In-situ Geomechanical Assessment of Carbonate Rocks Undergoing CO2-Saturated Brine Injection: A Preliminary Study

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Summary

The CO2 storage in saline aquifers or water alternating gas injection (WAG) results in the formation of acidic brine with 3-4 pH. This study highlights the impact of CO2-saturated brine injection on the mechanical properties of limestone rocks undergoing dissolution (i.e., generation of wormholes). Three Indiana limestone samples that are 1 inch in diameter and 2 inches in length were utilized in a coreflooding step. The coreflooding setup contained a linear variable differential transformer (LVDT) to monitor the changes of rock's Young's Modulus (E) and creep at in-situ conditions. The experiments were conducted at 60 oC, 1,500 psi pore pressure, 1,950 psi confining pressure, and 725 psi (5 MPa) deviatoric axial stress. Experiments were conducted at 0.5, 1-, and 2-mL flow rates, respectively, where 700 mL of carbonated brine was injected in each experiment. A continuous wormhole was generated in each experiment as indicated by the pressure drop data (i.e., zero pressure drop) and CT scan images. The rock geomechanics were altered due to dissolution, as indicated by the sharp increase in creep magnitude after CO2-saturated brine injection. Nevertheless, no changes were observed in the axial E as the wormholes created (1-2 vol%) were filled with an incompressible brine.

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Introduction

Carbon capture and storage (CCS) is a potential contributor to reduce societal CO_2 footprint and meet the world targets of CO_2 net zero-emission. Deep saline formations provide potential long-term storage sites due to their abundance, storage capacity, and favorable aspects such as CO_2 solubility in brine. Field cases such as the storage project in the Weyburn carbonate reservoirs (Cantucci et al., 2009) and experimental investigations indicate that deep saline limestone reservoirs are excellent CO_2 sinks. However, CO_2 interactions with water at high pressure and temperature result in the formation of carbonic acid with a pH of 3 to 4 (Peng et al., 2013). Limestone rock is mainly composed of calcite, that reacts with carbonic acid, resulting in pore enlargement and permeability enhancement. The continuous reaction results in voids in the rocks called wormholes that may improve injectivity but leads to questions about formation mechanical integrity.

Published studies on the impact of CO_2 injection on wormhole propagation and the accompanying changes to mechanical rock properties are rare. Madland et al. (2006) showed that chalk strength was significantly reduced after the injection of CO_2-saturated brine. Al-Ameri et al. (2016) have investigated the long-term impact of $scCO_2$ soaking on several limestone samples, showing a reduction of Young's Modulus (E). Zhang et al. (2020) showed the impact of injecting $scCO_2$, CO_2-saturated brine, and dead brine on wormhole generation. They found that $scCO_2$ caused dissolution, but only CO_2-saturated brine created a continuous wormhole that resulted in the most significant impact on the mechanical properties.

Al-Dhafeeri et al. (2023; 2024) conducted a thorough study on the impact of temperature and salinity on wormhole generation due to CO_2-saturated brine injection in limestone samples. The authors found that higher temperatures and salinities required larger volumes of CO_2-saturated brine to generate a continuous wormhole in the samples. That was attributed to the CO_2 solubility in brine, which was reduced at higher temperatures and salinity, resulting in less acidic brine. They also found that the generation of wormholes resulted in a 15-45% reduction in the rock's E, depending on the injection conditions and confining pressure. The experiments that required larger CO_2-saturated brine volumes for the wormhole generation resulted in the greatest reduction in the rock strength.

The evaluation of the mechanical properties in the previous studies was done after conducting the coreflooding experiments. The samples were removed and dried, and the E was measured at ambient conditions that were considerably different than the high pressure, temperature, and stress conditions during coreflooding. In this study, we utilized a coreflooding setup with triaxial capabilities to measure the changes in the rock's E while the wormholes were generated during CO_2-saturated brine injection. This is the first study, known to the authors, to assess the in-situ geomechanical impact at high pressure, temperature, and stress.

Method and/or Theory

This study aimed to evaluate the real-time geomechanical properties of a specimen during CO_2-saturated brine injection. We utilized the setup mentioned by Al Shafloot et al. (2021) that consists of a coreflood having an ISCO pump, Parr reactor, core holder, confining pressure, and back pressure regulator (BPR). The coreflooding setup was used to inject the CO_2-saturated brine into the core sample at high pressure and high temperature (HPHT) conditions. The samples were subjected to axial stress through end caps and confining pressure representing uniform horizontal stress. The installed linear variable differential transformer (LVDT) was used to estimate the sample deformation in real-time, hence both the E and the creep.

Two types of stresses, axial and confining, were applied during the experiment. The axial stress was altered during the experiments to measure the samples' E or to measure the long-term specimen creep, as shown in Figure 1. First, the samples were vacuumed for 2-3 hrs, and then a rock seasoning procedure was applied to condition the rock to the reservoir conditions. The deviatoric axial stress was increased, in steps, from 2 to 16 MPa and then reduced to 2 MPa, which was repeated in three cycles. The dry samples' E was reported during the third rock seasoning cycle. After that, the sample was saturated with 40,000 ppm brine, and the permeability was measured using Darcy's law by recording the pressure drop at different flow rates. The axial stress was then increased to 16 MPa and fixed overnight to measure the reference E_0 and creep before introducing the CO_2-statured brine to the sample. The sample CO_2-saturated brine was injected in two or three cycles, where the samples E and creep were recorded after each cycle of CO_2-statured brine injection, as shown in the figure.

Three cylindrical Indiana limestone cores that were 1-inch diameter by 2 inches in length were used. The rock samples had an average porosity of 14% and an average permeability of 13 mD. The CO_2-saturated brine was injected at different flow rates: 0.5, 1, and 2 mL/min, while the experiment conditions are shown in Table 1. Notice that 70% of the injected fluid contained brine while the remaining was CO_2.

Table1: *The experimental conditions during CO_2-statured brine injection.*

Temperature (°C)	Reactor Pressure (psi)	Back Pressure Regulator (psi)	Confining Pressure (psi)	Deviatoric Axial Stress (psi)	Brine Salinity (ppm)	Injected Brine Volume (mL)
60	1,500	1,480	1,950	725 (5 MPa)	40,000	700

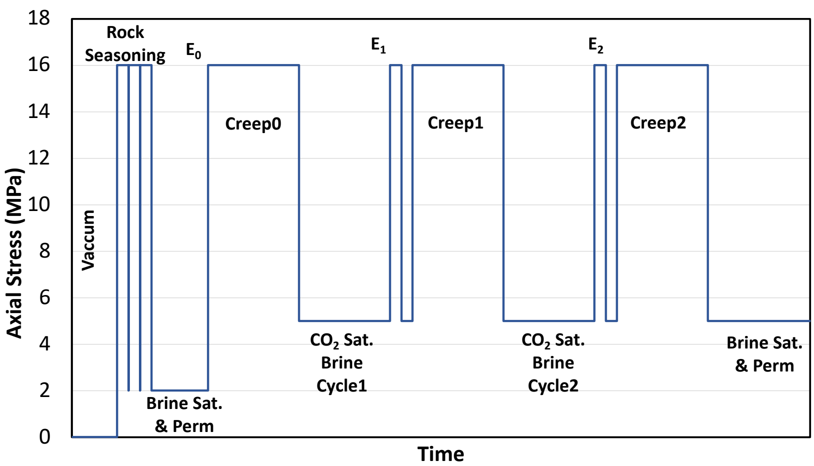

Figure 1: *Procedure to assess the geomechanical properties of the rock samples at different stages.*

Alteration of Rock Geomechanics

Figure 2 shows the changes in the rock's E during the experiment for one of the samples. The value reported is the scaled E, which is the E at any stage divided by that obtained initially during the rock seasoning. It is observed that the largest change in E happened after saturating the sample with brine. For instance, there was a 39% increase in E due to replacing the air in the sample with the high salinity brine. This is attributed to the high compressibility of brine compared to air, which was reflected in the strength of the sample. However, the sample's E did not change noticeably after three cycles of CO_2-saturated brine injection, that resulted in the generation of a continuous wormhole, as shown in Figure 3. Investigating the literature, the mechanical properties were measured at ambient conditions on dry samples. Nevertheless, the samples in this study were saturated with brine at 1,500 psi during E measurements. The incompressible brine replaced the 1-2 %vol. of the dissolved portion of the rock (i.e., wormhole); therefore, no noticeable changes were observed. The setup, however, measures the E in the axial direction, and the measurements of the E in the confining direction might reveal different outcomes. It is of note that the other two samples showed the same outcomes.

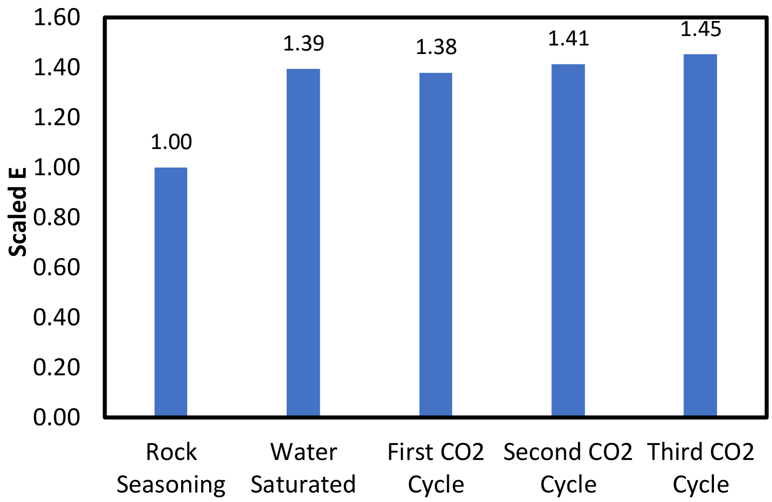

Figure 2: *YM of the sample at different steps within the experiment.*

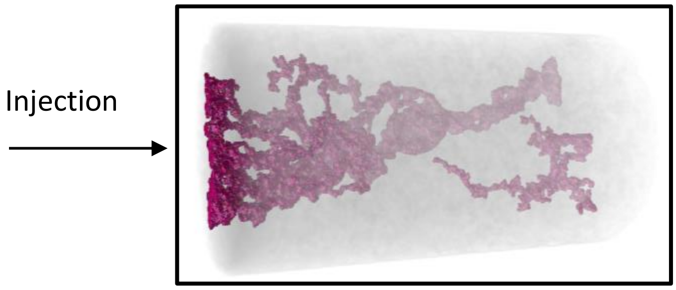

Figure 3: *Sample's microCT image showing a continuous wormhole in magenta due to CO_2-saturated brine injection.*

Figure 4 shows the creep behavior of the sample before and after CO_2-saturated brine injection. It is clear that CO_2 injection results in a significant increase in creep due to rock dissolution. The second cycle of CO_2-saturated brine injection resulted in an initial larger creep magnitude. Therefore, models should be created to understand the impact of creep at a large scale, considering thousands of years of CO_2 existence in deep limestone aquifers.

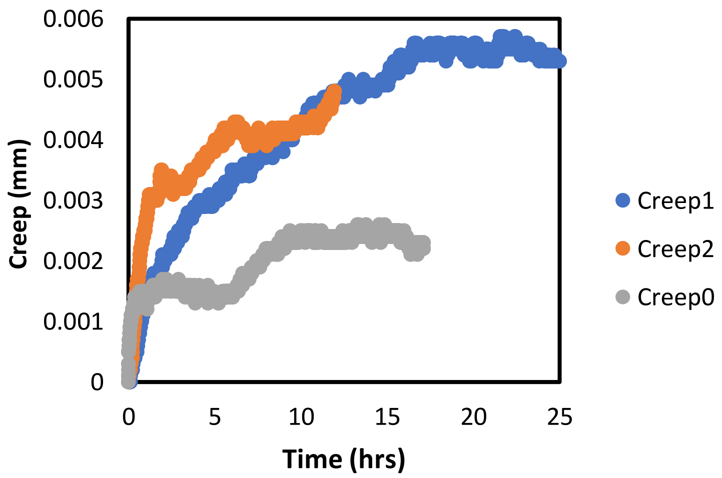

Figure 4: *Sample's creep at 16 MPa before and after CO_2-saturated brine injection.*

Conclusions

The injection of CO_2-saturated brine in limestone samples resulted in the creation of a continuous wormhole within the samples. The injection occurred in a setup that allows conditions of high temperature (60 ºC), high pore pressure (1,500 psi), high confining pressure (1,950 psi), and 5 MPa (725.2 psi) of deviatoric axial stress. The installed LVDT allowed for monitoring the changes in rock mechanics in situ while conducting the experiments. The CO_2-saturated brine injection altered the geomechanical properties of the specimen by increasing the rock creep when measured under high axial stress. However, the in-situ measurements of the sample's axial E did not show a noticeable change, unlike those reported in the literature. The observation could be attributed to the saturation of the sample with brine at high pressure during the measurements. The reported E in this study is static, while most of the ones reported in the literature are dynamic. Also, the setup in this study is limited to measuring the E in the axial direction, while the sample after wormholing is more vulnerable in the radial direction.

Acknowledgements

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