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EXPERIMENTAL STUDY ON SHEAR CREEP PROPERTIES OF MUDSTONE OF BADONG FORMATION

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ABSTRACT

The mudstone of Badong formation (T_2b) is taken as the research object about its shear creep properties with shear creep test. Relation between shear creep, shear creep rate and different normal stresses are firstly concerned. Besides, the fast-shear and shear creep tests determine its long-term strength and shear strength indicators C, φ. Moreover, linear fit relationship $\tau=A+B\sigma$ (A,B are constants) is obtained which subjects to Mohr-Coulomb criterion. Function $\nu=M\tau+N$ represents relation between average creep rate and different shear stresses while $\nu=Pe^{Q\tau}$ does for steady creep rate (M,N,P,Q are rock material parameters). In addition, instantaneous intensity which is determined by fast-shear tests is greater than the long-term strength by the shear creep tests; meanwhile, the calculations show that shear stress make more difference on cohesion than internal friction angle.

INTRODUCTION

As one of the significant mechanical properties, creep of rock is closely related to the project long-term stability and security. Reasonable description of rock's deformation and mechanical behavior as time going has important theoretical and practical significance. Former studies about rock creep properties have been a series of studies. Sun *et al*. (1999), Xie *et al*. (2004), Zhou *et al*. (2005) in terms of rock strength, creep deformation characteristics and the constitutive equations and other systematic exposition of the rheological behavior of rocks and related engineering applications. Zhu *et al* (2002) and Li *et al*. (2003) mainlytook water content analysis of the tuff and granite creep into consideration. Li *et al*. (2010) studied the nonlinear mechanical properties of jointed rock mass unloading and carried out a detailed study which revealed corresponding rheological deformation characteristics. Han *et al*. (2010) mainly studied creep properties of thin layers of rock under loading conditions using a modified grading Nishihara model for binary quartz schist creep deformation identification and fitting out of the creep test data based on the improved model parameters Nishihara.

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Yang *et al*. (2006) took saturated hard marble and green schist under triaxial compression rheological experiments and carried out the hard rock at different axial strain and analyzed plastic deformation under triaxial rheological test. Xu *et al*. (2010) proposed "stress threshold" to study the shear rheological properties of water-saturated sandstone. Hou *et al*. (2003), Shen *et al*. (2012, 2010) focused on the structure of the object rheological properties of the surface and analyzed with test to determine long-term strength of rock.

The literature (Sun Jun, 1999; Xu Wei-ya *et al*., 2005; Liu Jiang *et al*., 2006; Yan, 2010; Xu Wei-ya *et al*., 2006; You Ming-qing, 2007 and Li Ya-li *et al*., 2012) relied on different subjects (green schist, rock salt and silty mudstone, etc. instead of the conventional nonlinear rheological element linear flow change element corresponding elements are combined to establish a model to study the rock nonlinear plastic rheological constitutive model. Above studies focus different angle but targeted research about shear creep of mudstone of Badong formation which has low strength and bearing capacity, higher content of clay minerals, grain pores common development among the rocks and diagenesis is not complete [19] is uncommon and achieves rarely. Based on previous studies and results of creep tests, creep characteristics and constitutive model of mudstone of Badong formation performed detailed discussion. The results can provide a useful reference for relevant research and long-term stability of rock engineering studies.

Test equipment and solutions

Rock samples were weak-breeze mudstone whose natural density were 2.63g/cm^3, limit saturated uniaxial compressive strength were 27.9MPa and the average velocity is 4022m/s which were collected from Shennongxi slope of Yichang to Badong Expressway and taken from the same layer to eliminate discrete data error.Φ70mm×100mm rock cylindrical specimens were made and placed in a central location of 150mm×150mm×150mm cube mold, which was poured at both ends of the cylinder with concrete and 2cm seam with wood in the middle reserved. According to the sampling location slope height, gravity stress is calculated to determine normal load of 0.8MPa and use classification loading method to determine the four levels of the normal load of 0.2MPa, 0.4MPa, 0.6MPa and 0.8MPa. Shown in Figure 1, shear creep test use the CYL-series device of rock shear rheometer systems.

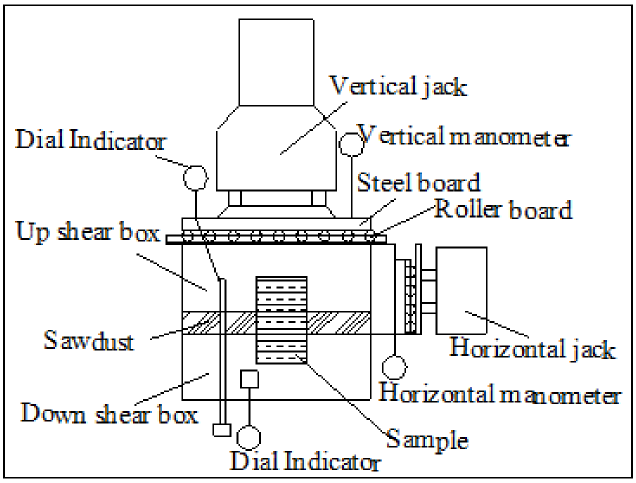


Figure 1. The CYL-series device of rock shear rheometer

Test results analysis

Shear creep test curve

According to Boltzmann superposition principle (Sun Jun, 1999; Xie He-ping *et al*., 2004 and Zhou Hongwei *et al*., 2005) analyzed the test data and showed as figure 2 (a)~(d) that mudstone of Badong formation as a typical soft rock, had obvious shear rheological properties and creep curve could be roughly divided into three stages:

(1) The initial stage

As seen from Figure 2, apparent instantaneous deformation appeared while horizontal shear stress instantly under constant normal load. Initial creep deformation immediately begun and initial displacement increased faster while creep rate rapidly diminished with time. This stage kept within 0~3h and deformation lasted short and was mainly for the relative sliding between the inside rock particles, rock internal microcracks gradually started to develop, some particles deformation potential had not yet got out. Creep curvature radius was gradually increasing with the increase of shear stress, but not particularly evident. Thus shear stress level made certain influence on the initial stage of creep curve.

(2) Steady develop stage

For this stage, strain curve showed approximate linear and tended to stable value while shear displacement slowly increased with time and cumulative deformation is small. Contrast under constant normal load, creep curves of different shear stress covered a relatively short and creep deformation was smaller while creep rate was quickly stable over time. With shear stress level developed, the stable creep stage lasted a long time and creep deformation increased gradually. Final shear deformation displacement increased with extended gradually and gradually stabilized, which was the important of mudstone aging characteristics.

(3) Accelerated creep stage

With the increase of shear stress in this final stage, mudstone entered the stage of accelerated creep under the last shear stress or directly damaged. While σ_n=0.8MPa, τ=3.0MPa, creep acceleration stage, characterized by ductile damage. Meanwhile, σ_n=0.2MPa, 0.4MPa, 0.6MPa mudstone creep directly damage after the stable creep stage, characterized by brittle failure. Thus, test suggested that the first two stages occupied as the main deformation stage, only under the condition of higher stress (σ_n=0.8MPa) accelerated creep appeared. At the same shear stress level, the normal load increased greater, the instantaneous displacement had a decreasing trend, which was the impact of normal stress of rock pressure for increasing the shear surface friction resistance.

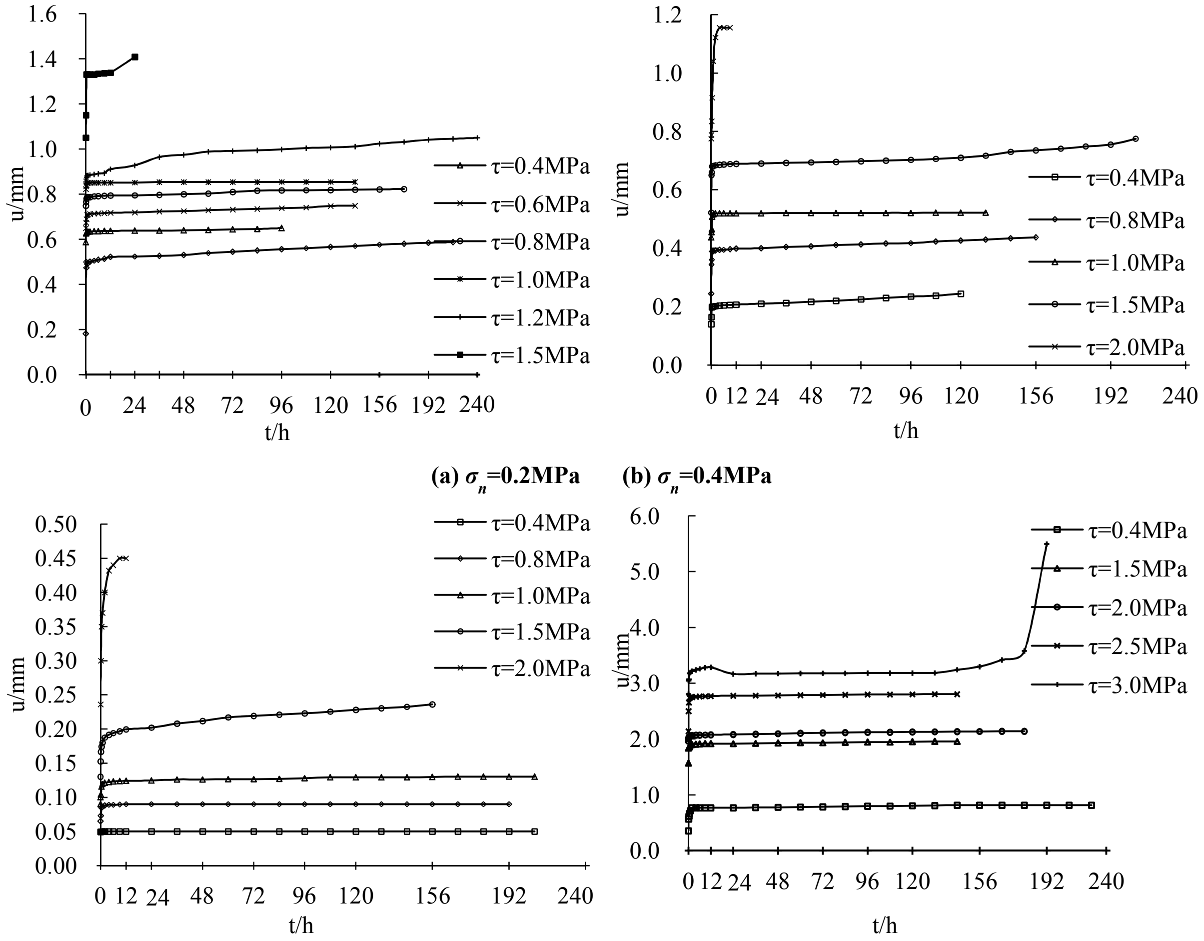
Shear creep rate

Figure 3 and 4 show mudstone average and steady creep rate under different shear stresses. Table 1 generalizes the material parameters for the creep tests. Function $v=M\tau+N$ represents relation between average creep rate and different shear stresses while $v=Pe^{Q\tau}$ does for steady creep rate (*M,N,P,Q* are rock material parameters).

Table 1. Mudstone creep rate and material parameters with fitting analysis

Normal stress/ MPa	Average creep rate/10^{-3}mm·h^{-1}			Steady creep rate /10^{-4}mm·h^{-1}		
	v=Mτ+N			v=Pe$^{Q\tau}$		
	M	N	R^2	P	Q	R^2
0.2	4.1860	4.8371	0.9522	4.2013	0.6483	0.9715
0.4	13.0006	0.0357	0.9471	2.5503	1.1269	0.9487
0.6	13.3920	-1.5350	0.9677	1.6961	1.1726	0.9660
0.8	3.2118	2.1894	0.9853	2.0610	0.5615	0.9639

Under the same shear stress level, the average is bigger than the creep rate steady creep rate, shows that various shear stress load and initial creep stage lasted a short moment and deformation is large, lead to the average creep rate significantly higher than the steady creep rate is higher. In addition, the figure 3 and 4 show, under the same conditions of shear stress, the average and stable creep rate and change slope of σ_n=0.2MPa and 0.8MPa are smaller than that of σ_n=0.4MPa and 0.6MPa.



(a) σ_n=0.2MPa (b) σ_n=0.4MPa

(c) σ_n=0.6MPa (d) σ_n=0.8MPa

Figure2. Shear creep curves of mudstone under different normal stresses

Table 2. Long-term strength parameters with 4 methods

Normal stress /MPa	fast shear		shear creep					
			tautochrone		steady creep		first inflection	
	shear strength /MPa	fitting analysis	shear strength /MPa	fitting analysis	shear strength /MPa	fitting analysis	shear strength /MPa	fitting analysis
0.2	2.2	$\tau=0.8\sigma+2.05$	1.22	$\tau=0.98\sigma+1.41$	1.65	$\tau=0.8955\sigma+1.0$	0.5	$\tau=0.775\sigma+0.$
0.4	2.4	$R^2=0.9846$	1.5	$R^2=0.9518$	1.72	7 $R^2=0.9442$	0.8	4 $R^2=0.9109$
0.6	2.5	C=2.05MPa	1.55	C=1.41MPa	2.03	C=1.07MPa	0.85	C=0.4MPa
0.8	2.7	φ=38.66°	2.0	φ=41.83°	2.2	φ=44.42°	1.0	φ=37.78°

Under lower normal load, rock mainly presents elastic deformation but internal micro-cracks extended over time, namely internal damage accumulated, appeared creep hardening phenomenon while the creep rate for a certain basic value. As normal load increases, rock internal friction force between particles increases gradually, it needs to overcome larger friction stress; When rock creep deformation comes into stable creep stage, the degree of internal damage degree is greater and creep rate accelerates gradually, then eventually occur along the weakest section of shear failure. Thus it can be seen that stable mudstone creep rate imposed by law in the process of test to the load and size of the shear stress are closely related.

Mudstone creep long-term strength

While stress rock suffered is greater than long-term strength, rock mass develops from stable creep stage into the accelerated creep stage and deformation presents from ductile-brittle failure to brittle failure (Xu Hui *et al.*, 2010). Combined with figure 2, shear stress-strain tautochrone curve (Hou Hong-jiang and Shen Ming-rong, 2003), steady creep rate method [11] the first inflection point method (Shen Ming-rong *et al.*, 2012) are made using of to determine the badong group of purple mudstone material intensity for a long time. figure 5 (a)~(d) shows that Mudstone isochronous curves of discontinuities under different normal stresses can approximate consists of three lines. At initial stage, shear stress and displacement is proportional to increase. Increasing with the shear stress, shear creep take from the elastic deformation stage gradually to viscoelasticity stage and relationship between shear displacement and shear stress is nonlinear, corresponding to the first inflection point at this time, remember as τ_{ll}. When sample by shear stress level is higher, deformation by viscoelastic deformation transition to a

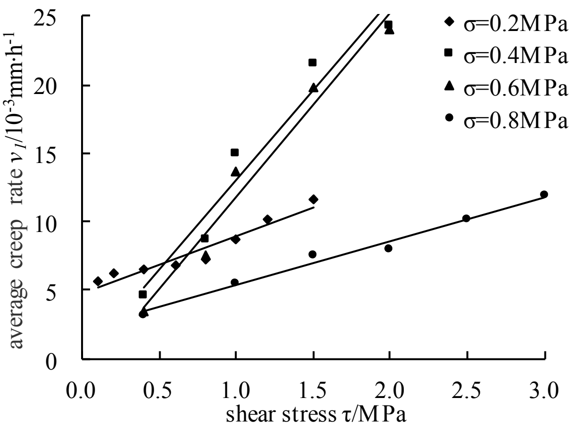


Figure 3.Mudstone average creep rate under different shear stresses

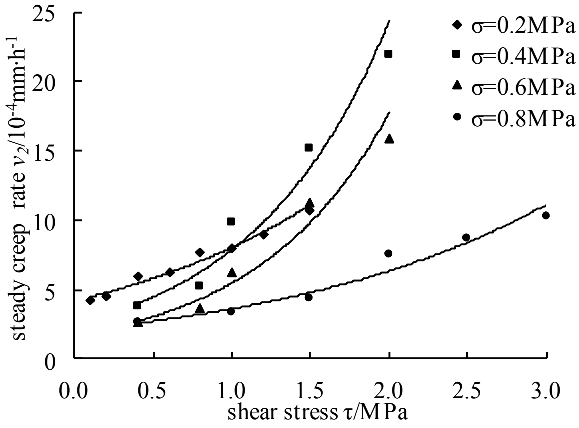
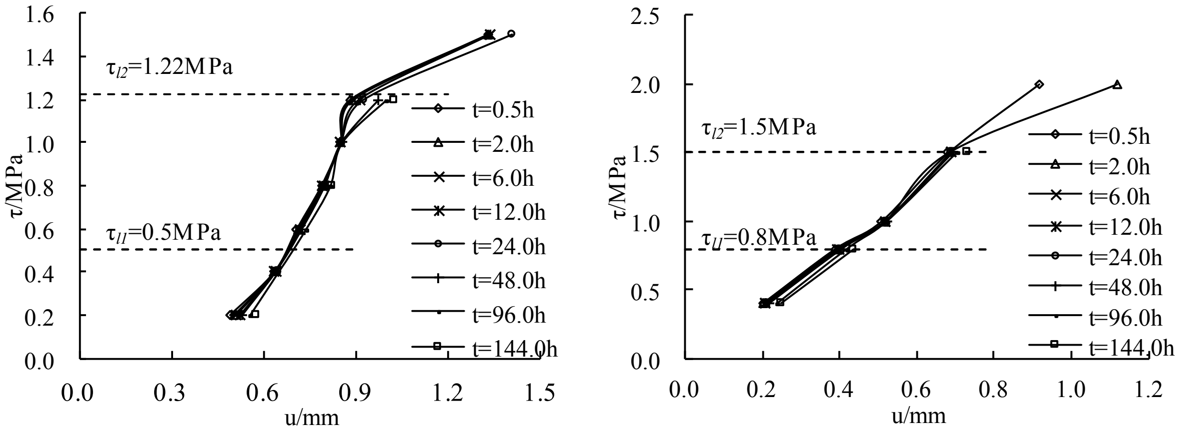
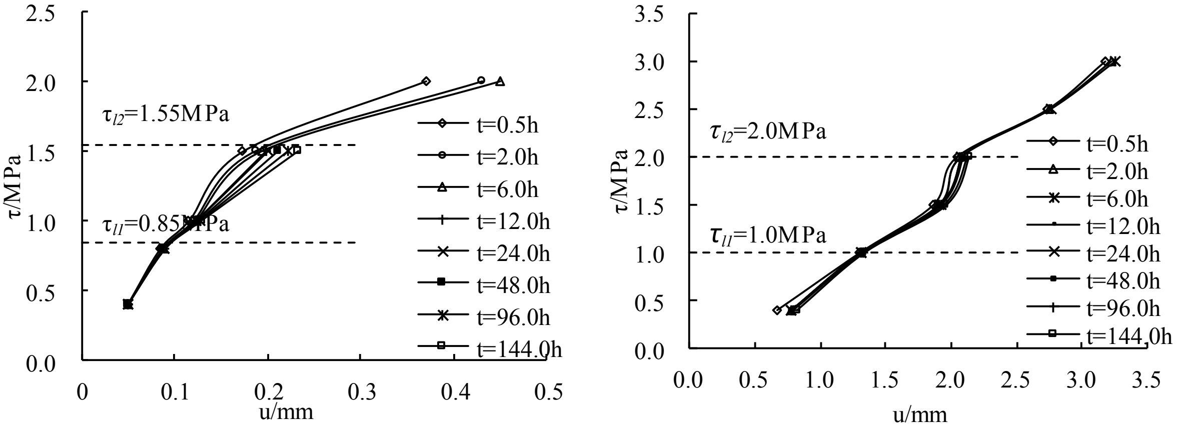


Figure4. Mudstone steady creep rate under different shear stresses



(a)σ_n=0.2MPa,τ_{l1}=0.5MPa,τ_{l2}=1.22MPa (b)σ_n=0.4MPa, τ_{l1}=0.8MPa, τ_{l2}=1.5MPa



(c)σ_n=0.6MPa, τ_{l1}=0.85MPa, τ_{l2}=1.55MPa (d)σ_n=0.8MPa, τ_{l1}=1.0MPa, τ_{l2}=2.0MPa

Figure5.Mudstone isochronous curves of discontinuities under different normal stresses

sticky plastic deformation, the internal structure of sample damage occurs, the shear displacement sudden increase, at this time of the shear stress remember as τ_{l2}.As seen from the figure 6 and table 2, three methods (tautochrone, steady state creep and the first inflection) to determine the long-term strength is smaller than the instantaneous intensity of direct shear test. Shear stress and normal stress are the linear fitting relationship between relationship, can be said for

$\tau=A+B\sigma$ (A, B are constant)

Meanwhile, correlation coefficients are all above 0.91 and obey the Mohr-Coulomb criterion, which calculated the mudstone shear strength index cohesion C, internal friction Angle φ. Fast shear test and shear creep test by three methods to determine the shear strength indexes: cohesion C are 2.05 MPa, 1.41 MPa, 1.07 MPa, 1.41 MPa, in turn, decreased by

31%, 47%, 80%; Internal friction Angle φ are 38.66° and 41.83° and 44.42° and 37.78°,less volatile, show that cohesion is influenced more by shear creep effect than the internal friction angle.

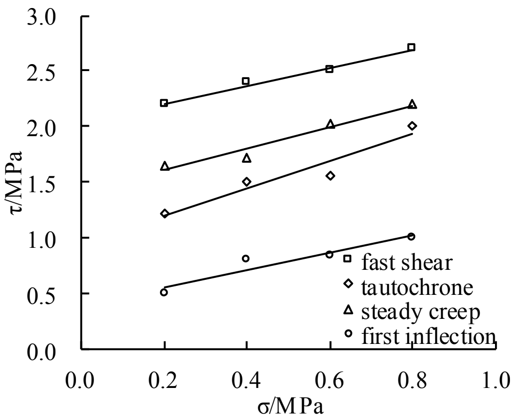


Figure 6.Mudstone creep normal stress - shear stress curves under different test methods

Conclusions

(1) As can be seen from the Figure.10, while shear stress τ=0.8MPa, three stages creep characteristics of mudstone change significantly. Figure 10 analyze the fit relationship between shear stress and steady creep rate according to the above six kinds of Elements-combined models and experimental data.

(2) Function $v=M\tau+N$ represents relation between average creep rate and different shear stresses while $v=Pe^{Q\tau}$ does for steady creep rate (M,N,P,Q are rock material parameters).

(3) According to the experimental data and creep theory, four kinds of method is used to determine the long-term strength is smaller than the instantaneous intensity of direct shear test. Shear stress and normal stress are the linear fitting relationship between relationship, can be said for

$$\tau=A+B\sigma \text{ (A, B are constant)}$$

Meanwhile, correlation coefficients are all above 0.91 and obey the Mohr-Coulomb criterion, which calculated the mudstone shear strength index cohesion C, internal friction Angle φ. Direct shear test to determine the instantaneous intensity is greater than that of the shear creep test and cohesion is influenced more by shear creep effect than the internal friction angle.

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