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Investigation of static/dynamic moduli and plastic response of shale specimens

Arash Kamali-Asl[a,*], Ehsan Ghazanfari[a], Ahmadreza Hedayat[b], Louisa Deering[a]

[a] Department of Civil and Environmental Engineering, The University of Vermont, 33 Colchester Ave., Burlington, VT 05404, USA
[b] Dept. of Civil and Env. Eng., Colorado School of Mines, USA

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ABSTRACT

High clay and organic content, irregular voids, presence of micro-cracks, and obvious bedding planes are among features of shale gas rocks that affect their mechanical response. These sedimentary rocks exhibit substantial degree of anisotropy and inhomogeneity, with non-linear response when subjected to axial loading. The laboratory characterization of these rocks is necessary to design an optimized hydraulic fracturing programme, and for reliable constitutive and numerical modeling of these formations. In this study, a series of triaxial multi-stage elastic and cyclic tests were performed on Marcellus Shale specimens, retrieved from a deep well (~2270 m deep) located in West Virginia, to characterize their elastic-plastic and hysteresis response subjected to loading/unloading cycles. The experimental results indicated a nonlinear response, particularly at low differential stress levels. In addition, the specimens with higher clay content exhibited a softer response with lower estimated static and dynamic moduli at different stress levels compared to those of specimens with higher calcite/quartz content. The ultrasonic P- and S-wave velocity measurements were found to be sensitive to the changes in the microstructure of the rock caused by variation in stress condition. In general, the estimated Young's modulus during unloading was found to be higher than loading. The plastic deformations were pronounced in the first cycle of loading, followed by a decreasing trend in the subsequent cycles.

1. Introduction

According to EIA,[1] there are more than 39 billion barrels of proved oil/gas reservoirs, the highest since 1972. Unconventional oil/gas resources such as shale gas and tight oil are significantly contributing to the oil/gas production.[1] Shale gas reservoirs have been exploited with a total technically-recoverable resources of about 660 trillion cubic feet[1] around the globe in countries such as China, United States, Mexico, South Africa, and Australia to name a few.[2,3] In the United States, development of Barnett, Haynesville, Marcellus, and Utica Shale among others has led to increased interest in evaluating properties of shale gas formations.[1]

Shale/clayey rocks, categorized into clastic sedimentary rock,[3] usually contain very fine grains resulting in very low permeability, and therefore, extraction of natural gas from these organic-rich rocks requires creation of fractures in the reservoir via hydraulic fracturing.[4,5] Despite recent advancements in understanding of the mechanics of hydraulic fracturing, the outcome of hydraulic fracturing operation, and also the fracture closure over time are variable and unpredictable in different shale/clayey formations.[3,6–9] This is, in part, due to lack of knowledge about the shale rock properties controlling the fracture initiation, propagation, and closure under reservoir conditions.[7,10,11] In order to optimize the required energy for hydraulic fracturing operation and production in shale gas reservoirs, it is important to evaluate both elastic-plastic and visco-elastic-plastic behavior of these rocks.[12–15]

Shale/clayey rocks are typically recognized by their extremely low porosity and permeability,[16–18] with a wide range of mineralogy and Total Organic Content (TOC), and are highly heterogeneous and anisotropic.[7,11,19] These characteristics significantly affect the outcome of hydraulic fracturing during stimulation stage and fracture closure during production stage in a shale gas reservoir.[20] For example, during hydraulic fracturing, shale/clayey formations with higher clay content, exhibit a more ductile behavior, and therefore tend to deform instead of shattering.[3,21]

The presence of clay/organic matters in shale/clayey formations results in significant visco-elastic deformations, which in turn, affect both short- and long-term deformation of these formations.[5,8,21–23] Time-dependent (i.e. visco-elastic) deformations might lead to change

* Corresponding author.
E-mail addresses: akamalia@uvm.edu (A. Kamali-Asl), Ehsan.Ghazanfari@uvm.edu (E. Ghazanfari), Hedayat@mines.edu (A. Hedayat), ldeering@uvm.edu (L. Deering).

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in the state of the stress, elastic and failure characteristics, and permeability of shale/clayey rocks.[9,17,24] Liu et al.[15] studied the effects of mineralogical composition, relative humidity, confining pressure, and structural anisotropy on creep response of resaturated and desaturated Cox claystone specimens and reported that active clay minerals significantly influence the creep strains. Liu et al.[18] found that structural anisotropy significantly influences the creep response of Cox argillite specimens, with increased strength due to visco-elastic-plastic deformations. Burgers' and Power-Law models have shown to be able to reasonably capture the long-term creep response of shale rocks.[8,22,24]

Laboratory characterization of shale rock specimens typically includes non-destructive and destructive petrophysical and geomechanical testing.[25,26] Elastic moduli (including Young's and shear moduli and Poisson's ratio), strength properties (i.e. cohesion, coefficient of internal friction, and unconfined compressive strength), hysteresis behavior (i.e. plastic deformation), and creep response are important to be addressed for geomechanical characterization of these shale formations.[7,8,11,19,22] Typically, these characteristics can be determined in laboratory by performing triaxial experiments in drained/undrained conditions, and by measurements of ultrasonic wave velocities at different stress conditions.[7,11,22] Both geomechanical and petrophysical properties are important for the optimized design of hydraulic fracturing stimulation programme, and improved accuracy of production models.

Shale rocks are reported to be highly-nonlinear material[7,11,19,22] with presence of micro-cracks, that affect their elastic properties, particularly at lower confining levels of up to ~10 MPa.[14,16,26] Moreover, fabric anisotropy and composition are reported to have a substantial influence on elastic moduli,[7,26–28] resulting in higher degree of pressure-depedency of stiffness compared to other rocks.[11,22] Furthermore, shale rocks exhibit significant variations in the measured static moduli during loading/unloading/reloading.[7,11] In addition, irrecoverable deformations make it difficult to interpret the static moduli as elastic properties.[14,22]

In shale reservoirs, due to creep deformation, the created fractures gradually close under in-situ stresses.[17,18] In order to maintain continued reservoir production, it is necessary to re-stimulate the reservoir. The response of shale rocks subjected to cyclic loading is more complex compared to other rocks due to their inherent fabric complexity. These rocks show a brittle, nonlinear, and highly-anisotropic plastic response as well as initiation of micro-cracks under successive loading/unloading cycles, which affect their stiffness and strength properties.[19,29,30] The permanent plastic deformations and degradation of elastic moduli due to fatigue of shale formations play a significant role in design and operation of re-stimulation process.[31]

Ultrasonic wave propagation is often used to estimate the elastic properties of the rocks, referred to as dynamic moduli. Typically, the estimated dynamic moduli are higher than the corresponding static ones.[32,33] The propagation of ultrasonic waves in rocks depends on volume, geometry, and distribution of pores and fractures.[34–38] In a triaxial test, usually during isotropic compression (hydrostatic stage), the ultrasonic velocities increase, however, during triaxial stage, the ultrasonic velocities show an increasing/decreasing trend.[27,39,40]

In general, shale rocks exhibit irregular intergranular spaces as void,[41] and high compressibility due to high clay content.[24] During hydrostatic and triaxial stages, shear and compressional wave velocities can be affected by closure of existing micro-cracks, potential porosity reduction, and creation of new micro-cracks.[42–45] For low porosity shale specimens, typically by increasing the mean stress, the P- and S-wave velocities monotonically increase during hydrostatic stage followed by subsequent decrease during triaxial stages.[40] It is worth noting that ultrasonic wave velocities are significantly affected by: (i) the type of pore fluid,[33] (ii) the level of saturation,[46,47] and (iii) the orientation of bedding planes with respect to applied differential stress.[25,48] It should be mentioned that in shales, existing/created fractures impact the transmitted waves by: (i) filtering high frequency content of the wave, and (ii) attenuating the signal.[49]

Although several studies are available on geomechanical characterization of different shale formations,[7,8,19,30] very limited studies are available on Marcellus Shale.[11,22,50] Given that Marcellus Shale is the largest shale formation in the United States, and there is an increasing demand for fundamental rock properties of this formation, this study focused on characterization of Marcellus Shale specimens retrieved from a deep well. This study reports the results from a set of multi-stage elastic and cyclic experiments on Marcellus Shale specimens, in attempt to characterize the elastic-plastic properties of the specimens. The time-dependent and strength properties of the shale specimens were investigated by performing creep and multi-stage failure tests on the specimens, and the results are reported in a companion manuscript by the authors.

Section 2 provides the information about the rock specimens used in this study, Section 3 discusses the experimental methodology, Section 4 presents the results followed by analysis and discussion in Section 5. Finally, the conclusions of this study are provided in Section 6.

2. Materials

The shale plugs (4 in. in diameter) were provided by West Virginia Geological and Economic Survey. As part of the Department of Energy Eastern shale gas program, one of the cored wells (EGSP West Virginia well #6) focused on Marcellus shale in Monongalia county, located in Morgantown, West Virginia (Fig. 1(a)). The cores had abundant disc fractures[51] and were stored at room temperature and ambient humidity conditions. The cores were oriented perpendicular to the bedding (Figs. 1(b) and 1(c)). Although it was desired to retrieve several 1.5-in. diameter sub-cores (both perpendicular and parallel to the bedding for anisotropy characterization) with aspect ratio close to 2, and despite the precautionary measures taken to avoid breaking the plugs while coring them, due to the brittle nature of the plugs, it was only possible to retrieve four sub-cores.

The specimens were drilled in the vertical direction, perpendicular to bedding planes as it can be seen from Fig. 1(c) and (d). Table 1 summarizes the information about the depth, dimensions of the retrieved specimens, and X-Ray Diffraction (XRD) analysis. Figs. 1(e) and (f) show the Scaning Electron Microscopy (SEM) images, indicating presence of different features such as micro-cracks sub-parallel to bedding, voids and inclusions. As it can be seen from Table 1, R1 and R2 specimeens are rich in calcite/quartz, whereas, R3 and R4 specimens are rich in clay. The TOC was determined as 2.7% using sample combustion method.[52] Using the comparison between average grain density and the bulk density of the specimen,[53] the porosity of the specimens were estimated as 6%. Due to brittle nature of these shale specimens, and the lack of information about the chemical composition of in-situ pore fluid, no attempt was made to re-hydrate the specimens at different saturation levels.

3. Experimental methodology

3.1. Specimen preparation

ASTM D4543 Standard[54] was followed for preparation of rock core specimens. The two ends of the specimens were lapped to 0.001 in./inch to avoid local bending and non-uniform loading, particularly during triaxial stage. Copper jacket was wrapped around the specimen, and the two overlapping ends were soldered and smoothened (Fig. 2(a)) to prevent the leakage of the confining fluid into the jacket and consequently into the specimen during triaxial testing. The wrapped copper jacket also facilitated attachment of the strain gauges (Fig. 2(b)). Then, the Vitton jackets were attached to the two ends of the copper-jacketed specimen. Moreover, as an additional layer of protection against leakage of the confining oil into the specimen, epoxy was also added on the seam of the copper jacket.