2.

In the second phase, the differential pressure suddenly increased again achieving higher level before it stabilized over certain times. In addition, the longitudinal and lateral strain of the specimen also increased at a little bit later period than the increase of differential pressure. At this phase, the injected CO_2 has already penetrated the specimen and begun displacing the saturated water out from the specimen pores. The increase of the differential pressure was due to the drop of the downstream pressure, probably related to the effect of capillary pressure. It is noted that very low flow rate of the CO_2 injection and low permeable characteristics of the specimen cannot diminish capillary pressure effect in the specimen. The specimen pores retained the saturated water until the injected CO_2 pressure exceeded the pore-water holding pressure. Richardson et al., (1952) and Dana and Skoczylas (2002) suggested this phenomenon as capillary end effect or capillary pressure effect, which occurs on two-phase displacement flow in sandstone. As long as the CO_2 pressure overrated the capillary pressure, more CO_2 will penetrate and more saturated water will be displaced out from the pores. Otherwise, CO_2 flow will be interrupted resulting in the drop of the downstream pressure observed. Besides that, the second phase was observed as the starting period for the increasing the specimen strains. The negative direction of the increasing strains indicated expansion of the specimen occurred as the pore pressure increased driven by CO_2 injection. Furthermore, it was observed that the increase of longitudinal strains were higher than that of the lateral strains (Figure 4). This suggested that, vertical deformation of rock mass is more pronounced than horizontal deformation when it is injected by CO_2 in axial direction. The flow of CO_2 was configured as axial flow from the bottom to the top of the specimen. Other considerable factor that may affect this result is that the confining pressure that resisted the lateral strain of the specimen is higher than the increasing hydraulic pressure.

In the third phase, the differential pressure slowly decreased. Since the injected CO_2 was able to break through the specimen in the end of the second phase, the downstream pressure begun to increase back. Such stepwise decrease of the differential pressure was observed at this phase, implying the process of CO_2-water displacement in Ainoura sandstone is more a sweep flow rather than a bypass flow. This is consistent with what Bennion and Bachu (2005) suggested as the characteristic of flow in tight rock matrix. Indeed, dominating fraction of micropores in the specimen pores generates relatively high capillary pressure that would become a barrier for CO_2 to flow, causing a considerable timely process of CO_2 flow. This process proves the capability of Ainoura sandstone in effectively retaining the flow of CO_2. The differential pressure would be constant at the end of this phase, as the downstream pressure steady increases to approach to the upstream pressure. However, the time for CO_2 becoming steady flow would be time consuming depending on how much irreducible water saturation in the specimen. The higher irreducible water saturation in the specimen, the slower process of CO_2-water displacement will be.

Pressure Margin and Volumetric Strain

The injection of CO_2 into the specimen increased its pore pressure and volumetric strain. As the experiments just set the confining pressure constantly at 20 MPa, only the pore pressure increased from the 10 MPa initial pressure. If pressure margin is defined as the gap pressure of pore pressure to confining pressure, the pressure margin decreased during the injection. The pressure margin was analyzed in this study since it is considerable parameter, contributing for hydraulic fracturing. The initiation of hydraulic fracturing will occur when pore pressure equals to the confining pressure (Jaeger et al., 2007). Figure 4 illustrates the relationship between the pressure margin and the volumetric strains measured in the experiment. It was found that the pressure margin increased as the volumetric strain increased. Beyond a certain pressure margin, the volumetric strains increased signifincantly. The transient increase of volumetric strain occurs at the transition of the incompressible water flow to the compressible CO_2 flow in the specimen pores as observed in the second phase of the experiment. After that, CO_2 flow breakthroughed the specimen, generating higher increase of the volumetric strain. Given by the trend of curves in Figure 18, the flow of CO_2 would generate significant increase of volumetric strain when the pressure margins above -9 MPa and -8 MPa for the tested Ainoura 2 and 1, respectively. It means the increase volumetric strain of higher porosity specimen would occur slower than that of lower porosity specimen. However, in the case of the magnitude of the strains generated, the specimen with higher porosity yielded larger volumetric strain compared to lower porosity specimen. As a result, the generated pore pressure in higher porosity specimen took short time to reach the confining pressure level. The results suggested the benefit of lower porosity Ainoura sandstones in which they would have a higher specific storage for CO_2 but generated lower deformation when being injected by CO_2 in low flow rate.

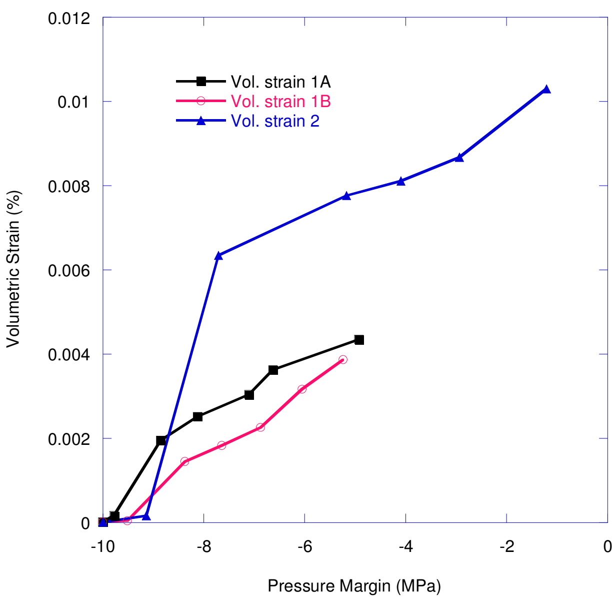

Figure 4. Pressure margin of pore pressure to confining pressure versus volumetric of the specimens.

4. CONCLUSIONS

1. Three phase of CO_2 flowing in the specimen was suggested based on the change of differential pressure observed in the experiment.
2. First phase, the only water flowed through the specimen with relative stable of its very low strain. Second phase, the injected CO_2 penetrated the specimen and displaced the water in the specimen pores. At this phase, the volumetric strain begun to increase. Third phase, the injected CO_2 flowed through the specimen with irreducible water saturation. This phase is the important period for the flow of CO_2 flow in Ainoura sandstone since its mechanical behavior affected hydraulic behavior.
3. The third phase is the time for the transient increase of volumetric strain resulting in the onset of dilatancy of the specimen, the increase of specific storage and permeability. The onset of dilatancy would take place if the pore pressure above 60% of the confining pressure for very low flow rate applied in the injection. The results have provided proper information to develop better understanding of hydromechanical response of low permeable rocks injected with supercritical CO_2 for designing future field scale application.

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