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Gas shales testing in controlled partially saturated conditions

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ABSTRACT

This paper provides quantitative experimental data that demonstrate the impact of changing partial water saturation on the static elastic and strength (UCS) properties of gas shales from two different unconventional plays. To achieve this goal, a testing set-up and experimental methodology based on the control of total suction were specifically developed. Two core samples from different unconventional shale gas reservoirs were tested. The obtained results clearly show a significant dependence of the Young's modulus on total suction, where a non-linear decrease of stiffness higher than 50% can be observed when suction is reduced during a wetting process. On the other hand, the Poisson's ratio is not highly influenced by different saturation states; it can be considered constant for suction values greater than 10 MPa. A significant impact on the uniaxial compressive strength was also observed, where a 20% decrease of this strength parameter was measured when gas shales are conditioned to lower suction value. To include the observed behavior of gas shales in elastic constitutive model, an empirical relationship to express the dependence of Young's modulus on suction is proposed. Besides a better understanding of the behavior of gas shales during the drilling procedures and hydraulic fracturing phase, the findings of this study are also of great relevance to understand the impact that exposure of core samples to non-controlled air humidity may have on the results of laboratory tests.

1. Introduction

Geomechanical properties of gas shales (such as stiffness and strength) play a fundamental role for an optimised exploitation of shale gas reservoirs: in wellbore design, they are needed for a proper evaluation of the required mud weight and to anticipate the occurrence of instability or breakouts[1–3]; in hydraulic stimulation, they are needed to evaluate the shale brittleness and to estimate the horizontal stresses, in order to predict fractures network and propagation and to design the stimulation treatment.[4–7]

In spite of their relevant importance, the reliable measurement of these properties for gas shales still represents a major challenge due to the complex features of these geomaterials such as heterogeneity, anisotropy, low porosity, low permeability, high stiffness, reactivity to pore fluid composition and sensitivity to changes in water content. With regard to the last aspect, it is worth to recall that gas shales are partially water-saturated in their native state as they host natural gas trapped in their pore space. In-situ changes in water saturation may be caused by the contact with drilling and fracturing fluids, and by the gas extraction process. When gas shales are analysed in the laboratory, further water saturation variations can result from core extraction, handling and specimen preparation for testing.

The water saturation is expected to have a significant impact on the geomechanical properties of gas shales as their mineralogical composition presents large clay content (10–60%). Indeed, there is already significant evidence on the role of water saturation for other clayey geomaterials such as mudstones, claystones, and organic-poor shales. Swelling and shrinkage response to wetting and drying processes respectively are typically observed; examples are found in[8–10] for shales, and in[11–15] for mudstones and claystones. Moreover, stiffness and strength properties of these geomaterials are also found to be affected by partially saturated conditions[16]; generally, an increase of these properties is highlighted as the water saturation decreases.[17–23]

Despite these expected impacts, the role of partial water saturation is not properly considered in the geomechanical characterization of gas shales. Indeed, laboratory tests carried out to investigate elastic and strength properties of organic-rich shales are usually performed without considering the water saturation state of the material; specimens are indeed tested either in the as-received state[24,25] or after resaturation,[26–28] ignoring the water saturation state of the material in its natural state and the effect of its variation on the measured mechanical properties that might occur due to air exposure of the material, core handling, and specimen preparation.

This study demonstrates how the geomechanical properties of gas

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shale cannot be properly evaluated without accounting for the effect of the water saturation. A testing set-up specifically developed to perform geomechanical tests on gas shale specimens is presented; the apparatus allows for the control of the water saturation of the tested specimens through the imposition of the pore water potential. Experiments on two different gas shale core samples are reported where the strength and the stiffness of the geomaterials are evaluated as function of the pore water potential.

2. Evidence of the impact of partial saturation

The impact of partial saturation on the mechanical response of gas shales can be easily demonstrated as shown in this section, where a first series of simple uniaxial compression tests is presented. Two cylindrical specimens (with a diameter of 20 mm and height of 40 mm) were obtained from the same gas shale core sample extracted at a depth of about 2100–2200 m from the Northeast U.S. shale formation. The shale had a rich organic content (4.4%), clay content of 20%, specific gravity of 2.57, as-retrieved water content (ratio of the weight of water to the weight of solid) of 0.72%, and presented a dominant pore diameter of 7 nm detected by mercury intrusion porosimetry (MIP).

To achieve different water saturation states, the two specimens were equalized to different relative humidity values (RH = 34% and RH = 92%) in two sealed glass desiccators; during the process their mass was regularly recorded for the back-calculation of the water content. For this evaluation, the dry masses of the specimens were obtained at the end of the test by oven-drying at 110 °C. After the preparation, water contents of the specimens were 0.46% and 0.48%. The difference with the water content of the core sample (0.72%) quantifies the desaturation process occurred during the preparation of the specimens.

Fig. 1 shows the evolution of the water content of the specimens during the equalization process in the desiccators. The specimen conditioned to a relative humidity of 92% experienced a wetting process (increase of water content), while the specimen equalized to a relative humidity of 33% was subjected to a drying process (decrease of water content). The equalization to the imposed values of relative humidity was significantly long; more than 40 days were required to achieve an acceptable stabilization of the mass evolution. A criterion based on the mass variation rate was defined to consider the equalization achieved; when the final mass variation rate (slope β_f of the curves) was lower than 5% of the initial mass variation rate (slope β_0 of the curves), the specimens were considered equalized to the imposed relative humidity values.

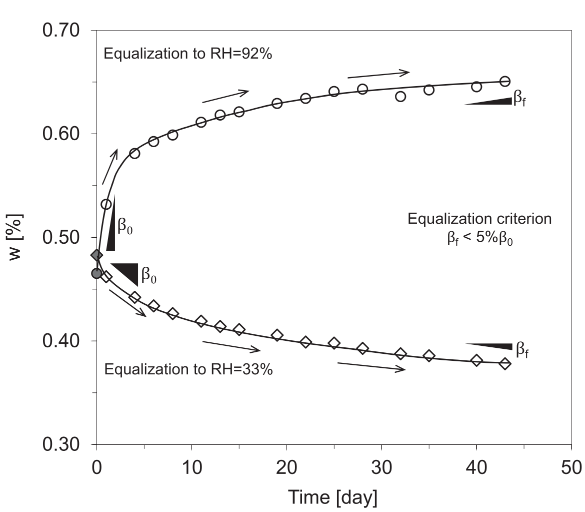

Fig. 1. Water content evolution in time of the tested specimens during the equalization to relative humidity values of 92% and 33%.

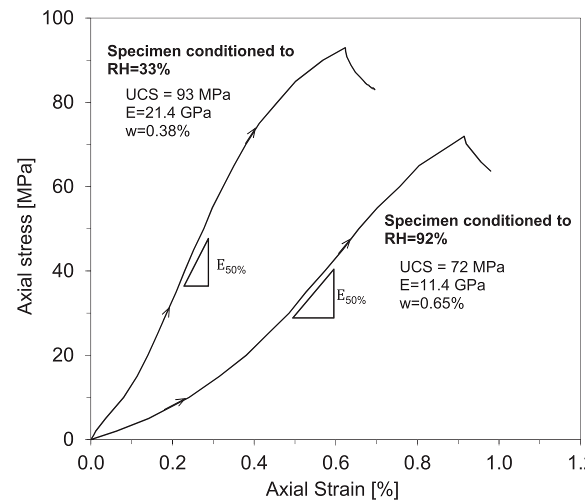

Fig. 2. Stress – strain curves for the two uniaxial compressive tests performed on Northeast U.S. gas shale specimens equalized to two different values of relative humidity.

Uniaxial compressive tests were performed on the two conditioned specimens. Axial stress was increased with a displacement rate of 1 μm/min up to the failure of the specimens. Axial strain was obtained from the measurement of the axial displacement with two external LVDTs.

Results of the two uniaxial compression tests are reported in Fig. 2 in terms of axial stress (σ_a) versus axial strain (ε_a), along with the different water contents of the specimens and the measured mechanical properties (uniaxial compressive strength, UCS, and Young's modulus, E). Final values of water content were 0.65% and 0.38% for the two specimens equalized to RH equal to 92% and 33%, respectively. The effect of the different water saturation states on the material response is clearly highlighted. Lower water content leads to higher strength and stiffness. Considering the UCS, the specimen equalized to relative humidity RH=92% showed a lower value (72 MPa) than the sample equalized to RH=33% (93 MPa). Moreover, the value of axial strain corresponding to failure condition is higher for the specimen with higher water content which indicates a softer response. This aspect is strictly related to the elastic stiffness of the material. Tangent Young's modulus (E) is calculated as $E=\Delta\sigma_a/\Delta\varepsilon_a$ at an axial stress equal to 50% of the UCS, where the stress-strain curve exhibits a linear trend. The specimen equalized to RH=92% is less stiff than the specimen equalized to RH = 33%, with a Young's modulus (11.4 GPa) almost half of the modulus of the specimen with lower water content (21.4 GPa).

3. Experimental methods

3.1. Challenges for gas shale testing in controlled suction conditions

The experiments discussed in the previous section show the importance of considering the water saturation state when testing gas shales. Testing soils in controlled partially saturated conditions is a well-established practice in soil mechanics. In this context, a good understanding of the water retention mechanisms (e.g. capillarity, adsorption) is of primary importance and the key role of suction has to be considered. Suction expresses the chemical potential of the pore fluid and its relation with the amount of fluid stored in the material (i.e. water content or degree of saturation, the last expresses the ratio of the water volume to the void volume) is given by the water retention curve. Different components of suction have to be considered when testing geomaterials in partially saturated conditions. Matric suction (s) considers the effects related to the presence of the solid matrix and it includes capillarity, osmotic (clay-related) mechanism, and electrostatic mechanism; osmotic or solute suction (π) accounts for the solute