CCUS: 4193621

Experimental Characterization of the Undrained Response of Caprock During CO_2 Breakthrough

Sangyeong Park[1, 2], Hangseok Choi[2], Kiseok Kim[1*], 1. Department of Petroleum Engineering, Texas A&M University, College Station, TX, 77843, United States. 2. Department of Civil, Environmental and Architectural Engineering, Korea University, 145 Anam-ro, Seoul, 02841, Republic of Korea.

This paper was prepared for presentation at the Carbon Capture, Utilization, and Storage conference held in Houston, TX, 03-05 March.

Abstract

Geologic carbon storage (GCS) requires caprock integrity to prevent CO_2 leakage. However, its geomechanical response during injection remains underexplored. This study investigates synthetic kaolinite mudrock under varying over-consolidation ratios (OCRs) using high-pressure consolidation and CO_2 breakthrough tests. The results show that higher OCRs reduced porosity and permeability, leading to increased CO_2 breakthrough pressures. During fluid injection, intricate deformation behaviors were noted, highlighting the interplay between fluid type, stress history, and CO_2 breakthrough. These findings enhance understanding of caprock behavior, offering insights for safe and effective GCS implementation.

Introduction

Geologic carbon storage (GCS) is a promising approach for mitigating atmospheric CO_2 emissions by securely trapping carbon dioxide in subsurface reservoirs. The success of this method hinges on the integrity of caprocks, which act as seals to prevent CO_2 leakage. Caprocks are characterized by their extremely low permeability, which leads to an undrained mechanical response under rapid loading conditions. Understanding the interplay between hydraulic and geomechanical behaviors of caprocks is critical for ensuring the long-term stability and effectiveness of GCS systems.

While significant research has been conducted on the hydraulic properties of caprocks, including permeability and CO_2 breakthrough pressure, the geomechanical responses during CO_2 injection and the stress history of these caprocks remain underexplored. These responses can significantly impact the structural integrity of the caprock. Neglecting these aspects could result in an incomplete assessment of the risks associated with CO_2 injection, particularly under dynamic subsurface conditions.

This study aims to bridge this gap by experimentally investigating the undrained geomechanical response of synthetic kaolinite mudrocks during CO_2 injection. By fabricating specimens with varying over-consolidation ratios (OCRs) and conducting CO_2 breakthrough tests, we examine the combined effects of stress history, pore structure, and fluid type on mudrock behavior.

Experimental Method

High-pressure consolidation tests were conducted using an oedometric cell (zero lateral strain) to prepare synthetic kaolinite mudrock specimens with different stress histories. The consolidation tests were performed with a loading increment ratio of one, allowing 24 hours for each increment, and utilized brine as saturation fluids. Stress histories were defined by OCR of 1, 2, and 4.

An advanced experimental setup allowed fluid injection tests to be conducted immediately following the consolidation tests, ensuring the preservation of specimen integrity. Under brine-saturated conditions, brine was first injected to measure the absolute permeability of the specimens. After sufficient time was allowed for pore pressure dissipation, CO_2 breakthrough experiments were conducted. Stepwise increments of CO_2 pressure were applied at the inlet, while the outlet pressure was maintained at a constant value. Throughout the experiments, specimen deformation was continuously monitored using a laser displacement sensor, and the volume changes in the inlet and outlet pumps were recorded. This comprehensive approach enabled a detailed investigation of the mechanical responses of the specimens under varying test conditions.

Results

During the primary consolidation phase, significant settlement occurred as excess pore water pressure dissipated and effective stress increased. In the subsequent secondary consolidation phase, although effective stress remained constant, very slow and continuous settlement was observed. The strain rates during secondary consolidation were approximately 1% per day under the highest vertical load for each stress history condition.

As the OCR increased, the specimens experienced greater loads, resulting in a reduction in porosity and average pore size. Consequently, higher OCR values led to lower absolute permeability and increased CO_2 breakthrough pressures. The deformation behavior of brine-saturated specimens varied depending on the injected fluid, as illustrated in Figure 1. When brine (wetting phase) was injected, the pore pressure increased immediately, reducing effective stress and causing elongation of the specimen. In contrast, CO_2 (non-wetting phase) injection resulted in settlement prior to breakthrough, followed by the specimen maintaining a constant length post-breakthrough. Notably, the strain rate before breakthrough was significantly lower than that during secondary consolidation. This behavior is attributed to the combined effects of partial CO_2 intrusion into the specimen's pores and the convergence of secondary consolidation over time. Additionally, the strain rate prior to breakthrough decreased with increasing OCR, likely due to the impact of pore size distribution on the dissipation rate of pore pressure.

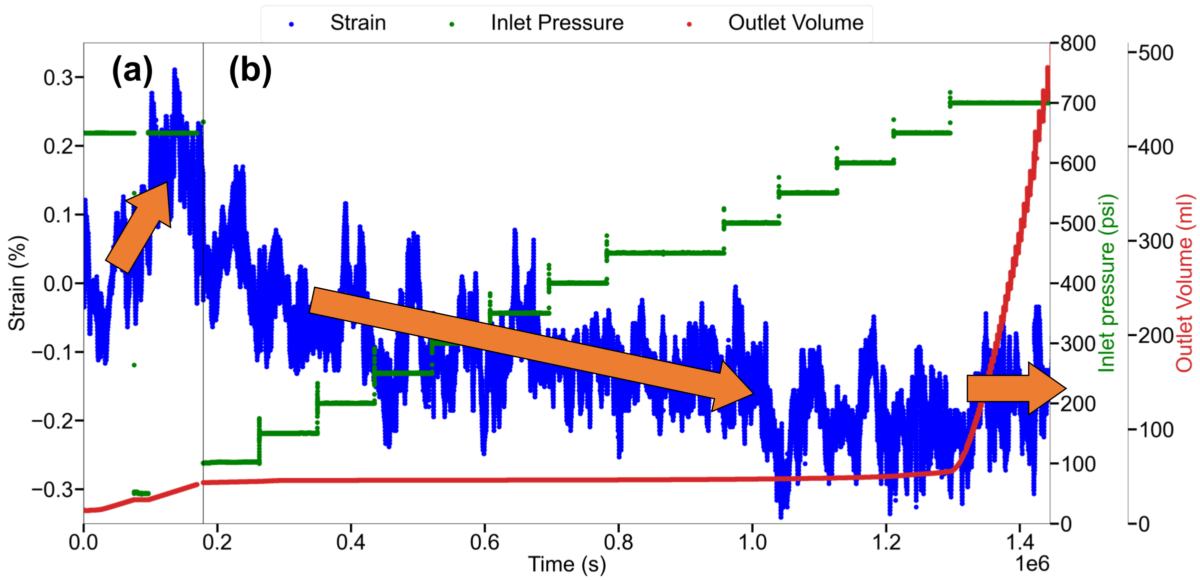

Figure 1. Experimental result during fluid injection under brine and OCR1 condition:
(a) Absolute permeability test and (b) CO_2 breakthrough pressure test

Conclusions

This study investigated the mechanical behavior of synthetic kaolinite mudrock specimens under varying stress histories. The results demonstrated that a higher over-consolidation ratio (OCR) reduced porosity and permeability while increasing CO_2 breakthrough pressures, highlighting the critical influence of stress history on mudrock performance. Complex deformation behaviors were observed during fluid injection, emphasizing the combined effects of fluid type, stress history, and CO_2 breakthrough. These findings offer valuable guidance for improving understanding of mudrock behavior under complex subsurface conditions.

Acknowledgement

This research was supported by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport (No. RS-2024-00410248).

References

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