Elastic behavior of partially saturated gas shales during unloading-reloading cycles in uniaxial compression

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ABSTRACT: Elastic properties of gas shales are of utmost importance for the exploitation of shale gas reservoirs. Static elastic properties are usually measured by performing unloading-reloading cycles in uniaxial or triaxial compressive tests. The response of gas shales typically observed during a stress cycle is characterized by nonlinearity and hysteresis due to the presence of cracks and their sliding during the stress change. However, this response is significantly affected when gas shales are tested in partially saturated conditions. The presented work shows evidence of this aspect obtained through a uniaxial compressive test performed on a gas shale with control of total suction to impose different water saturation conditions. Several stress cycles carried out at different total suction values were performed to analyze the elastic response of the material. A decrease of nonlinearity during unloading and opening of the loop was observed when stress cycles are performed after a wetting process. The reason for feature is attributed to sliding of cracks, which is influenced by the response of the material during the total suction variations applied to the tested material before performing the stress cycles. A misleading evaluation of the elastic properties might occur if these mechanisms are not properly considered.

1 INTRODUCTION

The static elastic properties of gas shales are usually measured in uniaxial and triaxial compression tests from either the linear part of stress-strain curves during compression before the specimen's failure or by performing unloading-reloading cycles in a stress interval below the strength of the material. The response typically exhibited by rocks during an unloading-reloading cycle is nonlinear with hysteresis. The non-linearity is caused by the presence of microcracks or crack-like voids in the material which can significantly affect the measured stiffness. Indeed, closed microcracks may experience sliding under a deviatoric loading if the acting shear stress on the crack's faces is higher than the corresponding shear strength of the crack. Hence, during an unloading-reloading cycle, cracks' sliding occurs in opposite directions (reverse sliding) causing a stiffer response at the beginning of the mechanical stress variation. A comprehensive explanation of the sliding crack mechanism can be found in Walsh (1965), Lawn and Marshall (1997), David et al. (2012).

The experimental results presented in this study show that an alteration of the hysteretic and nonlinear behavior during unloading-reloading cycles may occur when gas shales are subjected to wetting and drying processes prior to the mechanical stress variation. The application of wetting and drying processes is introduced in order to investigate the material's response considering partially water saturated conditions. The need to test gas shales under such hydraulic conditions is due to the fact that these geomaterials are not fully water saturated in their native state due to the presence of gas and water in the pore space (e.g. Ewy 2015). Moreover, changes in partial saturation occur during the hydraulic stimulation due to the contact with fracturing fluid and during the gas production phase. These variations induce volumetric strains that are responsible for issues related to the proppant embedment after the fracturing stage and the water uptake during flowback operation (Minardi et al. 2018a). In addition, gas shales have extremely small pore size in the order of tens of nanometers; this feature leads to capillary forces on the order of MPas. The presence of capillary forces is then expected to have a significant impact on the mechanical properties of gas shales (Ferrari et al. 2018)

The paper aims at quantifying the effect of the changes in partially saturated conditions through wetting and drying processes on the sliding cracks mechanism of a gas shale during mechanical unloading-reloading cycles. Results from a uniaxial compressive test are presented, where several unloading-reloading cycles were performed at different water saturated conditions of the tested specimen for the assessment of the elastic response.

2 MATERIALS AND METHODS

2.1 *Tested gas shale*

The adopted material for the experimental analysis was extracted from a shale gas reservoir at a depth of about 2700m. As-received conditions of the core were: water content w=1.7%, bulk density ρ_b=2.40 g/cm^3, degree of saturation S_r=61%, porosity between 6% and 7%, and dominant pores size between 5 and 20 nanometres.

2.2 *Experimental methodology*

The testing set-up presented in Minardi et al. (2018b) was adopted to carry out the experimental analysis. The apparatus (Figure 1) was developed from the high-pressure oedometric cell presented in Favero et al. (2016), and Ferrari et al. (2016); it allows testing a specimen in uniaxial stress condition at different water saturated conditions. To change the water saturation state of the specimen and analyse the material's response in partially saturated conditions, a methodology based on the control of total suction (Ψ), namely the vapour equilibrium technique, was adopted. This methodology allows controlling the relative humidity in a closed environment by using saline solutions (Delage et al., 2008). The psychrometric law can be used to convert relative humidity to total suction. Total suction represents the chemical potential of the pore fluid.

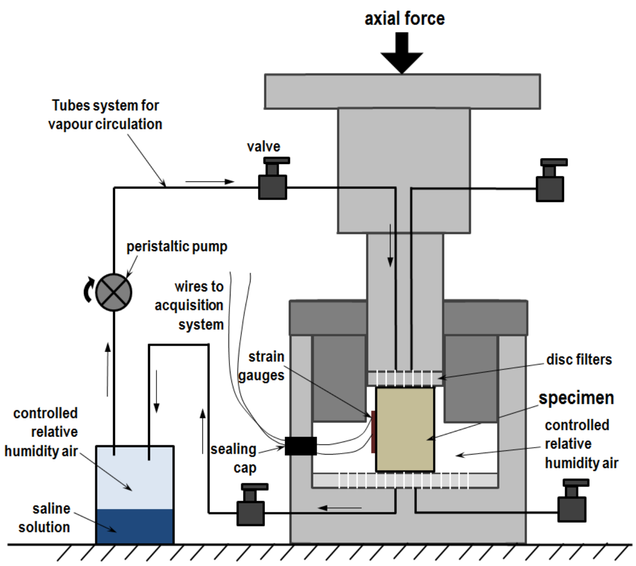

Figure 1: Uniaxial testing set-up adopted to perform the experimental tests (Minardi et al. 2018a).

As represented in the Figure 1, the vapour equilibrium technique was implemented in the adopted uniaxial testing set-up by connecting the apparatus to a glass container filled with a given saline solution. A peristaltic pump is used to force the vapour circulation between the container and the specimen. By using different saline solutions, it is possible to change the total suction in the system and apply wetting and drying processes to the tested specimen.

The set-up allows for the control of the axial stress (σ_a) up to 100 MPa and total suction (Ψ) in the range between 4 MPa and 300 MPa at same time. Hence, total suction variations could be applied at constant axial stress in order to perform several unloading-reloading cycles at different total suction on the same specimen. The following salts were used for the preparation of the saturated saline solutions: $MgCl_2$ (Ψ=150 MPa), NaCl (Ψ=39 MPa), KNO_3 (Ψ=10 MPa). Strain gauges were used to assess the response of the specimen in both axial and radial directions. Figure 2 summarizes the hydro-mechanical stress path adopted to carry out the test. The specimen was initially loaded to 15 MPa of axial stress and then equalized to 150 MPa of total suction under constant stress. A wetting process performed in two steps (to 39 MPa and 10 MPa of total suction) was then applied with a constant axial stress of 15 MPa; at the end of each step, an unloading-reloading cycle was performed between 15 MPa and 5 MPa of axial stress. Finally, a drying process was imposed, where the specimen was dried to 150 MPa of total suction with an intermediate step to 39 MPa; at the end of the drying to 150 MPa of total suction, a final unloading-reloading cycle was carried out. A total of four unloading-reloading cycles were performed on the specimen.

The tested specimen, with a diameter of 20 mm and height of 30 mm, was prepared with the bedding orientation perpendicular to the applied axial load.

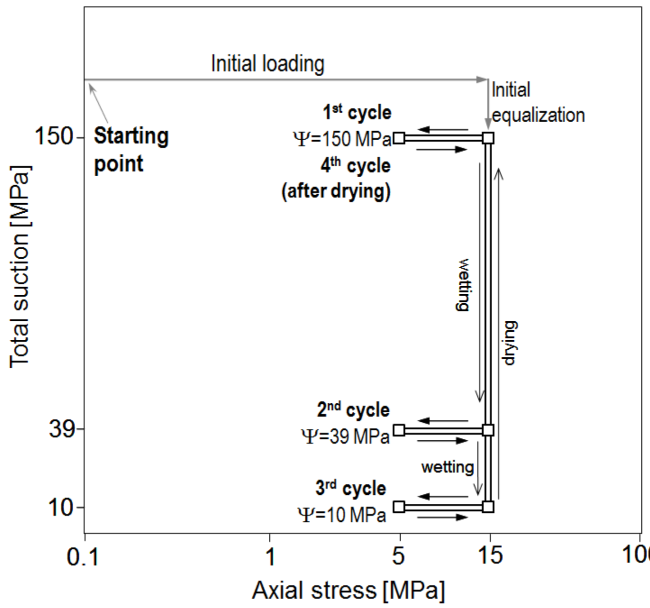

Figure 2: Total suction and axial stress variations applied during the performed test.

3 RESULTS

Figure 3 shows an overview of the specimen response during the mechanical and hydraulic loadings. As typical of clay geomaterials (e.g. Airò Farulla et al., 2010; Ferrari et al. 2014; Minardi et al. 2016), swelling response is observed during the wetting phase (decrease of total suction), and shrinkage response is highlighted during the drying phase (increase of total suction). A more detailed response of the specimen during the total suction variation process is illustrated in the Figure 4; the graph highlights the anisotropic response of the material, where the strain perpendicular to bedding (axial direction) is more pronounced compared to the strain parallel to the bedding (radial direction). This feature is of great importance to analyse the impact of the volumetric strain on the water uptake of gas shales (Minardi et al. 2018a). The graph in Figure 3 shows the dependence of the elastic modulus computed on the unloading phase of the stress cycles on the total suction to which the specimen is conditioned (Ferrari et al. 2018). Moreover, the hysteresis of the performed cycles is significantly affected, where a progressive opening of the loop as cycles are performed at lower values of total suction is exhibited. As previously stated, these features are related to the presence of cracks in the material and their sliding.

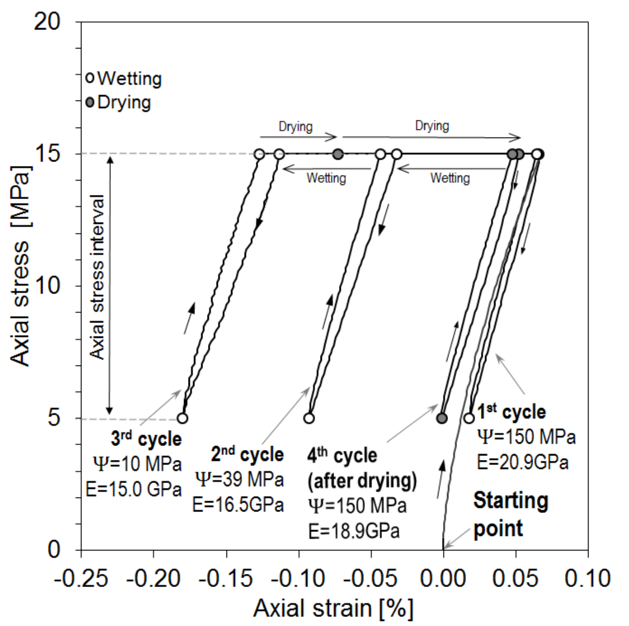

Figure 3: Overview of the specimen response during the test in terms of axial stress-axial strain relationship

Figure 5, Figure 6, Figure 7, and Figure 8 show the specimen's response during the unloading-reloading cycles performed at different values of total suction. As the cycles are carried out at lower values of total suction, a residual axial strain is observed at the end of the reloading phase of the cycle. This residual strain is due to an alteration of the sliding crack mechanism during the unloading phase caused by the wetting process applied prior to the unloading. Indeed, the 1st cycle (Figure 5) shows a significant nonlinear response during both the unloading and reloading phases of the cycle. This nonlinearity is highlighted by the difference between the elastic moduli computed on the initial part (E_0) and final (E^*) part of the unloading and reloading phases that is about 10 GPa. In the unloading phase of the 2nd cycle the difference between the moduli E_{0u} and E^*_u reduces to 1.3 GPa. Similar features can be highlighted for the unloading phase of the 3rd cycle, where the difference between the moduli is 0.6 GPa.

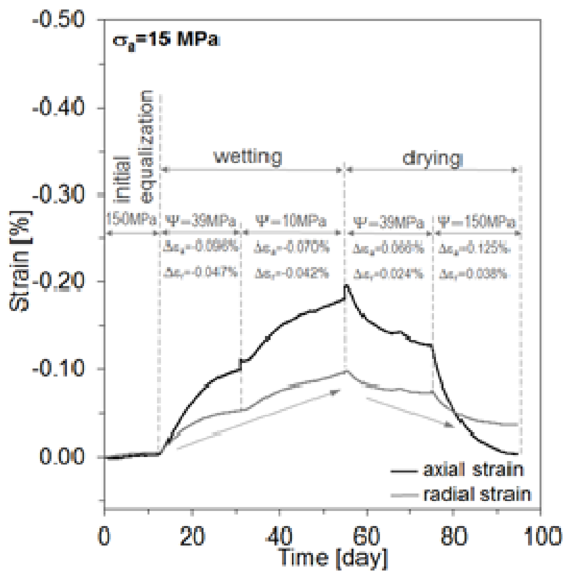

Figure 4: Specimen response in terms of axial and radial strains during the total suction variation process.

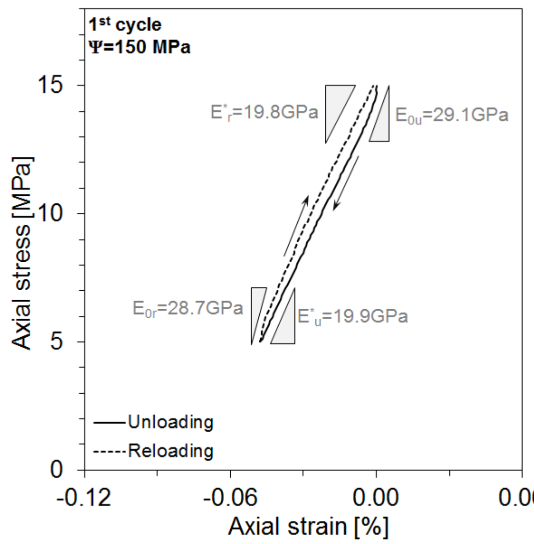

Figure 5: Relationship between axial stress and axial strain during the 1st cycle performed at 150 MPa of total suction.

On the other hand, the response during the reloading phase of the 2nd and 3rd cycles remains nonlinear, with a difference between the moduli E_{0r} and E^*_r of 9.1 GPa and 8.5 GPa respectively. This feature clearly indicates that the applied wetting process (reduction of total suction) has a more pronounced influence on the unloading phase of the stress cycle with respect to the reloading phase. The reason for this feature is attributed to the impact of the swelling response during the wetting process on the sliding crack mechanism that is normally controlling the nonlinearity of the material's response during the unloading phase. Indeed, when the unloading is preformed after a loading phase, reverse sliding of cracks occurs, leading to a stiffer response at the beginning of the unloading. However, in the performed test the unloading phases were always performed after a wetting process, during which the specimen experienced expansion. Moreover, as the wetting processes were always applied after a loading phase, reverse sliding may have occurred during the anisotropic expansion exhibited by the material. Therefore, once the unloading phase started, cracks in the materials were already sliding; this mechanism leads to more linear response of the specimen, and a lower discrepancy between the moduli on the unloading phase. On the other hand, reverse sliding always occurred during the reloading phase of the cycle, irrespective of the applied wetting process.

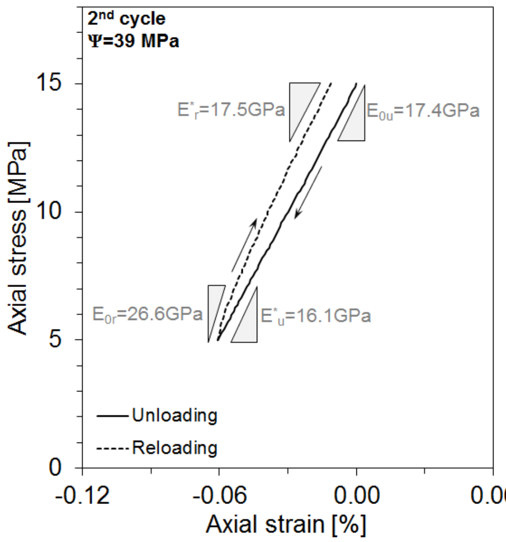

Figure 6: Relationship between axial stress and axial strain during the 2nd cycle performed at 39 MPa of total suction.

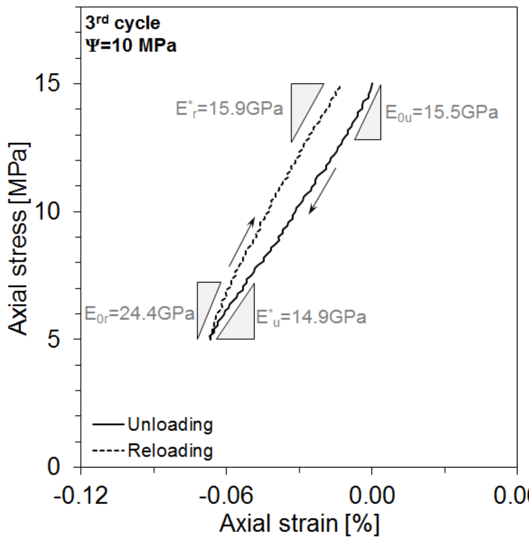

Figure 7: Relationship between axial stress and axial strain during the 3rd cycle performed at 10 MPa of total suction

This explanation is supported by the response of the specimen exhibited in the 4th cycle, which was performed after the drying process to 150 MPa of total suction. Because the drying induced shrinkage of the material, which is similar to loading, reverse sliding occurred at the beginning of the unloading. As a consequence, the nonlinearity of the material response was restored in the 4th cycle with a difference between the moduli E_{0u} and E^*_u which increased to 7.3 GPa.

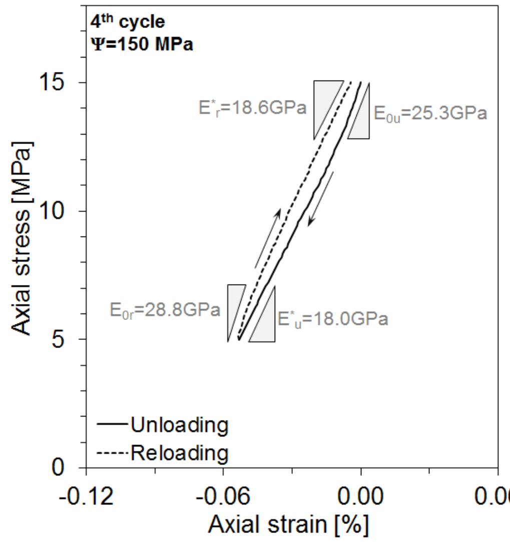

Figure 8: Relationship between axial stress and axial strain during the 4th cycle performed at 150 MPa of total suction

4 CONCLUSIONS

The presented experimental study demonstrated that the nonlinear elastic behavior of the tested gas shale is significantly altered when mechanical unloading-reloading cycles are performed after a wetting or drying processes. In particular, the behavior during the unloading is more affected than the response during the reloading phase. This feature leads to an opening of the loop during the mechanical stress cycles. The obtained experimental evidence demonstrates that the reason for this feature is strictly related to the sliding crack mechanism. Neglecting this aspect may lead to a misleading evaluation of the elastic properties of gas shales.

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