Mineralogy, Geochemistry, Petrophysics and Rock Mechanics of the Corvio Sandstone

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INTRODUCTION.

It is well known that the injection of reactive fluids (like CO_2) into geological formations trigger a series of interlinked thermo- hydro- chemo- mechanical phenomena (or THCM) affecting the properties of the reservoir, its seals or even the cementitious materials used in wellbores. Because water is always present in the pore space of these rocks, the forced injection of CO_2 (either as liquid, gas or supercritical fluid) induces its acidification and the onset of reactive processes which are especially notorious when carbonate or carbonate-bearing rocks are present. Accompanying CO_2, the co-injection of subordinated gasses (O_2, SO_2...) might exacerbate this reactivity owing the oxidation of reduced mineral phases already present or by promoting an enhanced acidity in the case of the S-bearing gasses.

Petrophysics and rock mechanics provide with an invaluable toolbox with which to assess key rock properties and to elaborate integrated reservoir models. When these techniques are used from a traditional viewpoint, they tend to neglect the crucial importance of the THCM couplings which are inherent, however, to reactive systems.

Core-flooding experiments performed at P-T conditions akin to those *in situ* have a great potential in helping us to unravel complex THCM processes provided that it is feasible the separation of each of their corresponding contributions. To this respect, in the present study we focus on the comprehensive characterization of a reference rock material with a dual purpose: First, as a necessary first step before proceeding with more complex experimental protocols (like reactive fluid injection); and second, to evaluate the adequacy of this material as laboratory standard for petrophysics and rock mechanics studies.

MATERIALS AND METHODS.

The studied material has the trade name of Corvio Sandstone®. Geologically speaking, this material defines the Corvio Mb which appears as a 20 m thick lithosome at the top section of the Frontada Fm (Campoó Gr; Lower Cretaceous). It is made of siliceous sandstones and conglomerates associated with braided fluvial channels showing dm to m trough-type cross bedding (Hernández el al., 1999).

Four blocks of the Corvio Sandstone (0.3x0.2x0.5 m each; Fig. 1) were used to obtain a total of 228 cylindrical plugs of 38.1 and 50 mm diameter. Additional irregular samples were selected in order to apply a number of physico-chemical characterization techniques: FRX (Bruker-AXS S4 Pionner), ATD-TG-FTIR (TA Inst. SDT 2690 coupled to Bruker Vector 22), DRX (Siemens D5000), CHNS (ThermoFinnigan FlashEA1112), BET (Micromeritics Gemini VII 2390a), SEM-EDS (JEOL JSM-6400), petrography, He pycnometry (Quantachrome Ultrapyc 1200e), Hg porosimetry (Quantachrome Poremaster-60). With respect the mechanical, petrophysical and hydrodynamic properties our assessment included the measurement of the indirect tensile (Brazilian), unconfined and confined (triaxial) strengths (MTS 815), P- and S- wave velocities, water and gas (N_2) permeabilities, immersion porosity and dry density. Based on the previous data the static and dynamic elastic moduli, as well as the critical stress states (Hakala et al., 2007) where computed. The characterization of the Corvio Sandstone was complemented with an X-Ray μCT-scan (XRadia MicroXCT-300).

On a general basis, 10 samples were used to assess the statistical significance of the properties determined.

fig 1. Rock blocks of the Corvio Sandstone after core plug extraction.

RESULTS.

Corvio Sandstone can be classified as a grain-supported quartzarenite with microcrystalline silica cement. The main mineral constituents are quartz (~94 wt. %) with subordinated kaolinite (~3.5 wt. %) and K-feldspar (~1.7 wt. %). Trace amounts of ilmenite (~0.2 wt. %) have been observed in the μCT scans while ~0.5 wt. % of carbonates is inferred from the ATD-TG-FTIR. Quartz grains are typically sub-rounded, well sorted and their average grain size hovers around 0.15-0.3 mm. In the studied samples fossils are reduced to scarce cm-size spots with remnants of vegetal debris (*cf.* Hernández *et al.*, 2009). Based on ATD-TG-FTIR, the weight % of hydrated minerals is ~0.5 while C, N and S-compounds are below 0.05 wt. %. The average BET specific surface is 1.09±0.07 m^2/g (n=12) while porosity and dry density are 14.45% (n=224) and 2037 kg/m^3 (n=227). Hg porosimetry shows that pore size spans from 2.5 to

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100 μm while the median is ~20 μm. μCT-scan data shows that although pores tend to have an equant-shape some of them may be compliant upon loading. This observation is supported by the stress-strain curves obtained.

Strength and Stress-Strain Behavior.

Geomechanical tests were performed on 50 mm diameter cylindrical plugs prepared to meet the recommendations of the International Society for Rock Mechanics. In the case of the unconfined compression strength (UCS) and triaxial tests, the axial strain was recorded with a dual-averaging, knife-edge type, extensometer while the lateral strain was measured with the aid of a circumferential, chain-type, gage.

The mean tensile strength of the Corvio Sandstone is 2.3±0.14 MPa (n=11) while UCS is 41.3±1.0 MPa (n=10). These data were combined with the results obtained in additional drained triaxial tests performed at 5, 10, 30 and 50 MPa which were needed to obtain the full strength envelope (Fig. 2). This was computed following the intact rock Hoek and Brown (1980) criterion (HB), as updated by Hoek *et al.* (2002). Assuming that the parameters s and a of the HB model are equal to 1 and 0.5, respectively, m_b is 15.0. Similarly, application of the linear Mohr-Coulomb criterion provides with an apparent cohesion (c) of ~20 MPa and a friction angle (ϕ) of 28.5º.

Taking into account the stress-strain behavior observed in the UCS tests, the static Young modulus (E) and Poisson ratio (ν) of the Corvio Sandstone are 11.41±0.35 GPa and 0.38±0.01, respectively. In addition, based on the computed volumetric strain and the methods discussed by Nicksiar and Martin (2012), the crack initiation and crack damage stresses occur at 6.2±0.2 and 26.0±0.8 MPa, respectively.

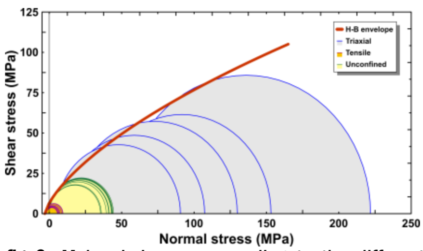

fig 2. *Mohr circles corresponding to the different mechanical tests performed (Brazilian, UCS and triaxial) with the Corvio Sandstone. The computed Hoek-Brown strength envelope computed from these tests is also shown.*

Ultrasonic P- and S- Wave Velocities.

P- and S- wave velocities were measured by applying the time-of-flight technique to cylindrical, 38.1 mm diameter plugs submitted to unconfined conditions and a small load (3 MPa) to improve the sample/transducer contact. A pair of stacked P-S_1-S_2 1.3 MHz transducers (ErgoTech) was located at the bottom (emitter) and top (receiver) of the plug. In order to check the anisotropy of the rock, 3 plugs cored in orthogonal directions were also extracted: one normal to bedding (Z) and two parallel to bedding (X and Y). Each one of these plugs was stepwise rotated (20º increment).

The average P- and S- velocity in the Y-Z directions are 3.32 and 1.72 km/s, respectively. However the velocities obtained in the X direction are smaller (2.99 and 1.53 km/s). These low values suggest that porosity is not equally distributed (larger in the X-direction) , what could obey to local changes in the cross bedding sets sampled by the X and Y plugs. The dynamic Young modulus and Poisson ratio computed from the previous velocities are 15.90±0.06 GPa and 0.316±0.001 (Y-Z directions) and 12.55±0.11 GPa and 0.323±0.002 (X direction). Static moduli, as expected, are lower than the dynamic ones because the latter only captures the elastic response of the rock under low stress conditions.

Hydraulic Conductivity.

The hydraulic conductivity of the Corvio Sandstone was tested in three 38.1 mm plugs sampled in the previously described orthogonal directions. The tests were conducted in a Hassler-type core holder (Temco THC) at different confining pressures (up to 30 MPa; fig. 3) and room T. In the tests, deaireated tap water was injected (Quizix SP-5400 syringe pump) at a constant P while flow was measured at the outlet of the plug at 0.1 MPa. P and flow was carefully recorded with the Quizix system. Attainment of the steady flow condition while keeping injection P constant makes possible the computation of hydraulic conductivity based on Darcy’s Law. Results show that the plug sampled in the X-direction has a higher conductivity than in the other two directions, which are similar. This is consistent with the observations made with P- and S- wave velocities. Significant hysteresis is observed when

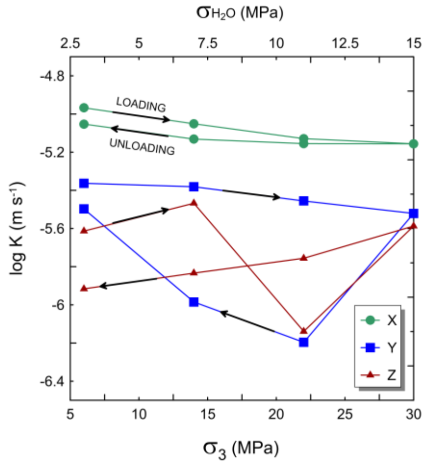

fig 3. *Log hydraulic conductivity vs. confining (σ_3) and pore (σ_{H2O}) pressures of three Corvio Sandstone plugs sampled in orthogonal directions: X and Y parallel to bedding and Z at right angle.*

considering loading/unloading stress paths, with lower conductivities in the unloading branch. Hysteresis is higher in the Y and Z directions. This behavior can be explained by the irreversible compaction of the samples.

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