



Experimental Investigation of Time-Dependent Deformation in Brittle Marcellus Shale

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Received: 14 September 2020 / Accepted: 9 July 2021 / Published online: 27 July 2021
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Abstract

Coal mining activity disturbs the natural equilibrium of in situ stress state such that the induced stresses deform the surrounding rock mass. Although the installation of roof supports typically prevents rock deformation, rock mass failure may still occur in bolted roof. The erratic failure of rock mass after few days to months and years of excavation is the result of time-dependent deformation of roof rock under constant surrounding stresses. In the current research, the triaxial laboratory creep experiments proved that Marcellus shale exhibits time-dependent deformation under constant stress that was smaller than the failure strength. However, unlike conventional experimental results, the time-dependent deformation did not depend on the level of constant stress. The often-neglected initial state of specimens and intrinsic heterogeneity highly influenced the time-dependent failure of Marcellus shale.

Keywords Underground coal mines · Marcellus shale · Triaxial stress · Time-dependent deformation

1 Introduction

Shale is the most common rock present in the immediate roof of underground coal mines [27]. As detailed in Table 1, the exposure of shale roof in mine entries and crosscuts endangers safe mine operations and sometimes leads to personnel fatalities. Table 1 shows that in addition to the activation of existing roof anomalies, such as slickenside formations, surrounding moisture also deteriorates shale roof and leads to the failure of permanently supported mine entries. Similarly, the high horizontal stresses in underground coal mines can generate cutter at the corners of shale roof, which can then propagate through the laminated stack of shale and lead to cutter failure [20]. In both moisture degradation and cutter failure [17, 18], time plays an important role in the deformational behavior of shale, such that it causes time-dependent deformation that inevitably leads to its permanent failure.

Time-dependent deformation, also called creep, is the continuous deformation of a rock subjected to a constant stress state [7]. Conventionally, creep deformation (or creep strain) in a rock is characterized through three distinct

phases [12]. As shown in Fig. 1, in the first phase, the rate of axial strain continuously decreases with time, referred to as the *primary creep phase*. In the next stage, the rate of axial strain remains constant with time, referred to as the *secondary creep phase*. In the last stage, the rate of axial strain exponentially increases with time, referred to as the *tertiary creep phase*. Installation of instrumented roof bolts in unstable mine entries is an effective method of analyzing continuous roof rock deformation [3]. In addition, laboratory testing is also a reliable method to analyze the creep deformation in intact rock mass [28]. In fact, according to the American Society for Testing and Materials (ASTM D7070) (2016), laboratory tests on intact rock core specimens provide quantitative parameters, which sometimes prove effective in determining the long-term stability of permanent underground structures.

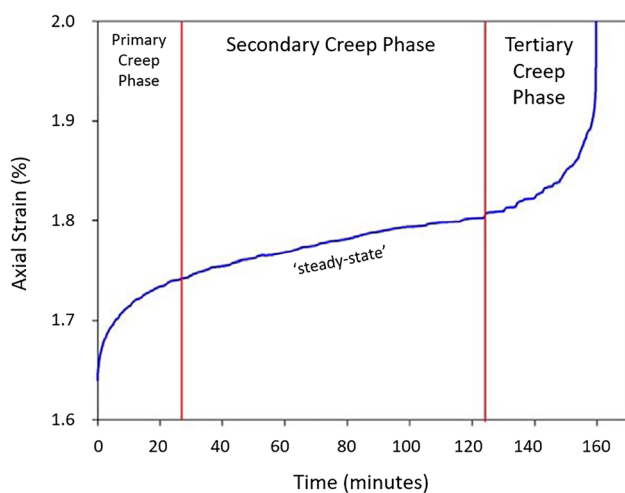
In the past, researchers conducted laboratory experiments on intact specimens and studied the creep behavior of shale or coal-measure rocks. Phillips [21] investigated the creep behavior of shale beam under transverse loading conditions, proposing a linear empirical relationship between deformation, load, and time. Griggs [8] proved that creep deformation of rock is an aggregation of pseudoviscous and elastic flow, also termed as elastoviscous deformation. Griggs also proposed the logarithmic relationship between strain and time. Later, other researchers including Nishihara [19], Price

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Table 1 MSHA reported roof fall accidents in underground coal mines [16]

Date	Mine	Condition	Immediate roof	Reason
4/20/2006	No. 1 Tri Star Coal LLC, Phelps, Pike County, Kentucky	Roof rock fell between the roof bolts and the coal rib	Laminated gray sand shale	Excessive entry width and bolt spacing
10/12/2006	No. 7 Mine, Jim Walter Resources, Inc., Brookwood, Tuscaloosa County, Alabama	Permanently supported roof fell without warning	Sandy shale	Deterioration of immediate mine roof and installed roof support
12/17/2006	Prime No 1, Dana Mining Company Inc, Maidsville, Monongalia County, West Virginia	Permanently supported roof fell without warning	Black thinly claystone	Weakening of immediate roof due to ground water inflow
9/3/2007	Bronzite Mine, Consol of Kentucky, Inc, Williamson, Mingo County, West Virginia	Mine roof fell without warning	Shale and claystone	Adverse roof conditions
4/28/2010	Dotiki Mine, Webster County Coal, LLC, Nebo, Hopkins County, Kentucky	Draw rock fell in the unbolted face of mine entry	Black shale overlain by gray shale with pyrite nodules	Activation of slickenside formation in unsupported area
2/23/2017	Mine No. 5, C K Coal Corporation, Delbarton, Mingo County, West Virginia	Inadequately supported roof rock fell, crushing the miner against the mine floor	Bed of shale rock ranged between 4 inches and 2 feet in thickness	Inadequate supports to control the mine roof

**Fig. 1** Classic trimodal creep curve [12]

[22], Hobbs [13], and Singh [25] also studied the creep phenomenon in shale. Their experimental research presented logarithmic or exponential relationships between steady-state creep rate and level of axial stress. Since these experimental configurations were limited to the uniaxial stress state, the influence of confining pressure and differential stress remained unknown. Bosman et al. [5] studied time-dependent deformation in hard brittle quartzite specimens with soft talcaceous infilling at the Hartebeestfontein Mine. The substantial difference in the creep rate of two different types of intact specimens indicated that the mechanical properties of intact rock mass might have less impact on time-dependent deformation. Instead, the presence of mica-ceous elements in substantial amounts dictates the creep

phenomenon in quartzite rock mass. Mishra and Verma [17] conducted several triaxial creep experiments on shale specimens and found that the rate of creep strain depends on differential stress and follows Norton's creep law. Song et al. [26] studied time-dependent deformation in marble, buchnerite, and rich ore, retrieved from the Jinchuan nickel mine in China. They observed that creep deformation in rock specimens had a positive correlation with differential stress. Their experimental studies also proved that shale exhibits a creep phenomenon, and the rate of creep deformation depends on the level of constant stress.

The primary objective of the current study is to assess the time-dependent deformation of Marcellus shale under triaxial stress state. It also aims to analyze the relationship between different parametric results of creep tests, such as rate of creep strain, time to reach tertiary creep phase, level of differential and confining stress, and inelastic volumetric strain. In addition, an effort has been made for direct visualization of microcracks in shale specimens using an X-ray computed tomography (CT) scanner. The chosen specimens were intact from outside even after entering in the tertiary creep phase.

2 Experimental Procedure

The current study tested shale specimens from the Marcellus formation, retrieved from the Devonian outcrop in western New York. The specimens were light gray in color with no visible laminations. The shale specimens are cored in two perpendicular directions, such that the longitudinal axis was parallel and perpendicular to the orientation of bedding

planes, termed as parallel (PL) and perpendicular (PD) specimens, respectively. The X-ray powder diffraction showed that Marcellus shale primarily contained calcite 75.14% by weight, followed by illite, quartz, and pyrite [11]. The following section describes the procedure of triaxial creep testing and the X-ray CT scan of shale specimens.

2.1 Triaxial Creep Experiment

This research performed its triaxial creep experiments in a servo-controlled triaxial test system, located in the rock mechanics laboratory of the Department of Mining Engineering in West Virginia University. The confining hydraulic oil filled in the triaxial cell applied the lateral (circumferential) stress on the shale specimen. The test involved sealing the specimen inside a polyolefin jacket to prevent absorption of confining hydraulic oil into surface cracks and pores. Both axial and radial linear variable differential transformers (LVDTs) were directly mounted on the test specimen and precisely determined the axial and lateral strain, as shown in 2. The experimental procedure of triaxial creep tests involved two stages in addition to the isotropic consolidation of the specimens at the desired confining pressure. In the first stage, the axial stress increased from isotropic consolidation stress at the constant rate of 0.48 MPa/s up until the predetermined level of axial stress [1]. In the second stage, both the axial and confining stress remained constant until the specimen entered the tertiary creep phase.

This study conducted triaxial creep experiments at two successive levels of differential stress, 75% and 85% of the differential (failure strength) at each of four confining pressures, such as 3.45, 6.89, 10.34, and 13.79 MPa. The

current study selected these levels of differential stress such that the creep experiments might conclude within a reasonable experimental duration [15]. Heap [12] conducted triaxial creep experiments on Darley Dale sandstone and found that the creep experiments completed in a reasonable duration for the differential stress chosen between the yield and dilation stress. Similarly, the current study determined the yield and dilation stress from the axial stress vs volumetric strain curve of triaxial compression strength tests [4], as shown in Fig. 3. Based on the value of yield and dilation stress, the chosen level of differential stress was 75% and 85% of the differential strength at respective confining pressures.

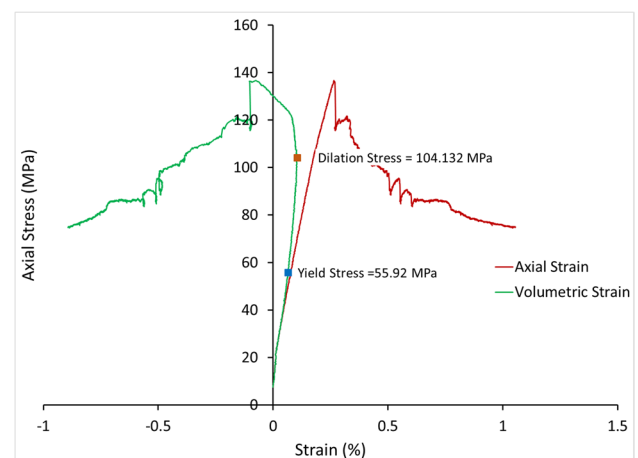
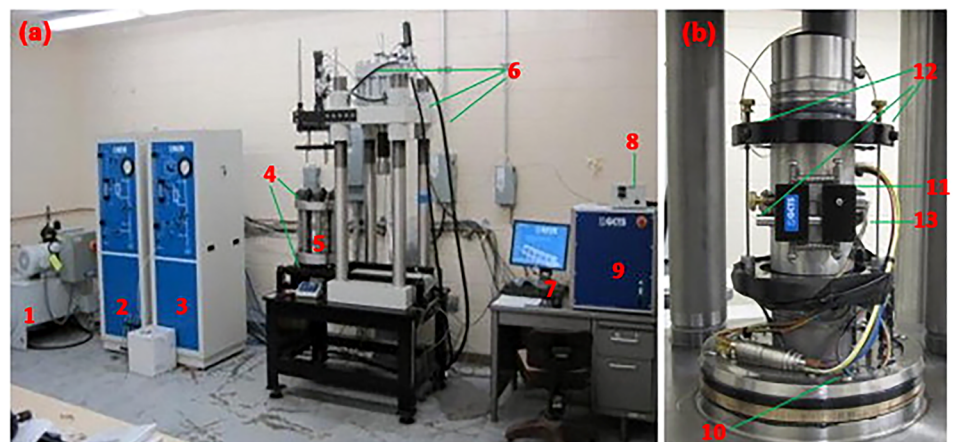


Fig. 3 Stress–strain curve for Marcellus shale in constant strain rate test at confining pressure of 6.89 MPa [9]

Fig. 2 **a** Servo-controlled triaxial equipment; **b** cylindrical rock specimen mounted with axial and lateral LVDTs [17]



- | | | |
|--------------------------------------|----------------------------|---|
| (1) Hydraulic pump | (5) Triaxial cell | (9) Digital controller |
| (2) Pore pressure intensifier | (6) Hoses | (10) Sensors |
| (3) Cell pressure intensifier | (7) Computer Software | (11) Specimen |
| (4) Input/output cell pressure holes | (8) Wall temperature meter | (12) LVDT 1,2,3 (13) Chain extensometer |

2.2 X-ray CT Scan

Once the shale specimen entered the tertiary creep stage and the triaxial experiment finished, the shale specimen was retrieved from the testing apparatus. The next step of the current study was to scan those shale specimens which remained intact from the outside with minor surface cracks using an Industrial X-ray CT (NorthStar Imaging M-5000) scanner, located at the National Energy Technology Laboratory (NETL) facility in Morgantown, West Virginia. The scanner includes an X-ray source, a rotating platform on which to place the test specimen, and a stationary detector, as shown in Fig. 4. The resolution of an X-ray CT image depends upon the size of the scanned specimen, ranging between 5 and 40 microns in each of the three mutually perpendicular directions.

The X-ray CT equipment scanned the entire length of shale specimens in the form of radiographs, producing two-dimensional (2D) cross-sectional slices, as shown in Fig. 4. The sequential stacking of 2D images reconstructed the three-dimensional (3D) image of the scanned specimen. Gupta [10] gives a brief description of the X-ray CT image processing and estimating the volume of microcracks.

3 Results and Discussion

In total, this study conducted twenty-eight triaxial creep experiments on perpendicular (PD) and parallel (PL) shale specimens at eight different triaxial stress states. Table 2

summarizes the specimen number, magnitude of triaxial stresses, time to reach the tertiary creep phase (T_f), and remarks on the experiments.

As mentioned in Table 2, four experiments from both types of bedding orientations were unsuccessful due to the failure of shale specimens before the differential stress became constant. In addition, among twenty successful creep experiments, shale specimens PL-20, PL-21, and PL-24 did not enter the tertiary creep phase, even after applying stress for 463.42, 953.06, and 721.15 h, respectively. The qualitative comparison of T_f with the level of differential stress showed that the specimens under similar levels of constant stress required different amounts of time to reach the initiation of the tertiary creep phase. For example, PL-15 and PL-25 took 144.15 and 305.06 h, respectively, to reach the tertiary creep phase. The level of constant differential stress was similar, equivalent to 85% of differential strength. Similarly, PD-15 and PD-32 took 159.49 and 1.48 h to reach the tertiary creep phase at similar levels of differential stress. Figure 5 graphically shows the comparisons of the logarithm of T_f with the level of differential stress for different confining stresses (C_p). Figure 6 presents a similar comparison for creep experiments on Barre granite by Kranz [14]. This figure shows that, for Barre granite, the value of the coefficient of determination (R^2) was very high, indicating towards the high dependence of T_f on the level of differential stress. Similarly, Heap [12] performed single-stage triaxial creep experiments on Darley Dale sandstone and Etna basalt specimens. He reported that, for sandstone, the time to reach failure increased from 10 min to 12,960 min with a decrease

Fig. 4 NorthStar Imaging M-5000 Industrial CT scanner: **a** an X-ray detector with vertical sandstone specimen; **b** X-ray source with sandstone specimen [23]

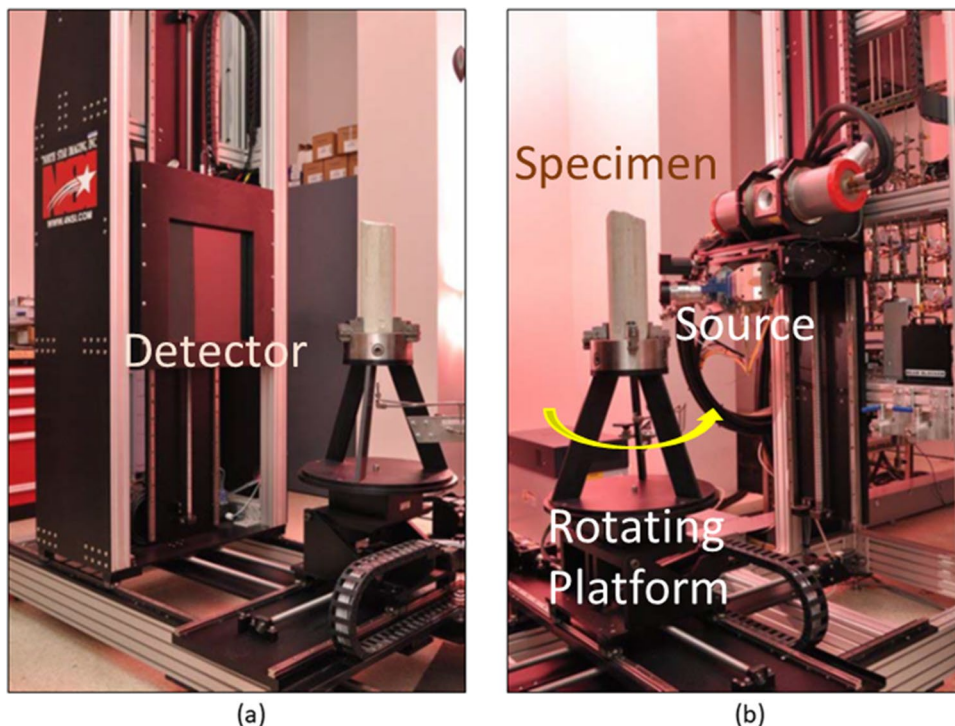


Table 2 Details of triaxial creep experiments on bedded Marcellus shale

Specimen ID	Differential strength (MPa)	Confining stress (MPa)	Percentage of differential stress (%)	Time to reach tertiary creep stage (T_p) (hours)	Remarks
PL-18	96.6	3.45	86.23	58.46	Entered tertiary creep stage
PL-19			76.21	64.86	
PL-20			76.29	463.4	Did not enter tertiary creep stage
PL-29			75.9	-	Failed before axial stress became constant
PL-30			75.9	81.52	Entered tertiary creep stage
PL-14	130.92	10.34	84.88	90.4	
PL-21			76.89	953.1	Did not enter tertiary creep stage
PL-28			76.11	221.72	Entered tertiary creep stage
PL-15			86.12	144.2	
PL-25			86.88	305.1	
PL-26	158.92	13.79	50.71	-	Failed before axial stress became constant
PL-27			74.36	-	
PL-16			85.5	-	
PL-17			74.5	209.3	Entered tertiary creep stage
PD-16			79.8	-	Failed before axial stress became constant
PD-22	97.42	3.45	81.1	-	
PD-24			84.15	-	
PD-26			75.5	38.75	Entered tertiary creep stage
PD-21			84.5	11.71	
PD-27			75.09	250.8	Entered tertiary creep stage
PD-33	118.36	6.89	75.42	0.63	
PD-34			75.45	721.2	Did not enter tertiary creep stage
PD-15			86.7	159.5	Entered tertiary creep stage
PD-32			86.9	1.48	
PD-28			75.02	3.49	Entered tertiary creep stage
PD-18	141.38	10.34	86.9	66.24	
PD-23			73.5	20.53	Entered tertiary creep stage
PD-20			85.5	-	Failed before axial stress became constant

in differential stress from 90 to 75% of peak failure strength. For basalt, the time to reach failure increased from 4.5 to 4500 min with a decrease in differential stress from 97.5 to 90% of peak failure strength. However, for Marcellus shale, the time to reach failure did not only depend on the level of differential stress, and the value of R^2 is significantly small between 0.0429 and 0.2481. This indicates that some other intrinsic parameter was also possibly influencing the failure of shale specimens.

In addition to the value of T_p , this study also compared the level of differential stress with the rate of creep strain during the secondary creep phase. Norton's power law, shown in Eq. 1, is a widely accepted empirical relationship between the rate of secondary creep strain and the level of differential stress. The logarithm of Eq. 1 transformed the power law into a linear relationship, shown in Eq. 2. As shown in Fig. 7, the specimen PL-28 entered the tertiary creep phase after 221.72 h of constant differential stress, equivalent to 76% of the differential strength (Table 2). The slope of the

best-fit line to the secondary creep phase determined the rate of creep strain in axial and radial directions. Table 3 summarizes the results of creep strain for individual creep experiments.

$$\frac{d\epsilon}{dt} = \epsilon_{ss}^{\circ} = A \times \sigma^n \quad (1)$$

$$\log \epsilon_{ss}^{\circ} = \log A + n \times \log \sigma \quad (2)$$

where

A, n = material constants.

σ = applied differential stress.

Based on Eq. 2, this study linearly compared the logarithm of the rate of creep strain with the logarithm of differential stress for parallel and perpendicular bedded shale specimens, individually. Figure 8 shows the results of the slope of the best-fit line and coefficient of determination (R^2) for four individual cases. In each case, the value of R^2 is very

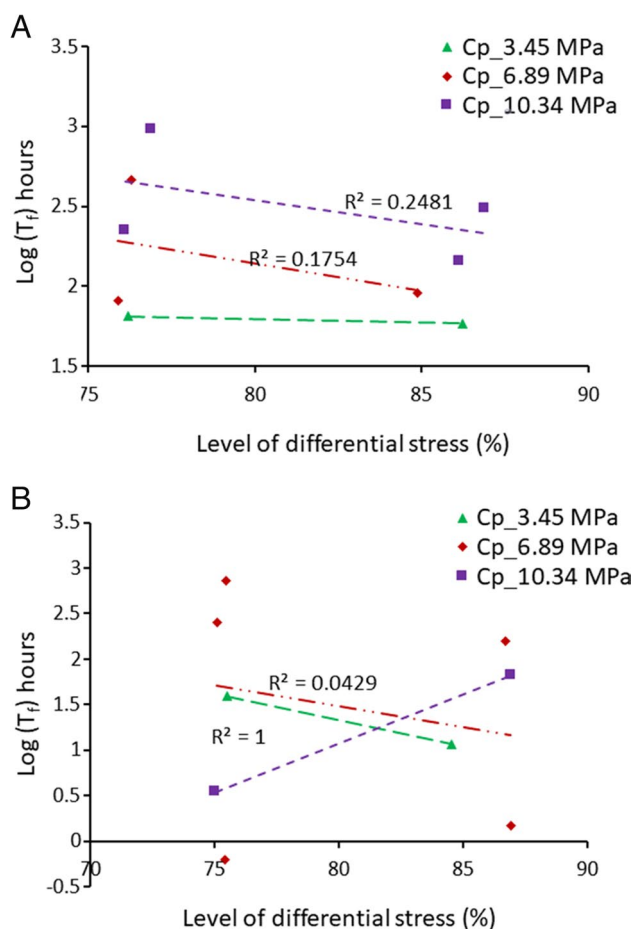


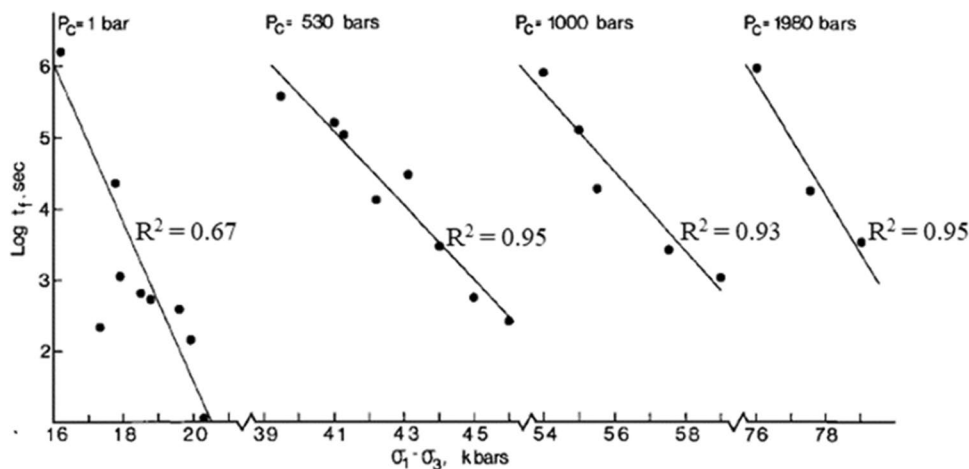
Fig. 5 Comparison between the time to reach the onset of the tertiary creep phase and level of differential stress for **a** parallel specimens and **b** perpendicular specimens

small, varying between 0.003 and 0.5833. In addition, the slope of the best-fit line is -10.812 for the axial creep rate of perpendicular bedded specimens (Fig. 8a). This implies that the rate of axial creep strain decreases with the increase

in differential stress. The significantly small value of R^2 and negative correlation of creep rate with differential stress for one of the four cases indicates that Norton's creep law is not completely valid, and the rate of creep strain possibly depends on additional factors, such as inherent heterogeneity or preexisting microcracks. The creep experiments performed by Heap [12] showed that, for basalt, the rate of steady-state creep strain increased from 2.4×10^{-9} to 2.7×10^{-6} per second for an increase in differential stress from 90 to 97.5% of peak failure strength. Similarly, for sandstone, the rate of creep strain increased from 3.7×10^{-9} to 3.5×10^{-6} per second for an increase in differential stress from 75 to 90% of peak failure strength.

As previous studies associated microcracking with the deformation of brittle rock under compressive stress [24], Kranz and Scholz [15] postulated a hypothesis of critical crack density for indirectly identifying the onset of tertiary creep phase. Their hypothesis stated that brittle rock enters the tertiary creep phase due to the accumulation of a critical value of inelastic volumetric strain. In addition, the critical value of inelastic volumetric strain only depends on the confining stress, where the level of differential stress only influences the time to reach the tertiary creep phase [14]. Griggs [8] first proposed the idea of the critical value of strain during creep experiments. Later, Cruden [6] found that, if the cracks' coalescence leads to rock failure, the critical crack density indicates the presence of critical strain. Therefore, Kranz and Scholz [15] suggested that, in a uniaxial stress state, the inelastic volumetric strain is the difference between the total and the elastic volumetric strain, as shown in Eq. 3. In addition, Eqs. 4 and 5 determined the total and elastic volumetric strains in the specimen, respectively. The symbols $\Delta V/V$, ϵ_z , ϵ_r , and Δ represent the volumetric strain, axial strain, radial strain, and inelastic volumetric strain at time instant t , respectively; E , ν , and σ represent the modulus of elasticity, Poisson's ratio, and uniaxial stress, respectively. In the current study, we followed a similar concept to calculate the inelastic volumetric strain in the specimen at the onset of

Fig. 6 Logarithm of the failure time in seconds versus stress difference in kilobars at confining stress of 1 bar, 530 bars, 1000 bars, and 1980 bars [14]. Best fit, least square regression lines, and R^2 are also shown



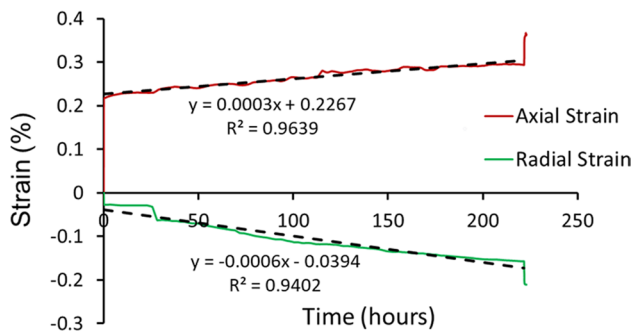


Fig. 7 Creep strain and time curve for parallel bedded shale specimen PL-28

the tertiary creep stage. However, the current creep experiments were triaxial in nature ($\sigma_1 > \sigma_2 = \sigma_3$). Therefore, Eq. 6 determined the inelastic volumetric strain, where σ_1 and σ_3 represented the axial and confining stress, respectively. Zhao and Cai [29] used a similar equation to calculate the inelastic (or plastic) strain in rocks that did not follow Medhurst's cycle of loading–unloading method. The use of Eqs. 3, 4, 5, and 6 in calculating the inelastic volumetric strain is critical to the value of the modulus of stiffness (E) and Poisson's ratio (ν). Kranz and Scholz [15] determined E and ν through separate constant strain rate tests on similar types of rock specimens. However, considering the heterogeneity of Marcellus shale, the current

study determined the value of E and ν separately for individual creep tests during the increase of axial load from isotropic stress state to the predetermined stress level. We calculated the secant modulus of elasticity and Poisson's ratio between zero and axial stress equivalent to 40% of the failure strength (ASTM, 2014).

$$\Delta(t) = \left(\frac{\Delta V(t)}{V} \right) - \left[\frac{1 - 2\nu}{E} \right] \times \sigma \quad (3)$$

$$\left(\frac{\Delta V(t)}{V} \right) = \epsilon_z(t) + 2 \times \epsilon_r(t) \quad (4)$$

$$\epsilon_z = \frac{\sigma}{E} = -\frac{\epsilon_r}{\nu} \quad (5)$$

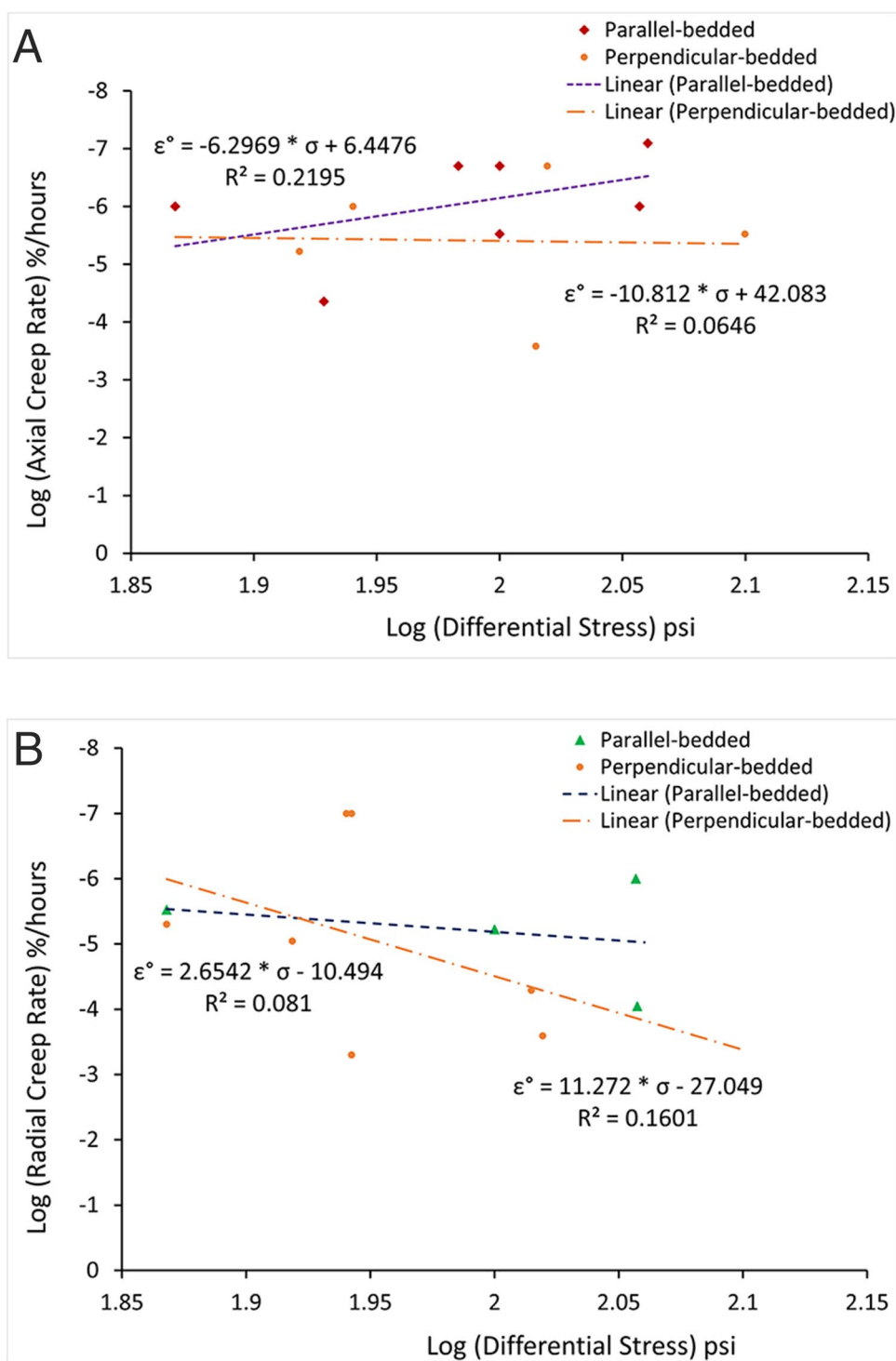
$$\Delta(t) = \left(\frac{\Delta V(t)}{V} \right) - \frac{[(\sigma_1 + 2 \times \sigma_3) \times (1 - 2\nu)]}{E} \quad (6)$$

Table 3 summarizes the results of total and inelastic volumetric strains at the onset of the tertiary creep phase for each creep experiment, as well as the value of E and ν . Figure 9 presents comparisons of inelastic volumetric strain at the onset of the tertiary creep phase with the level of confining stress in the form of a box and whisker plot.

Table 3 Results of the rate of secondary creep strain and inelastic volumetric strain during triaxial creep test

Specimen ID	Modulus of elasticity (E) (GPa)	Poisson's ratio (ν)	Volumetric strain at the onset of tertiary creep phase (%)		Rate of secondary creep strain (%/hours)	
			Total	Inelastic	Axial	Radial
PL-14	63.61	0.154	−0.0394	−0.151	-0.04×10^{-5}	0.02×10^{-4}
PL-15	55.96	0.166	0.0868	−0.0487	-0.01×10^{-3}	-0.9×10^{-4}
PL-17	43.01	0.014	0.1872	−0.0684	0.08×10^{-6}	0.01×10^{-4}
PL-18	30.18	0.04	−0.0351	−0.2911	0.04×10^{-3}	0.16×10^{-4}
PL-19	54.50	0.11	−0.041	−0.1454	0.01×10^{-4}	-0.03×10^{-4}
PL-20	63.63	0.003	−0.0995	−0.2533	-0.03×10^{-5}	0.01×10^{-5}
PL-21	60.27	0.003	0.2061	0.0425	0.02×10^{-5}	0.00
PL-25	51.51	0.025	0.1489	−0.06	0.01×10^{-4}	-0.01×10^{-4}
PL-28	74.67	0.007	−0.0212	−0.1524	0.03×10^{-4}	-0.06×10^{-4}
PL-30	64.76	0.009	0.1657	0.02	0.02×10^{-5}	0.09×10^{-5}
PD-15	48.07	0.003	0.2356	0.0211	0.02×10^{-5}	0.08×10^{-5}
PD-18	46.82	0.15	0.1854	−0.002	0.03×10^{-4}	0.06×10^{-5}
PD-21	49.81	0.003	−0.0622	−0.2262	0.06×10^{-4}	-0.09×10^{-4}
PD-23	55.89	0.009	0.2093	0.0165	-0.05×10^{-4}	0.03×10^{-4}
PD-26	49.99	0.001	−0.1365	−0.2826	-0.05×10^{-4}	-0.05×10^{-4}
PD-27	43.96	0.003	0.2385	0.043	0.01×10^{-4}	-0.01×10^{-5}
PD-28	72.92	0.02	0.1691	0.0339	2.6×10^{-4}	-0.5×10^{-4}
PD-32	89.88	0.008	−0.0854	−0.1991	-0.55×10^{-4}	-2.55×10^{-4}
PD-33	48.47	0.014	−0.1928	−0.367	-1.02×10^{-4}	5.02×10^{-4}
PD-34	40.88	0.004	0.2197	0.0091	-0.09×10^{-6}	-0.01×10^{-5}

Fig. 8 Fitting of linear trend between log (differential stress) and **a** log (axial creep rate) and **b** log (radial creep rate)



We compared the results with a similar study performed by Kranz [14] on Barre granite specimens, presented in Fig. 10. This shows that, for Barre granite, the inelastic volumetric strain is tensile for both constant strain rate and creep test, such that the mean value of inelastic volumetric strain increased towards dilation with the increase in confining pressure. In addition, the small length of the box

plot indicated the homogeneity in test results and lesser disparity from the mean value at individual confining pressures. However, for creep tests on Marcellus shale, the inelastic volumetric strain was tensile at a smaller confining pressure, and the mean value increased towards compression with the increase in confining pressure. This phenomenon was similar for both types of bedded specimens.

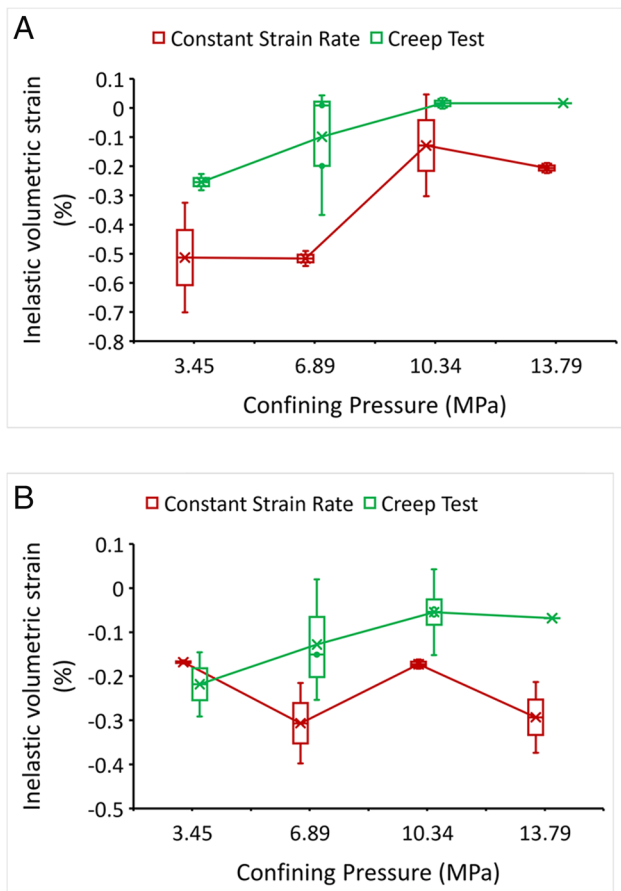


Fig. 9 Relationship between inelastic volumetric strain and confining pressure in constant strain rate and creep tests for **A** perpendicular bedded specimens and **B** parallel bedded specimens

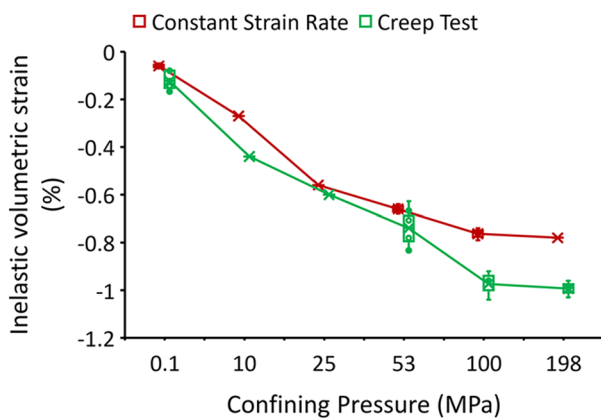


Fig. 10 Inelastic volumetric strain at the onset of the tertiary creep phase as a function of confining pressure for Barre granite specimens

In constant strain rate tests, the parallel and perpendicular bedded specimens experienced an increase in inelastic volumetric strain towards dilation and compression,

respectively, with the level of confining pressure. In addition, the result of inelastic volumetric strain was highly dispersed at particular confining pressures, indicating towards specimen heterogeneity. Therefore, the overall comparison of inelastic volumetric strain with confining pressure implied that, unlike Barre granite, creep failure of brittle shale is not always due to radial dilation. Axial compression is also responsible for creep failure. Additionally, the inelastic volumetric strain at the onset of the tertiary creep phase is not constant at a particular confining stress. The inherent heterogeneity in the specimens hugely influenced these results.

This study scanned the shale specimens that remained intact after the triaxial creep experiment using X-ray equipment for direct visualization of microcracks. The six shale specimens that remained intact after entering the tertiary creep phase are as follows: PL-14, PL-15, PL-17, PL-19, PD-15, and PD-27. Furthermore, this study analyzed the X-ray CT images to determine the volume of microcracks in respective shale specimens using the image analysis workflow proposed by Gupta [10]. Figure 11 presents the three-dimensional distribution of microcracks, showing that each specimen entered the tertiary creep phase with a well-defined plane of microcracks oriented parallel to the longitudinal axis of the specimen. The different colors of 3-D microcracks, such as red and green, represent the different 3-D local aperture of microcracks.

In addition, Table 4 summarizes the resulting volume of microcracks, and Fig. 12 presents the comparison between confining pressure and volume of microcracks. This shows that the confining pressure did not always increase the volume of microcracks in parallel bedded specimens. In perpendicular specimens, PD-15 and PD-27 contained significantly different volumes of microcracks, even after being stressed at similar confining stresses. Therefore, these results indicated that the theory of critical density of microcracks at the onset of the tertiary creep phase does not only depend on the level of confining stress. Other intrinsic parameters, such as specimen heterogeneity, might also play an important role in influencing the volume of microcracks.

4 Conclusions

The current research concluded that brittle Marcellus shale experiences time-dependent deformation at a constant stress state. However, the results of creep tests did not align with the previously reported creep test results on other types of igneous or sedimentary rocks. For example, the level of differential stress did not influence the time to reach the tertiary creep phase, and rocks stressed at similar levels of constant stress took significantly different times

Fig. 11 Three-dimensional distribution of microcracks in X-ray CT scanned shale specimens

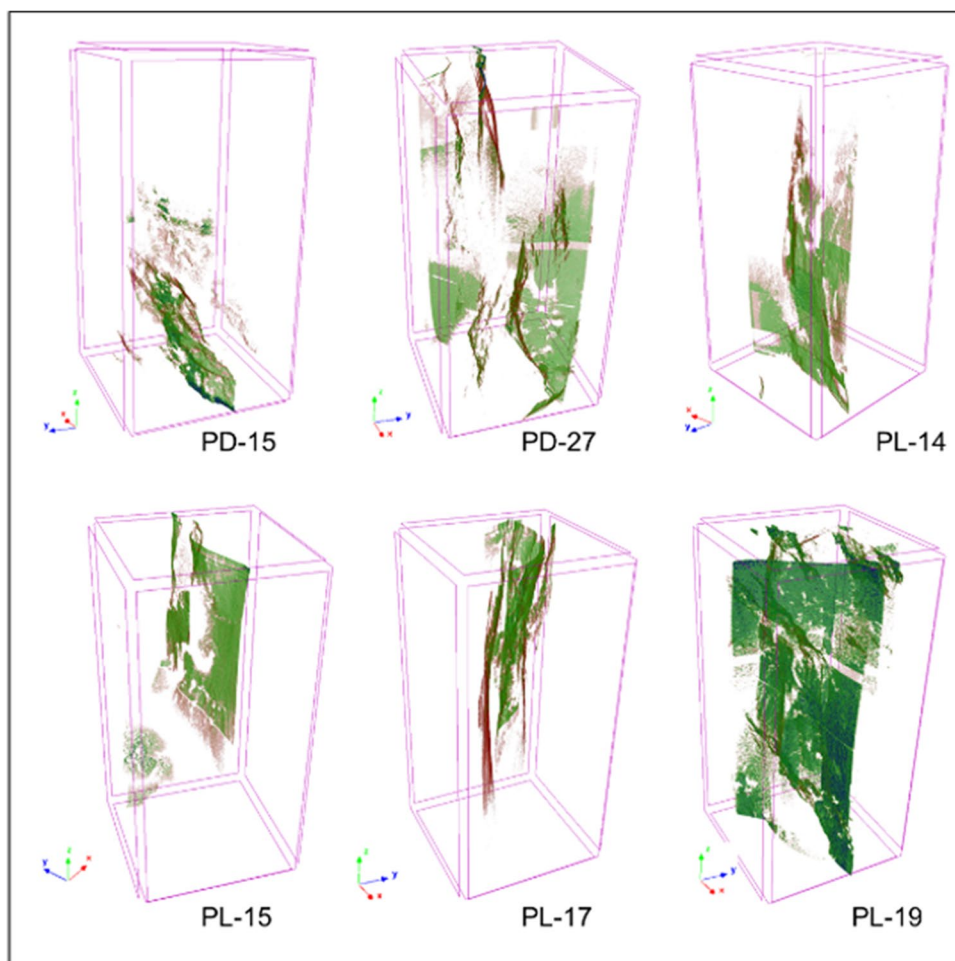


Table 4 Results of X-ray CT image analysis on shale specimens failed due to creep

Specimen ID	Confining pressure (MPa)	Volume of microcracks (mm ³)
PD-15	6.89	351.69
PD-27	6.89	892.35
PL-19	3.45	1,589.65
PL-14	6.89	533.80
PL-15	10.34	365.73
PL-17	13.79	911.01

to reach creep failure. The level of differential stress did not influence the rate of secondary creep strain and did not follow Norton's power law. In addition, unlike Barre granite, the inelastic volumetric strain of Marcellus shale increased towards compression with the increase in confining pressure. The authors believe that the inherent heterogeneity in the shale specimens and non-consideration of the initial state of tested specimens might be the possible reasons for the erratic nature of creep deformation.

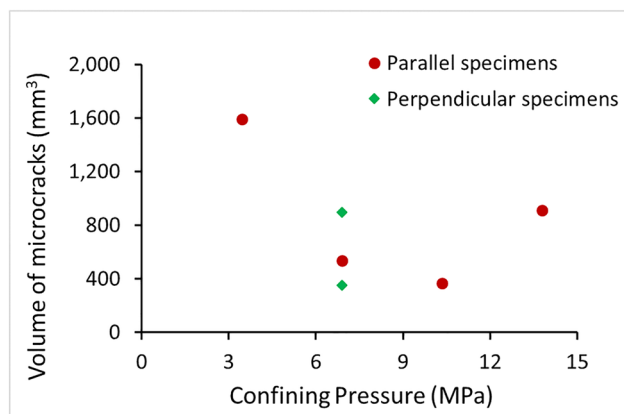


Fig. 12 Comparison between the volume of microcracks and confining pressure

Acknowledgements The authors would like to thank Sarah Brown, Johnathan E. Moore, and Bryan Tenant at the National Energy Technology Laboratory in Morgantown, WV, for the X-ray CT scan of shale specimens. The authors would also like to thank Dr. Karen Martin and Sarah McLaughlin from Animal Models and Imaging Facility (AMIF) of West Virginia University (WVU) for providing access to Bruker CTAn software.

Funding Financial support for this work was provided by the Centers for Disease Control and Prevention-National Institute of Occupational Safety and Health (No. 200–2016-92214).

Availability of Data and Material All data used to support the findings of the current study are available from the corresponding author upon request.

Code Availability.

Not applicable.

Declarations

Competing Interests The authors declare no competing interests.

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