Experimental study the viscoelastic properties of deep shale gas reservoirs in Sichuan Basin

Lichun Jia¹, Gui Tang¹, Dianchen Liu¹, Xin Shi²
1.CCDC Drilling & Production Technology Research Institute
No.88 Zhongshan Road, Guanghan, Sichuan Province, China
2.CCDC Geological Exploration & Development Research Institute
No. 83, Section 1, Jianshe North Road, Chengdu, Sichuan Province, China

jialcsc@cnpc.com.cn

Abstract: In recent years, the deep shale gas reservoirs has been a major shale gas target in Sichuan Basin. Usually, the burial depth of this target formation is more than 3500m, which is receiving increasing interests to get industrial natural gas. The deep shale gas reservoirs, characterized by fine-grained nature and low matrix permeability as the common shale, require good understanding of geomechanical properties to optimize drilling and fracturing strategies. Meanwhile, the shale reservoirs are anisotropic and inhomogeneous, exhibiting a nonlinear feature under stress loading. However, very limited studies are devoted to characterization of the mechanical properties of deep shale, as opposed to other shale formations. Due to an increasing demand for fundamental properties of this formation to meet the needs of development of this deep shale gas, a comprehensive characterization studies is needed. One of the most important investigation is to obtain the mechanical properties based on an integration of unconfined/triaxial compression tests and creep tests. In this study, the time-dependent, elastic, hysteresis, and strength properties of deep shale specimens, retrieved from a deep well in Sichuan Basin, are evaluating by performing a series of triaxial creep experiments. With respect to mineral composition, the shale cores are found to be organic-rich. The response of these shale specimens are found to be influenced by the planes of weakness and the presence of micro-cracks. The results of creep experiments show that shale tends to significantly creep under the applied stress. The time-dependent axial strain increase linearly with differential stress. And the Power-Law creep model can be used to describe the time-dependent behaviour of shale well. Moreover, the existence of bedding planes results in the creep anisotropy of shale. It is observed that the overall time-dependent axial strain normal to bedding is higher than the parallel to bedding. But the axial strain at 45° angle with respect to the bedding plane is highest. These research results are of great significance for safe and fast drilling in deep shale gas reservoirs. Also, it can be used to guide hydraulic fracturing.

1. Introduction
The deep Longmaxi formation has been the main unconventional shale plays in Sichuan Basin at the present time [1-2]. The typical deep shale reservoirs, burial depth more than 3500m, are in Zigong, Luzhou area [3]. Past experiences show that having a good knowledge of the mechanical properties of shale is very important in the placement and design of horizontal wells and hydraulic fracturing [4-5]. Usually, shale is a typical elastic and brittle sedimentary rock [6]. On the other hand, due to the clay and organic matter contents, shale also shows time-dependent inelastic properties [7]. The time-dependent behavior of shale could induce wellbore instability problems, such as borehole shrinkage, pipe-sticking and casing collapse and also cause the fractures closure during the shale gas production period [7]. The above problems indicate that it's important to investigate the time-dependent response of shale reservoir.

Generally, the creep properties of rock is investigated by the uniaxial and triaxial creep experiments using core samples [7]. For creep properties of shale, numerous experimental and theoretical studies have been performed by many researchers [8-21]. Li and Ghassemi (2012) showed that the relationship between creep strain magnitude and time can be analyzed by using a power-law function and the creep behavior of the Barnett, Haynesville, and Marcellus shale is dependent on the shale composition [10]. Sone et al (2014) conducted a series of laboratory triaxial creep experiments to study the time-dependent deformation of shale. The results shown that time-dependent behavior can be modeled by a power-law function and the creep strain is approximately linear with the magnitude of the applied differential stress and nearly insensitive to the confining pressure [11]. Rassouli et al (2014, 2015 and 2018) compared the short-term and the long-term creep experiments on clay- and carbonate-rich shale samples and found that a simple power-law model is capable of describing creep over multiple time periods [12-14]. Kamali-Asl et al (2018) investigated the elastic, viscoelastic, and strength properties of Marcellus shale and power-law and Burgers models were used to capture the creep response [15]. Liang et al (2019) used a revised power-law model to account for temperature effect on creep behavior of shale [16].

In addition, the shale also exhibits significant mechanical anisotropy due to the organized distribution of clay minerals, compliant organic materials and lamination caused by orientations. This certainly induces anisotropic creep behavior and creep of vertical to bedding is more than creep in parallel to bedding [7, 17-21]. Khosravi (2017) observed that the sample parallel to the bedding exhibits higher stiffness and a lower creep strain rate compared to the one normal to the bedding [17]. Geng et al. (2018) found that the differential stress and the bedding orientation can affect the creep behaviors of Touurnemire shale based on a series of triaxial creep experiments [18]. Li et al (2019, 2020) formulated an anisotropic microplane constitutive model to simulate creep and damage in shale and found that the the creep deformation and steady creep rate got maximum and minimum value at the 45°and 90° layer orientation, respectively [19-20]. Tang et al (2018) analyzed the influence of bedding and water on the creep characteristics of shale. And their results shown that the initial instantaneous elasticity of shale decreases exponentially with bedding angle, while it increases linearly with moisture content [21].

Although these above experiments are very useful to understand the viscoelasticity behavior of shale. The research on creep of deep shale is still insufficient. To accurately predict shale reservoir behavior and performance, it is essential to study the time-dependent characteristics of shale. In this paper, the triaxial creep experiments on shale with different bedding layer orientations are carried out by using deep shale samples. Then, the effects of bedding orientations and other factors on creep are investigated. Also, the creep mechanism of shale is analyzed in detail. Finally, some conclusions are obtained. The main purpose of this research is to better understand creep behavior of shale.

2. Experimental methods

2.1. Experimental Samples

The samples are drilled from full size cores at depth of 3989.48~3989.64m of Longmaxi shale at Luzhou area, Sichuan Basin. The mineral composition analysis shows that the shale sample is mainly
composed of quartz minerals, plagioclase, carbonate minerals (calcite, dolomite), clay minerals. Due to the high fractions of hard minerals, especially quartz at a fraction of 51.14 wt %, it can be inferred that the Longmaxi shale of Luzhou area is expectedly relatively brittle with a high elastic modulus. The total percentage of clay minerals is 15.81 wt % and the dolomite is 8.88 wt %. The fraction of calcite is 18.37 wt %, which is considered as cementing or bonding materials that fills the natural pores and cracks of shale. Furthermore, a small amount of pyrite (1.85 wt %) is present.

It is widely known that there is significant anisotropy in the microstructure of shale caused by the preferred orientation of clay minerals. As shown in Fig.1, the full size core sample has obvious macroscopic bedding planes. To investigate the effect of bedding planes on creep anisotropy, three group samples are cored form the full size core (Fig.1), which is 0° (normal to bedding), 45°, and 90° (parallel to bedding) angle with respect to the bedding plane, respectively. These above cylinder samples are prepared with 25mm in diameter and 50mm in length.

Fig.1 The full size core sample and experimental samples

2.2. Experimental procedure

In this study, the creep experiments are conducted under triaxial condition at room temperature and dry condition. A constant confining pressure 60MPa is used in all experiments, which was determined by the in situ stress situation of the deep Longmaxi shale gas reservoir. Then the differential stress (a difference between axial and confining stresses) in the axial direction was applied at constant in each experiment. Three group of differential stress, 30MPa, 60MPa and 90MPa are used to investigate the effect of differential stress on creep behaviour of shale. Table 1 summaries the detail scheme in experiments.

In each differential stress level, the creep test time was selected as 4 hours. During the experiments, the axial deformation is measured by a pair of LVDT transducers. While the radial deformation was not measured because this variable negligible compared to axial deformation as observed by Sone and Zoback (2014).

Table 1 The detail scheme of creep experiments

| Sample axis with respect to bedding | Confining pressure (MPa) | differential stress (MPa) | 1st | 2nd | 3rd |
|------------------------------------|--------------------------|---------------------------|-----|-----|-----|
| 0°                                 | 60                       |                           |     |     |     |
| 45°                                | 60                       | 30                        | 60  | 90  |
| 90°                                |                          |                           |     |     |     |

3. Results and discussions

3.1. Creep behaviour of shale

Fig.2 shows the axial train vs. time curves under different differential stress and bedding orientations. It is obvious that there are two creep stages, which are primary stage and secondary stage, in all time-dependent deformation curves. In the primary stage, sample generates instantaneous strain at the moment of loading. The micro-cracks and pores are closed under the confining pressure and differential stress. Then, the creep rate keeps constant in secondary creep stage. At the same bedding layer angle, the axial strain increases as the differential stress increases. While at the same differential stress, different bedding orientation shows clearly difference. The axial strain of sample with 45° is
highest, while the $0^\circ$ sample is second highest and $90^\circ$ is the lowest. This results show that anisotropy has significant impacts on the creep behavior of shale.

![Fig.2 The axial strain under different differential stress and bedding orientations](image)

In creep analysis, the empirical creep models are used to describe the creep deformation from primary creep. In these models, the elastic spring and viscous damper connected in series or in parallel or in both are modelling the time-dependent deformation behavior. Liang et al (2019) found that both Burgers model and the Standard linear solid model can be fitted only partially with laboratory data during the first and secondary stages of creep. In other investigations, a power-law function of time was found to be the best model fitting the triaxial creep data. The power-law model is of the following form [14, 16, 19]:

$$ \varepsilon = \sigma B t^n $$

$$ J = \frac{\varepsilon}{\sigma} = B t^n $$

Where, $\varepsilon$ is strain, $\sigma$ is the differential stress, $B$ and $n$ are empirical constants, and $J$ is the creep compliance factor. The constant parameters $n$ and $B$ can be determined from laboratory data by fitting a straight line to the data in a $\log(t)$-$\log(J)$ space. In this paper, the above equation is used to fit the experimental results. As shown in Fig.2, the power-law model shows good agreement with the experimental data. On one issue, some scholars argued that the power-law model may not be a good equation to fit the creep behavior due to without considering the anisotropic creep mechanism and temperature. Up to now, the fitting results of power-law model yield a better modeling.

![Fig.3 The correlation of steady creep axial strain and differential stress under different bedding orientations](image)
Fig. 3 presents the correlation of steady creep axial strain and differential stress under different bedding orientations. It is concluded that the steady creep rate increases almost linearly with differential stress, which mean that differential stress has significant influences on the magnitude of time-dependent deformation. On the one hand, the steady creep axial strain of 45° bedding orientation is highest. On the other hand, the axial strain normal to bedding is higher than that parallel to bedding. The explanation might be that the bedding layer is a weak plane, which contain much more micro-cracks, pores than the shale matrix. From this, there would be much more pore volume compaction normal to bedding.

3.2. Sources of creep and discussion

Due to the complex mineral compositions in shale, this rock also shows complex characteristics of creep behavior. Form this investigation and previous studies, the sources of creep mainly includes the following aspects:

(1) Content of clay and kerogen. As the mineral composition analysis of shale shown, the total fraction of clay minerals is 15.81 wt %. These clay minerals form the soft phases in shale, which has lower Young’s modulus than the hard quartz minerals. The nanostructural observations reveal that most of pore spaces in shale reside in the clays and organics, therefore, Sone and Zoback (2013) argued that compaction within clays and organics should be responsible for the creep deformation. And they found that the creep compliance increases with the amount of clays and organics [7]. Meanwhile, clay minerals have low friction and velocity-strengthening frictional properties that promote stable time-dependent sliding behaviour [11].

(2) Grain frictional sliding. Under the confining stresses and differential stress, the relative motion of the grains might facilitate grain rearrangement, which cause inelastic compaction during creep experiment. Moore and Lockner (2004) pointed out that presence of water in the pore spaces or between particles could significantly lower the frictional coefficient of the interface between clays and other minerals, which would affect time-dependent deformation [22]. In fact, Sone and Zoback (2014) found that grain motion by frictional sliding may have been more frequent in the room-dry samples [11]. Therefore, this point is still controversial.

(3) Propagation of microfractures. In the study of “brittle creep” in granites and sandstones, it has been demonstrated that the micro-crack growth produces time dependent deformations [11]. Rassouli and Zoback (2018) observed that microfractures mostly follow the interface between two different minerals or between matrix and grains, and dissipate in organic matter or high-porosity regions [14]. This contribute to near-perfect plastic deformation at crystallo-crystal boundaries, especially at temperatures of hydrocarbon reservoirs.

(4) Compaction. The strain suggests that there is volume compaction during creep. As mentioned in content of clay and kerogen section, the pores in clay minerals are compacted during creep tests [7]. At the same time, the particles themselves are compacted. In addition, shale exists abundant bedding layer, which contain much more micro-cracks, pores than the shale matrix. The compaction of these weak planes is also responsible for the creep deformation.

Fig. 4 The schematic of a layered shale model loaded perpendicular to the bedding and parallel to the bedding (Sone and Zoback, 2013 [7])
As observed in this study and other researcher’s investigations, shale shows creep anisotropy. Normally, the creep in the bedding-perpendicular direction is greater than the bedding-parallel direction. To explain this phenomenon, Sone and Zoback (2013) built an anisotropic shale model, which is a composite of soft and stiff layers (Fig.4). For the loading normal to bedding condition, the stresses carried by each layer are identical to the far-field stress. But in another case of loading parallel to the bedding layers, the stresses carried by each layer differ from the far-field stress, which is an isostrain condition. In this setting, creep occurs in the soft layer would be less than creep in first case [7]. But for the intermediate-state case, they did not make a clear analysis.

To characterize the creep behaviour of anisotropic shale, Li et al (2020) presented three basic creep patterns, which are the stress tensor normal to bedding, stress tensor parallel to bedding, shear component of the stress tensor along bedding and perpendicular to the bedding layer normal direction [20]. This explains why the creep axial strain of 45° bedding orientation is highest. The reason is that if there is a shear component acting on the bedding, the creep should be much larger compared with the deformation of the same size stress component acting on the shale matrix.

4. Conclusions

This study performed a series of triaxial creep experiments using deep shale to investigate its time-dependent deformational behavior. The samples are with respect to the bedding plane 0° (normal to bedding), 45°, and 90° (parallel to bedding), respectively. According to the current analysis and discussions, the following conclusions can be drawn:

(1) The deep Longmaxi shale obviously presents time-dependent deformational behaviour and contains two stage, primary creep and secondary creep. The time-dependent axial strain increase linearly with differential stress.

(2) The power-law function of time is in agreement with experimental data well. It is observed that the overall time-dependent axial strain normal to bedding is higher than the parallel to bedding, showing creep anisotropy in shale. Also, the axial strain at 45° angle with respect to the bedding plane is highest.

(3) The creep mechanism of shale includes content of clay and kerogen, grain frictional sliding, propagation of microfractures, mechanical compaction. While the explanation of creep anisotropy mainly focuses on the difference between mechanical properties of weak plane and stiff matrix

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