Study on the creep behavior and constitutive model of mudstone with different water content

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Abstract

In order to study the differences of the creep behavior of mudstone under different water content. Conventional uniaxial compression and uniaxial creep loading tests were carried out on the mudstone samples with different water content. The tests results show that, with the increase of water content, the instantaneous strength, creep failure stress and long-term strength of mudstone decrease exponentially, the steady creep rate and deformation increased; The stress sensitivity constant increases linearly with the increase of water content, indicating that the higher the water content is, the stronger the sensitivity of the corresponding force is; Based on the theory of fractional calculus, a fractional order constitutive model considering the influence of water content is obtained, and sensitivity analysis is carried out. The theoretical curve fits well with the experimental curve, which can simulate the whole creep process of mudstone under different water content.

Keywords

mudstone; water content; creep; long-term strength; fractional order; constitutive model.

1. Introduction

Mudstone is one of the most common rock materials in modern engineering construction, and its mechanical properties have been paid much attention by many experts and scholars. The rheological properties, especially the creep behavior, have attracted the attention of many scholars, in order to solve the long-term stability problems in engineering construction.

Mao[1] carried out creep tests on mudstone under uniaxial loading. The influence of temperature on the creep behavior of mudstone was analyzed, and a creep constitutive model for mudstone was established with the considering of temperature effect. Hu[2] studied the rheological characteristics of the mudstone during the shear deformation process. The creep test of the silty mudstone under the three axis stress state is carried out by Xu, and the relationship between the axial and radial strain is studied[3]. Fan[4] analyzed and discussed the mechanism of damage and denaturation in mudstone creep process, and put forward that the creep of rock is the result of interaction between damage effect and hardening effect. Fan [5] studied the creep characteristics and nonlinear model of clay soft rock. Zhang [6] studied the creep characteristics of three axes of purple mudstone under the condition of graded loading, and the creep characteristics of purple mudstone were described with H/M model. Wang [7] used the 6 element extended Burgers model to express the initial and steady creep test results of the mudstone. The nonlinear creep damage constitutive model of mudstone and its damage evolution equation are established by the creep potential of Jia[8] based on the Moore Coulomb criterion.

Various factors such as the structure of the aquifer, the material composition of the mudstone, the rainfall, the construction of the engineering and other factors all cause the change of the water content of the mudstone. The water absorption of mudstone will be softened, and the mechanical properties and stress state of its own will change, and the cementation force of the diagenesis will gradually disappear. Huang[9] consider that the shear strength change of soil is the result of the common effect of water content and compactness. Ma[9] carried experimental study on the variation of pore in the creep process of saturated fractured mudstone. Huang [11] carried out strength tests and creep tests for mudstone under different water contents, and analyzed the differences between basic mechanical parameters and creep characteristics of strength and elastic modulus.

Based on the above study, the uniaxial creep loading test of mudstone were carried out, The mechanical behavior of long deformation and strength of mudstone under different water content was studied. Based on the research results, a fractional variation damage constitutive model considering the influence of water content is established, and the sensitivity analysis and numerical simulation of the model were carried out in order to better describe the process of mudstone creep.

2. Test specimen

Test cores were taken from Sichuan Province, the natural state of average moisture content is 1.5%, the average density is 2.25g/cm3. The rock sample is processed into a standard cylindrical specimen with Φ50×H100. Except for the natural condition, the rest of the specimens were dried and soaked in 1D, 3D and 5D according to the "Rock test regulations for water conservancy and hydropower projects" (SL264-2001), and the moisture content of five specimen groups were 0%, 1.5%, 2.7%, 3.5% and 4.1%, respectively.

3. Test results and analysis

3.1 Conventional single axis test

In order to get the influence of water content on instantaneous strength and deformation of mudstone, five kinds of water bearing mudstones were tested by conventional uniaxial compression respectively, and the following stress-strain curves were obtained, as shown in Figure 1. From the chart we can see clearly that, mudstone stress-strain curves can be divided into four stages: compaction stage, elastic deformation stage, plastic deformation stage and the post peak stage. With the increase of water content, the more obvious the plastic deformation phase of the mudstone is, the greater the corresponding strain is, which indicates the softening and deterioration of the mudstone. With the increase of moisture content, the mechanical parameters of mudstone changed obviously, and the compressive strength and elastic modulus all decreased as a negative exponential function (see Figure 2). This is due to the negative charge on clay surface in mudstone, which can absorb water molecules, reducing the surface energy and increasing the spacing between layers. Therefore, the more water content is, the smaller the attraction between particles, and the smaller the compressive strength and stiffness.

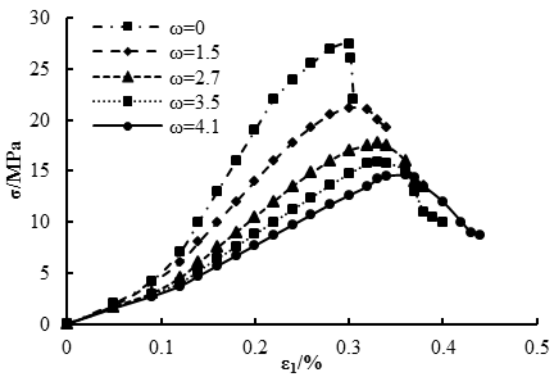


Fig.1 The stress-strain curves

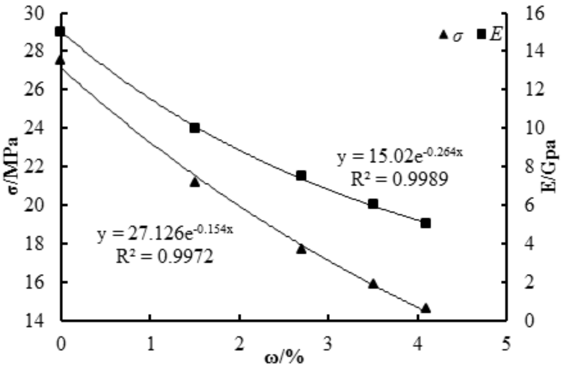


Fig.2 The relationship between instantaneous strength, modulus and moisture content

3.2 creep test results and analysis

3.2.1 creep deformation analysis

The grade loading test is carried out according to the step of step by step, and the duration of each level is 7d. In order to avoid the evaporation loss of water content in the test process, the preservation film was wrapped around the specimen. The creep diachronic curves are obtained as follows, as shown in Figure 3. It can be obtain that with the increase of water content, the creep failure stress of mudstone is lower and the creep deformation is greater. It shows that the softening effect of water on mudstone specimen is faster, and the higher the moisture content is, the more the instantaneous strain of each stage is, the more obvious the acceleration creep characteristic

is.

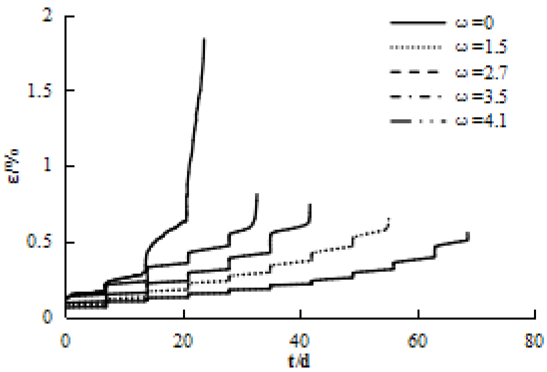


Fig. 3 creep characteristic curve

Under each water content, the steady creep rate of mudstone with the variation of loading stress is shown in Figure 4. It can be seen from the diagram that the higher the water content is, the greater the steady creep rate of the mudstone is under the same partial stress. When the water content is the same with the increase of the stress, the steady creep rate increases with the increase of the power function, and the power function is fitted and expressed in the form of the following form:

$$\dot{\varepsilon}(t) = A \cdot (\frac{\sigma_1 - \sigma_3}{\sigma^*})^n \quad (1)$$

In the formula, $\dot{\varepsilon}(t)$ is the steady state creep rate, A is the material fitting constant, and n is the stress sensitivity constant, which is the unit stress, and its value is 1. The relation between the stress sensitivity constant and the change of water content is shown in Figure 5. It can be seen from the graph that with the increase of moisture content, the stress sensitivity constant increases linearly, which indicates that with the increase of water content, mudstone has greater influence on stress and the more obvious rheological characteristics.

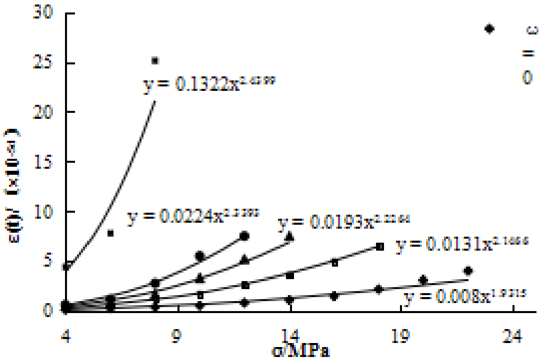


Fig. 4 The relationship between steady-state creep rate and stress

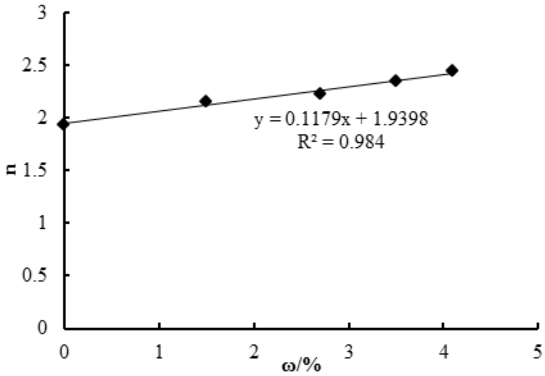


Fig. 5 The relationship between stress senstivity constant and water content

3.2.2 Fractional constitutive model considering the influence of water content on

In the last 30 years, fractional calculus has been widely used in the research and calculation of numerical models in various fields. Document [12] proposed a fractional viscoelastic plastic constitutive model for describing the creep stage of rock material in the three stage (see Fig. 6). Combined with the experimental data in this paper, the creep constitutive equation of mudstone was defined as follows:

$$\varepsilon=\begin{cases}\dfrac{\sigma}{E_0}+\dfrac{\sigma}{\eta_0}\dfrac{t^{\beta}}{\Gamma(\beta+1)} & (\sigma<\sigma_s;\sigma\geq\sigma_s,\varepsilon<\varepsilon_a)\\ \dfrac{\sigma}{E_0}+\dfrac{\sigma}{\eta_0}\dfrac{t^{\beta}}{\Gamma(\beta+1)}+\dfrac{\sigma-\sigma_s}{\eta_1}\dfrac{(t-t_a)^{\gamma}}{\Gamma(\gamma+1)}. \\ (\sigma\geqslant\sigma_s,\varepsilon\geq\varepsilon_a) \end{cases} \tag{2}$$

In the formula: E is the instantaneous elastic modulus; η1 and η2 is the viscoelastic coefficient; β, γ is the fractional order calculus, σs is the long term strength, ta and εa is the acceleration time and the corresponding variable respectively.

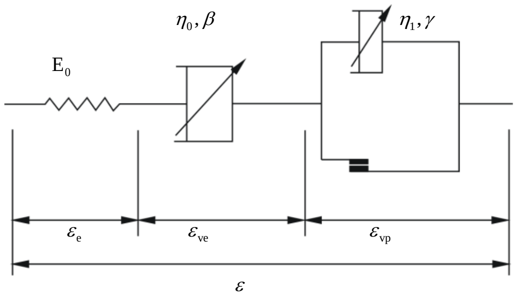


Fig.6 Fractional order viscoelastic plastic constitutive model

When the loading stress is less than the long-term strength, only hardening coefficient accured and viscosity increases; when the loading stress is greater than the long-term strength, thardening and damage combined, and the damage will gradually exceed the hardening effect, the rock into the accelerated creep stage, viscosity coefficient decreases. Therefore, according to the previous research experience[13-14], hypotheses of accelerated creep stage and coefficient of viscosity according to the following rules:

$$\begin{cases} \eta_1 = \dfrac{\eta_{10}}{\sigma^n}\dfrac{2\sqrt{t}}{c+2\sqrt{t}}(t<t_a) \\ \eta_2 = \dfrac{\sigma-\sigma_s}{B\sigma^n\left(t-t_a\right)^m+D}(t\geq t_a) \end{cases} \tag{3}$$

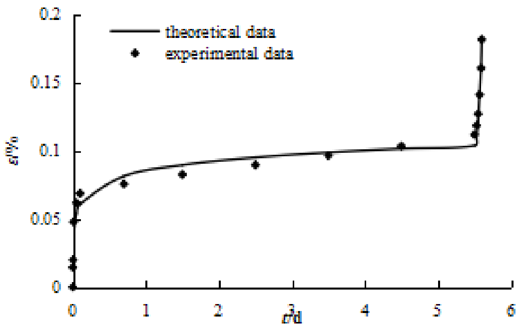
In the formula, η_{10} is the initial viscosity coefficient, t_a is the accelerated creep start time, B,D, c and m are the nonlinear constant. it can be seen from the above formula, coefficient of viscosity is a function of stress and time, which reflect the influence of stress size and loading time of rock creep. Through the analysis, the stress sensitivity constant increases linearly with water content, the equation can be written:

$$n = a\omega + b \tag{4}$$

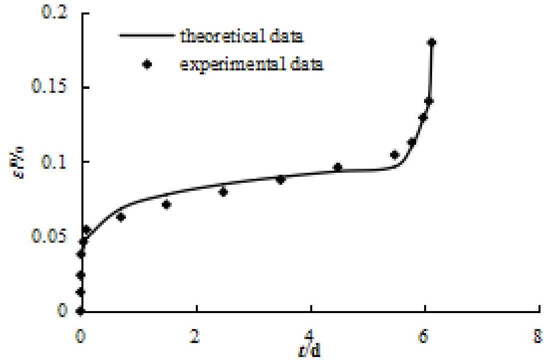
Combined (2), (3), (4), a fractional creep constitutive model considering the effect of water cut can be obtained:

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E_0} + \dfrac{\sigma^{a\omega+b+1}}{\eta_{10}}\dfrac{(2\sqrt{t}+c)t^{\beta-0.5}}{\Gamma(\beta+1)} \\ (\sigma<\sigma_s;\sigma\geq\sigma_s,\varepsilon<\varepsilon_a) \\ \dfrac{\sigma}{E_0} + \dfrac{\sigma^{a\omega+b+1}}{\eta_{10}}\dfrac{(2\sqrt{t}+c)t^{\beta-0.5}}{\Gamma(\beta+1)} + (B\sigma^{a\omega+b}(t-t_a)^m \\ +D)\dfrac{(t-t_a)^\gamma}{\Gamma(\gamma+1)}(\sigma\geqslant\sigma_s,\varepsilon\geq\varepsilon_a) \end{cases} \tag{5}$$

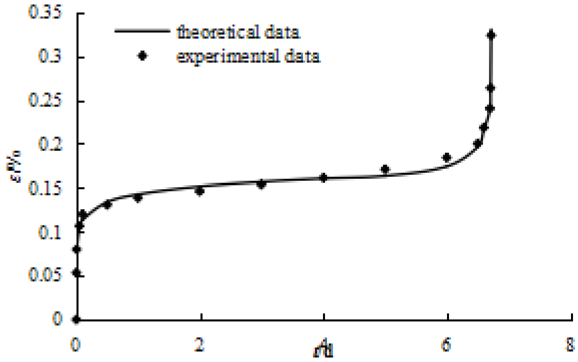
The above constitutive models were used to fit the test data of mudstone under every water content. Limited to the layout the paper only used the last stage of the test data to fit the results. The fitting results are shown in figures 7 and table 1. It can be seen from the chart, the model calculation data fitting well with the experimental data, the correlation coefficient of R^2 was greater than 0.95, shows that the model is available and reasonable.



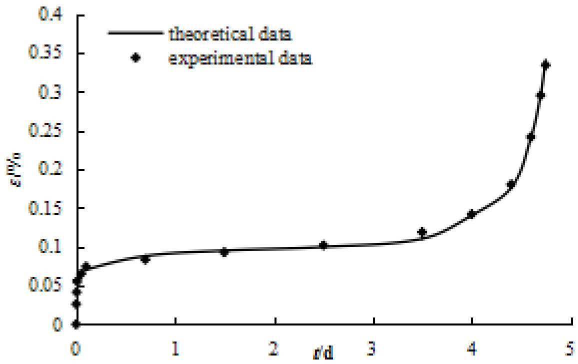
(a) ω=0%



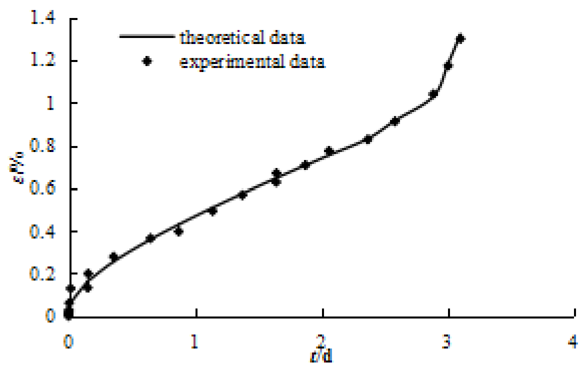
(b) ω=1.5%



(c) ω=2.7%



(d) ω=3.5%



(e) ω=4.1%

Fig.7 The fitting results are compared with the experimental results

Table 1 The model parameters value

ω/%	E/ GPa	η_{10}/ GPa·d^{γ}	γ	β	R^2
0	9.1	140	0.51	1.37	96.1
1.5	12.2	68.36	0.78	1.56	97.4
2.7	6.17	182.7	0.51	1.27	99.3
3.5	5.48	172	0.51	1.12	98.7
4.1	27.8	70.8	0.43	1.69	99.2

4. Conclusion

(1)The instantaneous compressive strength and modulus of elasticity of mudstone decrease exponentially with the increase of water content. The higher the water content, the more significant the softening effect is.

(2)Under the same stress, with the increase of water content, the steady state creep rate increases, and the damage development is faster. Under the same water content, the steady creep rate of mudstone increases with the power function type, and the higher the water content, the stronger the sensitivity of the corresponding force.

(3)Based on previous research experience, a fractional creep constitutive model considering the influence of water content is established. The model can simulate the whole creep process under all water bearing conditions. The theoretical fitting data agree well with the experimental data.

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