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The Effect of Oil Infiltration on the Geomechanical Response of Mudrocks for Geologic Carbon Storage

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Abstract

Depleted oil and gas reservoirs are recognized as one of the most promising candidates for geologic carbon storage, due to their proven capacity to contain hydrocarbons over geological timescales, and also their well-characterized geological properties. However, due to their past containment of hydrocarbons, the adjacent caprocks to the reservoirs may have been infiltrated by oil. In most cases, these caprocks contain clay minerals (mudrocks), which – unlike clean reservoir rocks – have geomechanical and hydraulic responses affected by water. This raises a crucial question: How does oil infiltration affect the geomechanical response of mudrocks, which is directly related to the integrity of the sealing layers? We seek to understand the fundamental deformation behavior of mudrocks, by examining both short- and long-term responses under different stress states and pore fluid conditions.

In this study, we conduct high-pressure consolidation experiments using kaolinite and prepare synthetic mudrock specimens, while varying the pore fluid from brine to light oil. At each loading stage, we monitor the displacement over 24 hours to capture both primary (short-term) and secondary (long-term) consolidation behaviors. The stress history effect is studied as we repeat loading and unloading cycles. We calculate key parameters—including porosity, permeability, and consolidation coefficients—and compare them across different fluid compositions to assess the impact of oil infiltration on the geomechanical response of mudrocks. Results showed that the type of pore fluid affects the deformation behavior during consolidation. While oil infiltration had no effect on the short-term response, it significantly impacted the long-term behavior.

The novelty of this study lies in the simple, but meaningful experimental approach of conducting high-pressure consolidation tests to characterize the short- and long-term response of synthetic mudrocks. This implies that it is crucial to properly understand the pore fluid and adopt accurate geomechanical properties of mudrocks for simulations, particularly considering the long-term responses for simulation models.

Introduction

Geologic carbon storage has become a more viable long-term solution to mitigate greenhouse gas emissions. Selecting an appropriate reservoir or geological host formation is crucial to ensure storage integrity and preventing gas leaks into the atmosphere (Bielicki et al., 2015). Depleted oil and gas reservoirs are often considered over other storage sites because of their established properties and proven containment capacities (Li et al., 2005). Moreover, oil reservoirs are thoroughly characterized, with data from seismic surveys to core samples (Gallo et al., 2002) – including properties such as, porosity and permeability, cap rock integrity, and fault structures (Li et al., 2005).

Evidence exists that oil infiltration in caprocks compromises their sealing integrity and geomechanical properties, which can be critical for successful geologic carbon storage. Hydrocarbons can alter the clay mineral – water interaction, where the water adsorption and double water layers can be affected (Schlömer and Krooss, 1997; Huang et al., 2024). These perturbations can influence the geomechanical response of mudrock in compaction, time-dependent and inelastic behavior (Cosenza et al., 2023). Therefore, it is important to understand the poromechanical behavior of mudrock, especially considering the pore fluid (Cosenza et al., 2023).

In this paper, we implemented a robust and simple experimental setup to measure the geomechanical properties of mudrocks. We prepared synthetic mudrocks that consist of kaolinite with varying pore fluids, such as oil and water. The geomechanical behavior was monitored during the loading and unloading stage throughout the consolidation experiment, allowing assessment of the short- and long-term responses under different pore fluid conditions.

Methods

We selected white kaolinite clay and conducted high-pressure consolidation experiments. Two samples used brine as the pore fluid, while the other two used light oil, to simulate overconsolidation ratios (OCR $= \sigma_{max} / \sigma_v$) of 1 and 2 for each pore fluid. The oedometric cell consists of an 8 inch hollow shaft with two 5 inch rods fitted into the shaft to hold the sample. These rods have pore channels with a filter paper, allowing only the fluid to escape during the consolidation test. A hydraulic ram connected to an ISCO pump applies vertical stress on the specimen throughout the consolidation experiment. A laser displacement sensor monitors the vertical deformation with an accuracy of 0.1 mm and linearity of ± 0.1% of range. Vertical load was applied from 1.812 MPa and was doubled up to 14.50 MPa (OCR 1) and 28.99 MPa (OCR 2), allowing 24 hours at each load stage.

Results and Discussion

The porosity, coefficient of consolidation, and primary and secondary consolidation were calculated from the vertical displacement measurements. During each 24-hour consolidation loading stage, the short-term response (primary consolidation) and the long-term response (secondary consolidation) were monitored. Results demonstrated that total displacement at each loading stage decreased as vertical stress increased. Notably, the loading-unloading response differed significantly, as the displacement during loading was not fully recovered during the unloading, indicating a plastic behavior of mudrock. For the pore fluid, the brine and oil both showed an identical response. However, the long-term response showed a significant difference, where the secondary consolidation were more pronounced for brine.

Conclusions

This study demonstrates that the pore fluid composition impacts the long-term geomechanical behavior of mudrocks. Results revealed a plastic response in mudrocks, indicating hysteresis between loading and unloading. While oil infiltration showed similar short-term consolidation results to brine, it resulted in a significant difference in the long-term behavior. Accurate characterization of poromechanical properties is essential for long-term subsurface storage simulations. These findings highlight the importance of considering fluid composition in assessing caprock integrity for carbon storage.

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