Strength, creep and frictional properties of gas shale reservoir rocks

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ABSTRACT: The deformational properties of gas shale reservoir rocks from the Barnett and Haynesville shale formations were investigated using a triaxial apparatus. The samples tested varied in their mineralogical composition, the degree of diagenesis, the total organic content and the degree of maturity of the organic material. In general, rocks with more cement and less clay show higher elastic moduli, higher intact strength and higher frictional strength. In addition, the amount of time-dependent creep under constant triaxial load correlates strongly with the Young’s modulus and clay content in the samples, but does not show any correlation with the Poisson’s ratio. Viscoplastic creep in these rocks will impose challenges in effectively stimulating production by slick-water hydraulic fracturing by raising the frac gradient and reducing the amount of induced brittle deformation.

1. INTRODUCTION

Recent technological advances in exploiting unconventional tight gas reservoirs have been facilitated by the combination of horizontal drilling and multi-stage reservoir stimulation by slick-water fracturing. A better understanding of this process is needed to predict how these reservoirs respond to stimulation which is essential in designing optimal stimulation strategies.

Experiences from the Barnett shale indicate that injection pressures required to carry out the slick-water frac operations vary along the horizontal section of the well and there are often variations of the effectiveness of stimulation and the extent to which microseismic events are distributed within the reservoir [1]. In fact, operators sometimes encounter certain intervals that require injections pressures above the capability of their equipment, forcing them to back away from the interval [2, 3]. Some injections create microseismic events concentrated along a plane as in conventional hydraulic injections, while others seem to stimulate a broad region in the reservoir [3]. Comparison with logs has suggested that the reservoir behavior during injections tend to correlate with various petrophysical and geophysical parameters.

These observations have generally lead to empirical approaches of identifying “brittle” intervals along a well which are expected to be more prone to fracturing. For example, one quantifies a parameter “brittleness” computed from the Young’s modulus and Poisson’s ratio obtained through sonic logs which could help identify intervals along the well that are easier to stimulate [4]. However, these empirical approaches still demand verifications through laboratory testing. Other factors that should affect the outcomes of fluid injection operations include the state of stress along the well. Successful stimulation of gas shale reservoir production should involve both the characterization of the rock itself and the geomechanical setting of the reservoir.

We conducted laboratory experiment in an attempt to obtain rock mechanical data relevant to understanding the mechanical response of gas shale reservoir rocks against fluid injection. Samples come from Barnett shale, TX and Haynesville, LA. We focused on obtaining the intact and frictional strengths to understand how deformational properties may vary between samples. Creep deformation is also investigated in order to characterize the ductility of the samples, since it will not only affect the deformational response of the rock, but also because ductile deformation can alter the state of stress. Finally, inference is made on how the elastic properties and material composition correlate with the deformational properties of the rock.

2. EXPERIMENT DESCRIPTION

2.1. Sample Description

Samples used in the experiments come from two different gas shale reservoirs: the Barnett shale and the Haynesville shale. Samples for Barnett shale come from
various depths of about 2600 m and we categorize them into 2 groups according to their visual appearance as “light” and “dark” colored groups which are thought to reflect their carbonate and clay content based on log elemental analyses. Haynesville samples come from depths of about 3500, and the mineralogical contents are known from XRD analyses of nearby samples (Table 1). Although visual appearances of Haynesville samples do not vary significantly as in Barnett samples, we call samples with more carbonate content as the “light” group and the other as “dark” group to match the description of the Barnett samples.

Samples were kept under room humidity condition prior to the test and experiments were performed under dry and drained condition. Due to the dry condition of the samples, we were able to eliminate poro-elastic effects so our data represents the mechanical behavior of the dry framework. All samples were shaped to 25.4 mm (1 inch) diameter. For all Haynesville samples, sample lengths were 50.4 mm (2 inch) and the axes of the cylindrical samples were perpendicular to the bedding plane. Lengths of Barnett samples varied between 38-56 mm (1.5-2.2 inch) except for one short sample (28 mm, 1.1 inch) whose rock strength data was neglected from the analyses. Barnett samples included those cored parallel and perpendicular to the bedding plane.

2.2. Experimental Procedures
Cylindrical samples were tested for its mechanical properties in a triaxial apparatus (Autolab2000, New England Research Inc.) under hydrostatic and triaxial loading conditions. Axial and radial deformations were measured by two pairs of individual sensors, and the confining pressure and differential load on the sample were monitored by a pressure gauge and an internal load cell, respectively, during the experiments.

A typical experiment is performed in 3 stages, hydrostatic, triaxial, and failure & friction, as shown in Figure 1. In the hydrostatic stage, samples were subject to 3 steps of isotropic pressures, after which the pressure was held constant for 3 hours to observe any possible hydrostatic creep deformation. After each 3 hour holds, the pressure was decreased and increased over several minutes before proceeding to the next pressure step, in order to measure the elastic bulk modulus of the sample.

In the triaxial stage, the axial differential load was increased in two steps while holding confining pressure constant at 20, 30, or 60 MPa. Differential load was increased in 2 steps, after which the load was held constant again to observe creep deformation and unloaded to measure the Young’s modulus and Poisson’s ratio. The size of the differential loads was chosen to reach about 50% of the rock strength after 2 load steps.

Finally in the failure and friction stage, the sample was taken to failure while the differential load was servo-controlled to produce constant axial strain rates of about $10^{-5}$ s⁻¹. After rock failure was observed, the sample was allowed to slide along the failure plane until a steady frictional strength was observed. After the experiment, the angle of the failure plane was measured relative to the sample axis to obtain the shear and normal stresses resolved on the failure plane. The experimental condition for each sample is summarized in Table 1.
3. LABORATORY RESULTS

3.1. Elastic Properties

Figure 2 displays the measured Young’s modulus and Poisson’s ratio of the samples tested during the first triaxial load step. In both Barnett and Haynesville samples, the light groups were observed to be stiffer than the dark groups, which may be caused by the abundant cement contents in the light samples. Also Barnett samples are generally stiffer than Haynesville samples. Poisson’s ratio may tend to increase with increasing Young’s modulus but the trend is not clear. The accuracy of these measurements is confirmed by comparing the bulk modulus calculated by using Young’s modulus and Poisson’s ratio, and the bulk modulus obtained from the hydrostatic stage. The differences between the two estimates of bulk moduli were distributed within 2.5 GPa standard deviation.

3.2. Ductile Properties

Ductility of the sample was studied by observing the creep strain during constant differential load. Samples first show instantaneous shortening in response to a step of differential load, and then show creep strain over time. Figure 3 shows the time-dependent creep strain portion of 4 samples during the first of two triaxial load steps. Creep strain is generally observed to be greater for the dark sample groups and also for Haynesville samples.

Comparison of creep strain between the first and second differential load steps does not show a consistent trend (Table 1). Barnett dark and Haynesville light samples creep about twice as much in the second load step compared to the first load step. However others including Haynesville dark sample crept almost the same amount in the first and second load step. In terms of confining pressure dependency, creep tests conducted on same sample groups under different confining pressure (Table 1) did not show clear difference in creep behavior.

3.3. Strength and Friction

The peak axial stress observed in the failure stage of the experiment represents the strength of the samples and the frictional coefficient was calculated by the ratio of the shear and normal stress resolved on the failure plane after the fault was formed. Strengths and friction data generally followed the same trend as the elastic modulus, where the strength of both the Barnett and Haynesville samples decrease markedly with increase in clay content (Table 1). Friction data is plotted against Young’s modulus in Figure 4. There is a clear positive correlation between the coefficient of friction and the Young’s modulus and an inverse correlation with clay content (Figure 5). Estimates of UCS (unconfined compressive strength) based on few strength data at different confining pressure are also shown in Table 1. They seem to follow similar trends as frictional coefficients, but more tests are needed to confirm the UCS.
4. DISCUSSION

Our laboratory results reflect the variety of mechanical and deformational properties gas shale reservoir rocks exhibit within a reservoir, as well as between different reservoirs. Thus, it is essential to identify key parameters that correlate with and control the deformational characteristics of these rocks. Laboratory data suggests that Young’s modulus is a good proxy to evaluate the relative differences in friction and ductility between gas shale rocks. Data in Figure 4 show a near monotonic correlation amongst these parameters. On the other hand, Poisson’s ratio does not seem to be a good proxy for ductility nor strength (Figure 6).

There are various parameters that could control the strengths, friction and ductility of a rock, such as porosity, texture, cementation, mineralogy, etc. Comparison with the mineral contents shown in Table 1 gives us some insight. The similarity of properties observed between Barnett dark and Haynesville light samples suggests that clay content may be one of the controlling factors. It is seen that Barnett dark and Haynesville light samples have similar clay contents while quartz and carbonate content differs significantly. Together with the fact that the clay-rich Haynesville dark samples exhibit low-strength/high-ductility and clay-poor Barnett light samples exhibit high-strength/low-ductility, these results suggest that clay content is the strongest control on various deformational properties amongst other parameters. Figure 6 shows that creep strain and frictional coefficient correlates well with the clay content. The idea is also supported by the fact that clay minerals have anomalously low frictional coefficients and mixing of clays reduces the friction of geological materials [5].

Quantitative characterization of the ductile behavior of gas shale reservoir rocks is important for the successful exploitation of the resource. Ductility not only influences the proneness of reservoir rocks to hydraulic fracturing, but also affects the long-term reservoir response during depletion. Over geologic time scales, ductile deformation could also alter the state of stress as
commonly observed around salt domes. Past studies of creep behavior of reservoir materials have suggested various formulations for the constitutive law describing time dependent creep deformation [6, 7, 8, 9]. Amongst which, a power law function of pressure and/or time is known to explain creep of geological materials well. However, our data so far suggests that creep strain is linearly proportional to the logarithm of time, which tentatively suggests a logarithmic formulation to describe creep deformation. The pressure dependence of creep strain is so far unclear and needs to be understood in order to constrain the constitutive relation of these rocks. Further studies with emphasis on the comparison with detail mineralogy are needed for a comprehensive understanding.

5. SUMMARY

- Laboratory results show that the mechanical and deformational properties of gas shale reservoir rocks are variable.

- Young’s modulus correlates well with the amount of viscoplastic creep and frictional strength of gas shale reservoir rocks. It appears to be a much better proxy for these properties than Poisson’s ratio.

- The coefficient of friction and the amount of viscoplastic creep in the Barnett and Haynesville shales vary strongly with clay content.

- For both the Barnett and Haynesville samples investigated, variations of compressive strength appear to correlate with clay content.

REFERENCES


