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Assessing the injection well-reservoir discontinuity: Triaxial Direct Shear Tests at high confining stress for Carbon dioxide geological storage

Evaluando la discontinuidad pozo de inyección - reservorio: Ensayos de corte directo triaxial a altas presiones de confinamiento para el almacenamiento geológico de dióxido de carbono

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ABSTRACT: Carbon Capture and Storage (CCS) is a geoengineering/technological practice to reduce the increasing rate at which this greenhouse effect gas is being emitted. Numerous studies are underway to evaluate the feasibility of employing different rock formations as carbon dioxide (CO_2) underground storage. Given its role as climate change mitigation, this practice requires a rigorous risk assessment to stablish its viability as a long-term solution. One prevalent concern in CO_2 stores is the presence of mechanical discontinuities, highlighting the interface of the injection well with the reservoir rock. The current study investigates the mechanical behavior of this type of discontinuities when exposed to supercritical carbon dioxide ($scCO_2$). In this context a series of high confining pressure direct shear triaxial tests were conducted on samples emulating the cement - rock discontinuity, both before and after their exposure to $scCO_2$. Changes in the reservoir rock's color after it's CO_2-ageing could be observed. Mechanical behavior analysis indicates contraction-dilatancy in the samples at cement-rock interfaces, with stress peaks observed at small displacements. Moreover, the cement-rock interfaces exposed to $scCO_2$ exhibit mechanical degradation, resulting in a reduction of peak shear strength.

KEYWORDS: triaxial direct shear test, reservoir rock-wellbore cement interface, CO_2 geological storage, CO_2-aged sandstone.

1 INTRODUCTION

1.1 Mechanical Discontinuities in Carbon Capture and Storage

Carbon Capture and Storage (CCS) is a technological practice that arose as a mitigating solution for global warming. When proposing a certain rock formation as possible reservoir for CO_2, a series of different studies must be performed with the aim of verifying not only the safety of the facilities but also the economical convenience. Failure mechanisms such as fault reactivation, induced shear failure, hydraulic fracture, borehole instability, and casing failure are being studied in geo-energy infrastructures such as deep geothermal (Cornet et al., 2007), oil-gas industry or geological storage (Hawkes et al., 2005). A common topic in the mentioned failure mechanisms is the presence of discontinuities. Discontinuities from an engineering point of view can be faults, fractures, and contacts between different materials, such as wellbore cement-reservoir-caprock and reservoir-caprock discontinuities, as shown in Figure 1. In the context of CCS, the interface between the injection well and the reservoir and cap rocks represent a critical weak point in the system to ensure the integrity of the subsurface reservoir.

Researchers have concentrated on studying different aspects to assess discontinuities in the context of CO_2 injection. For instance, Cerasi et al. 2015 and Stroisz et al. 2019, have studied the debonding of cement-rock composites when subjected to tensile stress, which seems to be one of the failure mechanisms present in the transition between the wellbore cement and the reservoir or caprock. Another example is the study of the chemical interaction developed in the interface defined by different materials due to CO_2 injection (Jobard 2013, Manzanal et al., 2013, Jahanbakhsh et al. 2021). Finally, the effect of roughness of mechanical discontinuities over real and synthetic rock specimens has been recently evaluated with high confining pressure direct shear triaxial test. Results show the effect of the surface roughness on contractive–dilative behavior and shear strength of the discontinuities in synthetic rocks (Casagrande et al. 2022). The aim of this study is to analyze the variation produced in the behavior of reservoir rock-wellbore cement discontinuities present in a CO_2 underground storage due to the injection of CO_2 to assess the safety of the reservoir facilities. The study analyzes the variation produced in the behavior of the mechanical discontinuity between the wellbore cement and the reservoir rock in a supercritical CO_2-rich environment at a laboratory scale.

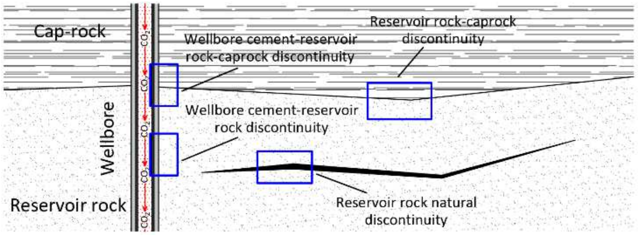

Figure 1. Schematic depiction of the vicinity surrounding the carbon dioxide injection well and potential mechanical discontinuities.

1.2 *Geological Storage in Argentina*

In Argentina, according to Grasetti et al. 2022, there are several geological basins that meet the necessary conditions to be considered potential sites for CO_2 underground storage, such as Claromecó, Neuquina and Golfo San Jorge Basin. This is an indicator of the importance CO_2 disposal is gaining in the country.

Regarding Golfo San Jorge Basin, researchers focus on understanding the mechanical properties of its reservoir rocks and their interaction with $scCO_2$. They gain insights into the diverse petrophysical and geomechanical properties exhibited by outcrops from several hydrocarbon-producing formations, including the Salamanca (Laskowski et al., 2023), Bajo Barreal (Vidal et al., 2022), Castillo, and Pozo D-129 (Cortes et al., 2024, Manzanal et al., 2024) formations.

The evolution of geomechanical parameters under supercritical CO_2 ($scCO_2$) has been studied experimentally and numerically for rocks, cementitious materials, and discontinuities (Manzanal et al., 2013, 2024; Vilarasa et al., 2019; Barria et al., 2023; Laskowski et al., 2023).

The current study investigates the mechanical discontinuity occurring at the interface between the injection well and the reservoir when exposed to supercritical carbon dioxide ($scCO_2$). A glauconitic sandstone from Golfo San Jorge Basin was proposed as the case of study, with the aim of obtaining wellbore cement-reservoir rock specimens to represent in-situ conditions. The chosen rock is characterized for presenting not only high porosities (Rodríguez et al. 2014) but also high permeabilities, necessary when selecting a CO_2 disposal site as they imply great volumes available for fluid disposal and an economical injection of the fluid. In addition, the selected layer is in contact in its upper part with a claystone stratum, which stands out for having low permeability values, and acting as a natural caprock (Foix 2009). In mineralogical terms, according to Laskowski et al. 2024, the glauconitic sandstone used in the preparation of the cement-rock cores is composed of quartz (30%), plagioclase, feldspars, glauconite, carbonates, and volcanic rock fragments. It should be noted that the plagioclase has a prevalence of anorthite over albite, which implies an increase in the content of calcite and clays minerals when exposed to CO_2 (Hangx et al. 2009, Cui et al. 2017, and Peng et al. 2022), indicating mineral trapping of the greenhouse gas. All in all, these intrinsic characteristics of the rock made it a suitable material to represent a reservoir rock for CO_2 in the tests to be performed.

To study the behavior of this group of discontinuities, a series triaxial direct shear tests were performed, analyzing in detail the variation produced in the Shear Strength vs. Shear Displacement curves due to the specimen's exposure to a CO_2-rich environment. With these results, it would be possible to lay the groundwork for a possible methodology to evaluate the long-term safety of one of the several migration pathways in CO_2 underground reservoirs.

2 MATERIALS

2.1 *Sample preparation: Sandstone and class G cement*

The rock used in this research is a glauconitic sandstone obtained from outcrops in the from "Punta Peligro Norte" near the city of Comodoro Rivadavia (Figure 2). This outcrop represents the reservoir rock of the Salamanca Formation of the Golfo San Jorge Basin in the Patagonian Region of Argentina.

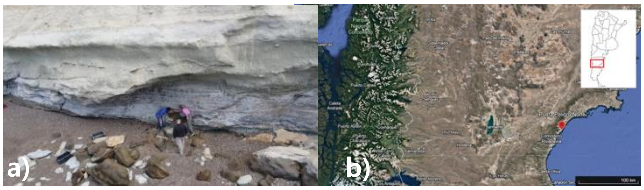

Figure 2. a) Right; Sandstone outcrop sample obtention. B) Left: Punta Peligro Norte location (45°31'31''S 67°13'14''W).

The cement used is a Class G Portland Cement provided by PCR S.A. (Petroquímica Comodoro Rivadavia S.A., Argentina). It is made with clinker and calcium sulfate of high sulfate resistance grade to satisfy the chemical requirements of the American Petroleum Institute (API) Specification 10A for cement (API Specification 10A, 2010): C3S 52.8%, C3A 1.6%, C2S 21.1% and C4AF 15.5%.

Molds were designed to recreate the discontinuity between reservoir rock and well cement in a CO_2 injection well. The specimens were cylindrical, approximately 35 mm in diameter, and equal in length. The discontinuity divided the sample into two equal halves with each material (Figure 3a).

The sandstone half-cylinders were obtained using a coring machine and saw, while the cement grout was poured directly into the mold after placing the rock specimen. After pouring the cement grout, the specimens were left in the mold for 24 hours, then unmolded and cured in a water bath at room temperature for 30 days to reach maximum cement strength. At this point, the physical characteristics of the specimens were registered.

The specimens were divided into two groups: the first one comprised specimens to be tested in their pristine state, while the second group underwent a 30-day CO_2-exposure process before testing. Once this was completed, the specimens were individually stored in a constant humidity and temperature chamber.

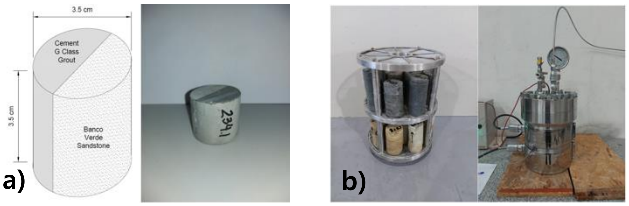

Figure 3. a) Rigth: Scheme of the cement-rock discontinuity and cylindric specimen obtained; b) carbonation cell used to subject the discontinuity specimens during a 30-day period to a CO_2-rich environment.

3 METHODS

3.1 *CO_2-exposure process in supercritical state*

CO_2 is injected underground for geological storage in a supercritical state (Working Group III of the Intergovernmental Panel on Climate Change (2005)). To achieve this state, CO_2 needs to reach a temperature above 31.48ºC and pressures exceeding 7.38 MPa. In this study, we aimed to replicate reservoir conditions using a carbonation cell containing $scCO_2$ at a pressure of 10.5 MPa and a temperature of 60ºC (Figure 3b).

To enhance CO_2-difussion within the rock, the specimens were submerged in a water bath for 24 hours. This allowed water to saturate the pore volume, being this the fluid in charge of disseminating the $scCO_2$. After this initial step, the specimens were distributed in the tray holder, verifying they would be equally exposed to the CO_2-rich environment (Figure 3b). The tray-holder was introduced inside the carbonation cell (Figure 3b), adding a certain volume of water at its bottom to maintain a humid environment. At this point, the cell was closed, and the CO_2 inlet was permitted until the cell was filled. The following step was to increase the temperature and pressure until the desired conditions were reached. With the aim of not producing abrupt changes in the cell's interior conditions, the temperature was risen in 20ºC/hour steps. Once the CO_2 reached the super-critical state, the samples were kept inside the carbonation cell under constant environmental conditions during a 30-day period. Once this period was completed, the temperature and pressure were carefully reduced, until the initial conditions were restored. The result of this process was the obtention of carbonated specimens, which were stored in a constant humidity and temperature chamber, until their testing.

3.2 *Direct Shear Triaxial Test*

The tests were performed over dry samples using direct shear triaxial equipment. This last consisted basically of a triaxial cell with its platens adapted in such a way that a shear stress could be generated in the plane of discontinuity. To fulfill this condition, the platens of the equipment were composed of half a cylinder of a highly non-deformable material and the resting half cylinder of a highly deformable silicon (Figure 4). This arrangement allows applying a vertical load at a velocity of 3x10-6 m/seg in the opposite halves of the core's heads, generating the shear stress desired, as explained by Casagrande et al. 2022.

The specimen is covered with a heat-shrinkable membrane and placed between the adapted platens. It is of great importance to verify that the discontinuity plane of the specimen matches the discontinuity plane defined by the transition between the highly non-deformable material half cylinder and the highly deformable silicon half cylinder of the platens. At this point, the membrane is heated with the aim of shrinking it tightly to both the specimen and the platens, fixing also in this way the specimen to the platens. Finally, the membrane is adjusted and secured to the platens by performing a tourniquet with a wire.

With the specimen adequately fixed to the adapted platens, the direct shear test is ready to be performed. To begin, the platens containing the specimen are placed in the lower platen of the triaxial cell. Two LVDTs were installed to measure vertical displacements and circumferential displacements were performed with chain surrounding the specimen with another LDVT to measure discontinuity separation. Afterwards, the triaxial cell is closed and sealed. The following step is to fill the triaxial cell with the confining fluid, and apply the confining pressure desired to the discontinuity specimen. To finish, the vertical relative displacement between the two half-cylinders of the specimen is applied, provoking the shear stress in the discontinuity. The test is completed once the shear stress becomes constant.

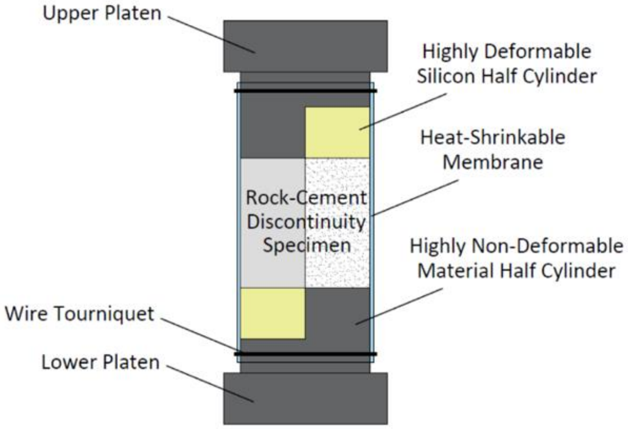

Figure 4. Simplified scheme of the platens containing the reservoir rock-wellbore cement discontinuity specimen.

4 RESULTS AND DISCUSSION

After aging for 30 days in the carbonation cell with supercritical carbon dioxide, the samples consisting of half cement class G and half glauconitic sandstone change the coloration of the cementitious portion, being it initially grey, and reaching an orange color after its exposure to CO_2 (Figure 5). Barria et al. (2022) presented a similar effect on cement samples with comparable water-to-cement ratios subjected to the CO_2-exposure process, indicating an increase in porosity in the area exposed to $scCO_2$. Even when there seems to be no visual changes in the glauconitic sandstone, it should be mentioned that in previous investigations in which the main aim was to study the evolution of the reservoir rock when exposed to a CO2-rich environment by itself, variations were detected. For instance, changes such as the variation from the greenish grey original color of the sandstone to an orange grey after its CO_2-exposure, as well as a slight vertical cracking of the external surface of the cores after being subjected to a CO_2-rich environment. One of the reasons why these changes might not be so clearly noted in the composite cores is that such variations in color produced in the wellbore cement after its CO_2-exposure overshadow the ones in the glauconitic sandstone.

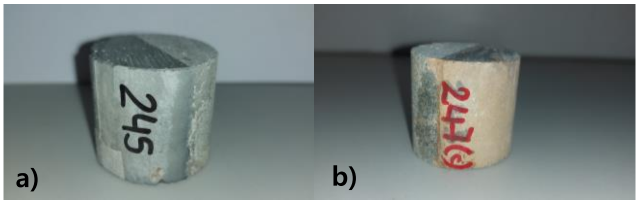

Figure 5. a) Pristine and b) 30-day carbonated composite samples.

Regarding the glauconitic sandstone portion, Laskowski et al. (2024) illustrated significant changes in the mineral components of complete samples of this rock. According to the microscopical observation of several thin sections of pristine glauconitic sandstone (Figure 6), it could be observed that it is composed of two different groups of grains, which seem to be reacting with the injected CO_2. On the one hand, glauconite clasts, containing clay minerals. In this context, the clay mineral presence in grain contacts should also be mentioned as their reaction with CO_2 reduces the rock's resistance, also producing fine migration (Othman et al., 2018), and porosity reduction. On the other hand, the presence of anorthitic plagioclase clasts indicates there will be an increase in calcite content after the exposure is produced (Hangx et al., 2009).

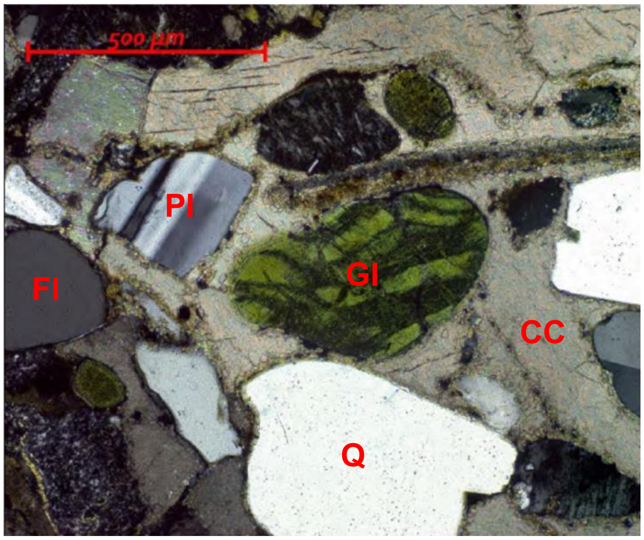

Figure 6. Thin section of pristine sandstone under cross polarized light. Q: quartz, Gl: glauconite, Fl: Feldespar, Pl: Plagioclase, CC: calcite cement.

Visual examination reveals changes in mechanical characteristics at the interface between both halves. Although the microstructure evaluation of these composite samples using mercury porosimetry tests, SEM, and analysis of amorphous and non-amorphous behavior variations has not yet been conducted, the impact of the CO_2-exposure process on the interface is evident in the mechanical behavior, which will be discussed below.

To study the mechanical behavior of the interface defined between the CO_2 injection wellbore and the reservoir rock in which the CO_2 is to be stored, two sets of tests were performed. Each set of tests was composed of three direct shear tests conducted employing the triaxial cell with the corresponding platens, choosing the following confining pressures: 10, 20, and 30 MPa, bearing in mind that the objective was to recreate as accurate as possible the reservoir depth conditions. One of the set of tests was performed using the group of pristine composite specimens, and the other was conducted with composite specimens 30-day aged in the carbonation cell. With the results obtained from these six tests, it is possible to make two separate analyses. The first one, analyzing independently the behavior of the group of pristine and carbonated composite cores. The second analysis, related to the variation produced in the behavior of the discontinuity due to the specimen's exposure to a CO_2-rich environment.

Table 1 resumes the peak and residual results obtained from the direct shear tests performed for three confining pressures (10, 20 and 30 MPa and the two types of specimens tested: pristine and 30-day carbonated. Figure 7 and Figure 8 compare two complete tests for a pristine and a 30-day carbonated composite specimen for a confining pressure of 20MPa. Figure 7 plotted the shear stress in terms of the vertical displacement in the discontinuity, while Figure 8 represents the normal displacement in terms of shear displacement.

Table 1. Peak and residual shear strengths for the different testing confinement pressures, in terms of the CO_2 time of exposure of the tested discontinuity specimen.

Testing Conditions		Discontinuity Specimen Type	
Shear Strength Type	Confining Pressure [MPa]	Pristine	30-day carbonated
Peak [MPa]	10	16.45	15.86
	20	26.46	19.83
	30	33.52	28.10
Residual [MPa]	10	12.22	12.00
	20	17.44	18.36
	30	24.21	27.66

Figure 7 not only allows observing the existence of a peak and residual shear strengthin pristine composites and the presence of only residual shear strength in carbonated composites, but it also allows to introduce the study of the variation produced in the behavior of the sandstone-cement interface due to the injection of CO_2. From this plot, two aspects can be highlighted. On the one hand, CO_2-exposure seems to vary the behavior of the interface from presenting a shear strength peak before its failure to not presenting it. On the other hand, it seems evident to the sight that the residual shear strength of both pristine and carbonated composite samples is the same, meaning that there is no apparent variation in the residual shear strength due to CO_2-aging. This behavior might also be observed in the results obtained when performing the direct shear tests with 10 and 30 MPa of confinement pressure on both types of specimens, pristine and CO_2-exposed (Table 1). From observing Table 1, where the general strength results for the whole set of tests performed are presented, it might be highlighted that as the confinement pressure increases, it is more notable the reduction in difference between the peak shear strength and the residual shear strength presented by the 30-day carbonated cores as should be expected. This behavior is not observed in pristine cores. In contrast, pristine cores seem to present a notorious peak no matter the testing confinement pressure in the analyzed range between 10MPa to 30MPa.

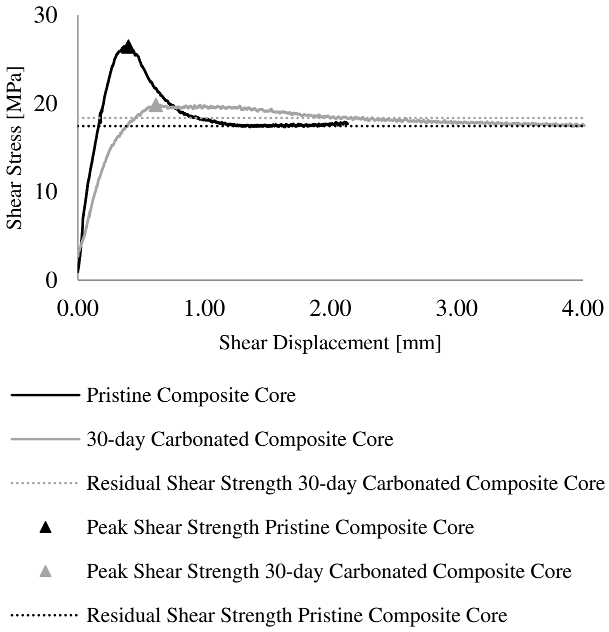

Figure 7. Pristine and 30-day carbonated composite core behavior under a 20 MPa normal stress applied (Shear Stress vs. Shear Displacement), indicating both peak and residual shear strength.

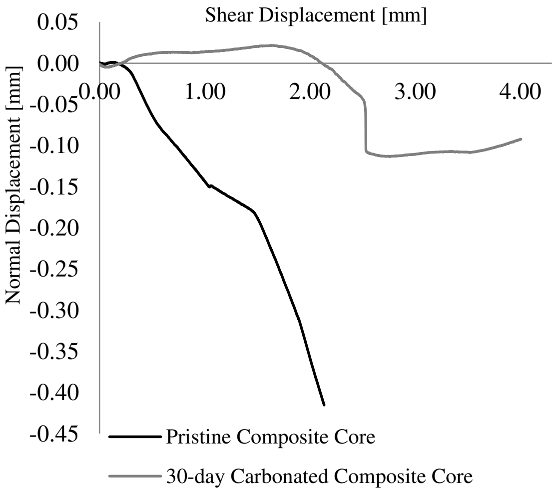

Figure 8. Pristine and 30-day carbonated composite core behavior under a 20 MPa normal stress applied (Normal displacement vs. Shear displacement).

From observing both Figure 7 and Figure 8, it might be noted that the peak shear strength is reached for identical shear displacements when comparing equal testing conditions but different CO_2-exposure periods. Additionally, it should be mentioned that in pristine composite cores, the residual strength is reached at smaller shear displacement values than the ones at which the residual strength is reached in 30-day CO_2-exposed specimens.

Centering on a deeper analysis of the results plotted in Figure 8, the following findings should be mentioned. Firstly, it might be noted that the peak strength is reached in coincidence with the highest dilatancy in the pristine specimens. Secondly, from observing the pristine core Normal vs. Shear displacement curve, it can be said that the behavior is mainly dilatant. In contrast, the 30-day carbonated composite specimen presents a contractive behavior with a slight dilatancy zone at the final part of the test.

Combining the mechanical results obtained from performing six triaxial direct shear tests over pristine and 30-day carbonated composite cores, and the microstructural and mineralogical results obtained in previous studies, a series of conclusions could be reached. Changes in both rock and the cement were visually noted. These were supported by the mineralogical changes detected from analyzing the thin sections of pristine cores and XRD and FRX results corresponding to unaltered and carbonated specimens. Both variations would lead to consider changes in the rock-cement interface were developed during the specimen's exposure to $scCO_2$. For instance, during the performing of the triaxial direct shear tests, it could be observed that pristine cores presented a peak shear strength while CO_2-exposed ones didn't. This modification in the behavior, indicates the need to further analyze the alterations produced in terms of microstructure and mineralogy within the interface due to the diffusion of CO_2 in the zone. Furthermore, an evolution in the interface's behavior from mainly dilatant to mostly contractive was noted when carbonating the cores. This could be related to a change in the rock-cement discontinuity's friction, but as it was previously mentioned, mineralogical and microstructural analyses at the interface should be carried out for a better understanding of the phenomenon taking place.

5 CONCLUSIONS

This paper summarizes the results obtained from performing a state-of-the-art test on the discontinuity defined by the CO_2 injection cement wellbore and the reservoir rock in which the fluid is intended to be stored. A total of 6 triaxial direct shear tests were performed in both pristine and 30-day carbonated composite samples with the aim of evaluating the variation produced in the mechanical properties of the wellbore cement-reservoir rock interface when injecting CO_2. From the results obtained, it could be observed:

- Changes in the coloration of the cement composing the composite samples after exposing it to a CO_2-rich environment during a 30-day. Less changes were observed in the glauconitic sandstone after its CO_2-exposure period. Although microstructural changes have been observed in complete cement and sandstone samples, these findings require verification through further microstructural testing on cement-sandstone discontinuities
- As the test's confinement pressure increases, the peak shear strength and the residual shear strength presented by the 30-day carbonated cores are more alike. This behavior is not observed in pristine cores.

- The peak shear strength presented by pristine cores seems to disappear with the CO_2-exposure process. Even when 30-day carbonated specimens don’t present a peak, both type of specimens have equal residual shear strengths for equal testing conditions.
- When comparing tests with equal testing confinement pressure, both pristine and carbonated composite specimens reach the peak strength for equal shear displacement.

Finally, to better understand why there is a reduction and even disappearance of the peak in the Shear Strength vs. Shear Displacement curve of the mechanical discontinuity studied, microstructural and mineralogical laboratory tests in the discontinuity zone should be carried out. This, combined with the knowledge of how each of the individual materials, reservoir rock and wellbore cement, react to CO_2 exposure, would allow visualizing the chemical reactions produced during the composite specimen’s CO_2-aging between the cement and the rock due to the presence of CO_2.

6 ACKNOWLEDGEMENTS

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