Carbon dioxide impact on the mechanical properties of a sandstone from San Jorge Gulf Basin (Argentina)

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ABSTRACT: During the last few years, there has been an increase in awareness related to global warming. In this context, carbon capture and storage comes into play, intending to reduce the emission of greenhouse gases. This research focuses on reservoir rocks from the San Jorge Gulf Basin (Argentina). To analyze the feasibility of storing CO_2 in the reservoir layer, this research studies the evolution of the rock's porosity and mechanical properties, using samples obtained from outcrop. With this aim, a series of tests such as Mercury Intrusion Porosimetry, X-Ray Fluorescence, and Uniaxial Compressive tests were performed over both unaltered and CO_2-altered specimens. Preliminary results show a variable affectation of the porosity, mainly in the carbon dioxide contact zone. Carbonated samples also seem to present modifications in their mechanical properties.

Keywords: carbon dioxide, CO_2 geological storage, sandstone, mechanical characterization.

1 INTRODUCTION

Since 1979, the year in which the World Meteorological Organization first brought up the climate change topic, there has been an increasing interest in finding alternatives to mitigate global warming. Considering the fact that this phenomenon is produced due to the high rate at which greenhouse effect gases are emitted (Saddiqui et al. 2022), more particularly CO_2 (Working Group III of the Intergovernmental Panel on Climate Change 2014), attention is being paid to the handling of these fluids.

Carbon capture and storage (CCS) is a widely known option for reducing the atmospheric concentration of carbon dioxide. This proposal consists of capturing the greenhouse gas either directly from its emission source or the atmosphere and injecting it into an underground suitable rock. According to Bachu (2000), different formations have been proven to be adequate for carbon dioxide storage, such as oil and gas reservoirs, unminable coal beds, and deep saline formations.

In this article, the stratum proposed as a case study for CO_2 storage is part of an oil and gas formation. The reservoir rock chosen is part of the San Jorge Gulf Basin, located in the Argentinian Patagonian region. This rock is a well-sorted glauconitic sandstone, formed of marine sediments, which constitutes the shallowest oil reservoir of the basin, depleted at present (Foix 2009).

When considering whether if a certain reservoir rock is adequate for carbon storage, it is necessary to analyze the evolution of the rock's properties when altered by supercritical carbon dioxide ($scCO_2$). Among the properties to which more attention should be paid, porosity, composition, and strength should be considered. The variation in the rock's microstructure is of particular interest due to its direct influence over the reservoir's storage capacity and the trapping mechanism involved in the CCS process (Bradshaw et al. 2007). These characteristics combined with the evolution in the strength of the studied rock would determine the reservoir's integrity for CO_2 long-term-storage (Hawkes et al. 2004).

Given the fact that CCS is a booming topic nowadays, several authors have studied the modification produced in the behavior of reservoir rocks and more particularly sandstones, under the action of carbon dioxide (Rosenbauer et al. 2005, Wigand et al. 2008, and Marbler et al. 2012). Bearing this in mind, this article aims to analyze the evolution of the properties of a San Jorge Gulf Basin (Patagonia-Argentina) sandstone when altered by $scCO_2$. As there is little information related to the geomechanical characterization of the studied sandstone in its pristine state, the behavior of the unaltered and carbonated rock will be examined.

2 MATERIALS AND METHODS

2.1 Sandstone-core obtention

2.1.1 Pristine sandstone cores

The studied sandstone belongs to a Formation of the San Jorge Gulf Basin, located in the Patagonian Region of Argentina. This rock stratum is a shallow depleted oil and gas reservoir, considered to be a feasible storage for carbon dioxide. This statement is based on two main facts. The first one is that it is one of the alternatives for storing CO_2 mentioned by Bachu (2000), given the fact that it is a sandstone with high natural porosity and permeability (Rodríguez et al. 2014). The second one is that this rock layer has already been considered and used as a subsurface gas reservoir (Rodríguez et al. 2014).

To characterize the sandstone at both states, pristine and carbonated, samples were obtained from outcrop considering that obtaining deep reservoir samples was unaffordable. Once samples were available, a coring machine and a saw were employed to extract the specimens that would be furtherly tested, following the specifications of the ASTM D 4543 – 01.

2.1.2 Carbonated sandstone cores

To obtain scCO2-altered sandstone cores, it was first necessary to establish a series of parameters, which would ensure that the exposure of the studied rock was as close to reality as possible. In particular, the temperature and pressure of the CO_2 had to be determined, ensuring its supercritical state, which according to Ranjith et al. (2013) is reached for temperatures and pressures above 31.48ºC and 7.38 MPa. Considering the reservoir reaches a mean temperature of 60ºC, and an estimated confinement pressure of 18 MPa, these were the target values for the CO_2 injection.

Once the properties of the $scCO_2$ were defined, the core-alteration began. The sandstone cores were water-saturated by submerging them for 24 hours, bearing in mind that CO_2 diffusion is more effective in saturated environments. Afterward, the saturated cores were introduced into the reaction cell and water was poured into the cell's bottom to maintain a saturated environment. CO_2 flowed in the cell until it was filled and the valves were closed, isolating the whole system. At this point, temperature was risen in steps of 20ºC/hour until the desired value was reached. The final pressure registered was of 10.5 MPa, indicating the CO_2 was in a supercritical state. When the proposed 30-day-exposure period was fulfilled, the temperature and pressure inside the cell were taken to room conditions by performing a series of steps to avoid the breakage of the rock cores, first reducing the temperature and then the pressure. Finally, the carbonated cores were extracted from the cell.

2.2 *Mechanical property determination*

With the aim of analyzing the evolution in the mechanical properties of the studied sandstone, Uniaxial Compressive tests were performed, following the ASTM D 3148 – 02 specifications. It should be noted that the specimens didn't verify the length/diameter ratio condition, mainly due to the core breakage through weakness planes during their coring process.

Two groups of sandstone cores were tested, the first group was composed of sixteen intact rock cores, and the second group was formed of six 30-day-carbonated cores. All of the specimens tested were adequately measured and weighed, after which, horizontal and vertical strain gauges were pasted to their surface to furtherly plot their stress-strain curves.

2.3 *Microstructural property determination*

When determining the microstructural properties of the sandstone at both its pristine and carbonated state, the aim was to study in general terms the evolution of the rock's porosity as well as the reactions produced during the short-term CO_2 exposure. This would lead to a detailed analysis of the variation in the mechanical properties of the rock in terms of the microstructural properties. Another more focused objective was to study the reach range of the carbon dioxide alteration inside each core.

As a means of achieving the mentioned goals, X-Ray Fluorescence (XRF) and Mercury Intrusion Porosimetry (MIP) tests were performed for the cores subjected to the Uniaxial Compressive tests. Given that both tests need small amounts of material with no particular shape, pieces of sandstone were obtained from the center and the edge of the 30-day-carbonated sandstone cores, to analyze the penetration degree of the CO_2. To study the evolution in the microstructural properties due to the scCO_2 exposure of the sandstone, pieces of the pristine tested cores were also extracted.

3 RESULTS AND DISCUSSION

3.1 *Uniaxial compressive strength*

In the following graphs (Figure 1 and Figure 2), the results obtained for the Uniaxial Compressive tests performed for the pristine and carbonated sandstone cores are presented. As it was previously mentioned, the cores presented certain variability in their length/diameter ratio, reason why the Uniaxial Compressive Strengths (UCS) determined during the tests were corrected and standardized for a two-value-ratio, using the recommendations stablished by the ASTM D 7012-10.

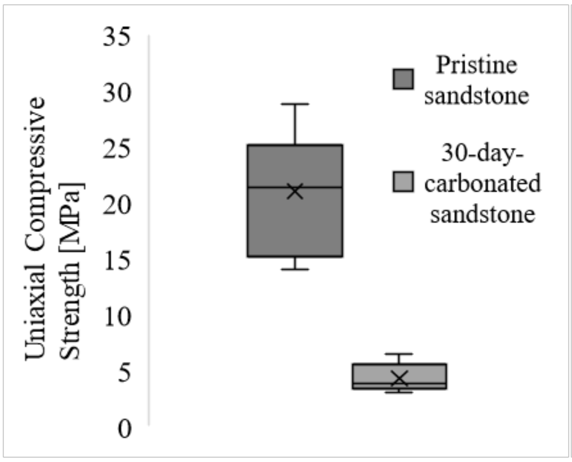

Figure 1. UCS results obtained from performing Uniaxial Compressive tests.

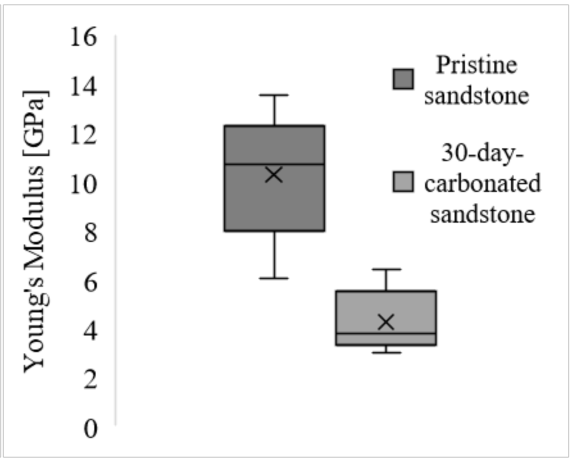

Figure 2. Young's Modulus results obtained from performing Uniaxial Compressive tests.

As it might be observed from Figure 1 and Figure 2, the mean UCS and Young's Modulus values for the pristine rock are 21.04 MPa and 10.29 GPa respectively, while the 30-day-carbonated-sandstone presented values of 12.67 MPa and 4.27 GPa. From these results, we can conclude that there is a reduction in the UCS when the rock is exposed to scCO_2, a behavior also noted by Rathnaweera et al. (2015). It might also be noted that there is a change in the breakage behavior of the rock, becoming more ductile after the scCO_2-aging.

3.2 Mercury intrusion porosimetry

When analyzing the results obtained from performing the MIP tests on the different pieces extracted from the intact and CO_2-altered cores, the porosity was determined. The values determined could be divided into three different groups in terms of the type of specimen analyzed: a) pristine sandstone, b) 30-day-carbonated sandstone obtained from the center of the tested cores, and c) 30-day-carbonated sandstone extracted from the edge of the tested cores. Bearing this classification in mind, the results have been plotted in the following graph (Figure 3).

As it might be observed in Figure 3, an important reduction in the sandstone's porosity occurred after the 30-day-CO_2 exposure. The decrease in the porosity in the edge of the cores tested is around 50% regarding the sandstone's porosity before being introduced into a CO_2-rich environment. It can also be seen that there is a greater dispersion in the porosity results obtained for the pristine sandstone than for the altered rock. This is mainly because the amount of available intact sandstone sample was larger than the scCO_2-aged one, being it more probable for the heterogeneity of the rock to show up.

When analyzing the variation in the rock's properties in terms of the carbon dioxide's reach range inside of the core, it might be noted that the center of the cores also suffered modifications in their porosity. It must be brought to attention that the reduction in the center's porosity is smaller than the one produced on the edge of the core. This is an expected result given the short period of exposure to which the sandstone cores were submitted. It is also important to consider that the edges were influenced by the action of scCO_2 from the beginning, while the center of the specimens was exposed for a shorter time. This statement refers to the fact that the core's center came into contact with the carbon dioxide once its diffusion through the water had occurred.

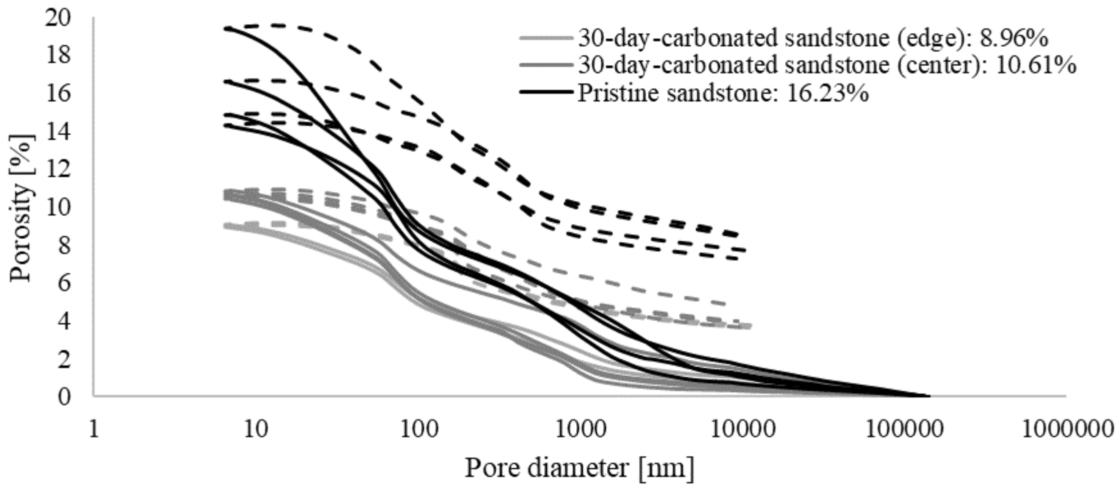

Figure 3. Results obtained from performing Mercury Intrusion Porosimetry.

3.3 X-Ray fluorescence

The results obtained from performing the X-Ray Fluorescence (XRF) test on the different types of sandstone specimens are presented in the following table (Table 1). As it might be observed, in general terms, the variation in the content of the different elements which compose the 30-day-carbonated sandstone specimens is more notable in the ones extracted from the core edges. This was the expected result considering that the edges of the specimens were directly exposed to the CO_2 action from the beginning and was corroborated when analyzing the MIP results.

Table 1. Results obtained from performing the X-Ray Fluorescence test.

Main elements	Specimen description		
	Pristine sandstone	30-day-carbonated sandstone (center)	30-day-carbonated sandstone (edge)
Al_2O_3	5.24	5.55	5.57
CaO	16.61	14.65	11.28
Fe_2O_3	6.30	4.10	8.70
MgO	0.66	0.65	0.76
SiO_2	49.35	55.41	50.05
Others	21.84	19.64	23.64

When analyzing the XRF results more deeply, it might be mentioned that there is a notable increment in the content of Al_2O_3, Fe_2O_3, SiO_2, and MgO. According to Othman et al. (2018), these modifications in the composition are produced during the dissolution of clay minerals, present in the intact sandstone studied (5% reported by the X-Ray Diffraction test performed). The increase in SiO_2 could also be a consequence of quartz dissolution (unaltered sandstone contains 26% according to the X-Ray Diffraction test performed). The observed decrease in the concentration of CaO, indicates that during the $scCO_2$ injection, calcite present in the unaltered sandstone is dissolved (28% reported by the X-Ray Diffraction test performed).

The modifications produced in the composition of the studied rock after being exposed for 30 days to a CO_2-rich environment, are directly related to the UCS and porosity decrease. On the one hand, the dissolution of quartz and clay minerals produces a reduction in the sandstone's strength as its rock matrix is altered (Rathnaweera et al. 2015). On the other hand, the precipitation of clay mineral dissolution has been proven to produce pore-blocking (Othman et al. 2018), producing consequently the diminution in the porosity of the rock.

4 CONCLUSION

Climate change and global warming produced due to the rise in carbon dioxide emissions to the atmosphere represent a worldwide problem. Carbon capture and storage is considered to be an adequate mitigation alternative to the effects produced by the presence of greenhouse effect gases in the environment. In this article, a glauconitic sandstone from the San Jorge Gulf Basin was studied as a possible carbon storage. The proposed storage would be an oil and gas-depleted reservoir type.

With the aim of analyzing the feasibility of the reservoir rock as a carbon storage, a series of mechanical and microstructural tests were performed on unaltered and 30-day-carbonated sandstone specimens. From the results obtained, it was possible to observe a reduction in the Uniaxial Compressive Strength and a modification of the sandstone after being exposed to carbon dioxide for 30 days. It could also be seen a reduction in its porosity, more notable in the regions in which the sandstone was in direct contact with the CO_2 from the beginning of the exposure. The compositional analysis performed on the different specimens allowed a better understanding of the reduction of the rock's UCS and porosity. It could be observed that there was quartz and clay dissolution, which produced pore-blocking and rock-matrix alteration.

Further research should include the analysis of Scanning Electron Microscopy imaging, X-Ray Diffraction, and permeability tests performed on altered sandstone, to widen the comprehension of the evolution in the microstructural properties produced during its carbonation. It would also be of interest to study the modifications induced to the rock when exposed to $scCO_2$ for longer periods.

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REFERENCES

ASTM D 3148 – 02. 2002. *Standard Test Method for Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression.* American Society for Testing and Materials: West Conshohocken.

ASTM D 4543 – 01. 2001. *Standard Practices for Preparing Rock Core Specimens and Determining Dimensional and Shape Tolerances.* American Society for Testing and Materials: West Conshohocken.

ASTM D 7012 – 10. 2010. *Standard Test Method for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperature.* American Society for Testing and Materials: West Conshohocken.

Bachu, S. 2000. *Sequestration of CO_2 in geological media: criteria and approach for site selection in response to climate change.* Energy Conversion & Management 41: pp. 953-970.

Bradshaw, J., Bachu, S., Bonijoly, D., Burruss, R., Holloway, S., Christensen, N. P. & Mathiassen, O. M. 2007 *CO_2 storage capacity estimation: Issues and development of standards.* International Journal of Greenhouse Gas Control I: pp. 62-68.

Foix, N. 2009. Doctoral thesis. *Tectónica de sedimentación del registro paleógeno (Formaciones Salamanca y Río Chico), Cuenca del Golfo San Jorge, Argentina.* Universidad Nacional de la Patagonia San Juan Bosco, Comodoro Rivadavia, Argentina.

Hawkes, C., Mclellan, P. & Bachu, S. 2004. *Geomechanical factors affecting geological storage of CO_2 in depleted oil and gas reservoirs.* Journal of Canadian Petroleum Technology 44 (10).

Marbler, H., Erickson, K., Schmidt, M., Lempp, C. & Pollman, H. 2012. *Geomechanical and Geochemical effects on sandstones caused by the reaction with supercritical CO_2: an experimental approach to in situ conditions in deep geological reservoirs.* Environmental Earth Sciences 69: pp. 1981-1998.

Ranjith, P., Perera, M. & Khan, E. 2013. *A study of safe CO_2 storage capacity in saline aquifers: a numerical study.* International Journal of Energy Research 37: pp. 189-199.

Rathnaweera, T., Ranjith, P., Perera, M., Haque, A., Lashin, A., Al Arifi, N., Chandrasekharam, D., Yang, S., Xu, T., Wang, S. & Yasar, E. 2015. *CO2-induced mechanical behaviour of Hawkesbury sandstone in the Gosford basin: An experimental study.* Materials Science & Engineering A 641: pp. 123-137.

Rodríguez, J., Bardelli, J., Tichno, M. & Limarino, C. 2014. *Integración petrofísica-geológica en la caracterización de la porosidad de un reservorio de gas en el yacimiento Diadema (Formación Salamanca, Paleoceno).* Resúmenes XIV Reunión Argentina de Sedimentología: pp. 239-240. ISBN: 978-987-96296-5-9.

Rosenbauer, R., Koksalan, T. & James, L. 2005. *Experimental investigation of CO_2-brine-rock interactions at elevated temperature and pressure: Implications for CO_2 sequestration in deep saline aquifers.* Fuel 86: pp. 1581-1597.

Siddiqui, A., Hasnain, M., Alam, M. & Fatima, S. 2022 *Climate Change: Causes, Impacts and Solutions.* International Research Journal of Engineering and Technology 9: pp. 928-934. e-ISSN: 2395-0056.

Othman, F., Yu, M., Kamali, F. & Hussain, F. 2018. *Fines migration during supercritical CO_2 injection in sandstone.* Journal of Natural Gas Science and Engineering 56: pp. 344-357.

Working Group III of the Intergovernmental Panel on Climate Change. 2014. *AR5 Climate Change 2014: Mitigation of Climate Change*. Cambridge University Press, United Kingdom and New York, USA.

Wigand, M., Carey, J. W., Schutt, H., Spangenberg, E. & Erzinger, J. 2008. *Geochemical effects of CO_2 sequestration in sandstones under simulated in situ conditions of deep saline aquifers.* Applied Geochemistry 23: pp. 2735-2745.