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Effect of loading rate change on the mechanical properties of mudstone under uniaxial compression

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Abstract: To study the effect of the loading rate change on the deformation and strength properties and creep behavior of mudstone, a series of uniaxial compression tests and graded loading creep tests was conducted on mudstone specimens at four loading rates (0.005, 0.05, 0.5, and 3 mm/min). The test results find that the mudstone exhibits an obvious loading rate change effect, which is represented by an isotach viscosity behavior. When loading at a constant rate, different stress-strain relationships are observed and corresponded to different constant loading rates. When loading at variable rates, as the loading rate changes, the stress-strain relationships also change. In addition, the loading rate of mudstone prior to creep has a large impact on the creep deformation and creep rate. As the loading rate of mudstone increases before creep, the amount of creep deformation and creep rate show a gradually increasing trend. The mudstone creep rate shows a gradual decay trend over time, and the decay process can be divided into three phases: linear decay, logarithmic decay and stable decay. Furthermore, based on the three-component model and loading rate variation effect, an elasto-viscoplastic constitutive model was established. The developed constitutive model was used for the numerical modeling of mudstone laboratory tests. Compared the modeling results to the laboratory test results, it is found that the elasto-viscoplastic constitutive model can properly simulate the loading rate change effects on the mechanical properties of mudstone under uniaxial compression conditions.

Keywords: mudstone; loading rate; creep; graded loading; viscous property

1 Introduction

Soft rocks are widely distributed in the world such as mudstone, shale, siltstone and argillaceous rocks. Among the different types of soft rock, mudstone and shale are the most widely distributed soft rocks, which accounts for nearly 50% of the soft rocks on the earth surface[1]. In the construction of the tunnel, roadway, dam and slope engineering, mechanical properties of soft rock have an important influence on the engineering stability[2−3]. The loading rate of various load sources such as engineering construction, structural squeezing, and rock burst normally has an obvious impact on the mechanical properties of rocks in engineering practice[4−8]. For instance, stress distribution and stress evolution law of the working face and the host rock masses are often affected by tunnelling speed and coal mining operation, while the actual loading rate is a dynamic variable such as actual driving rate and mining rate.

Some studies found that soft rock (especially the mudstone) has an obvious loading rate effect, which is mainly manifested in that its deformation and strength characteristics vary largely as loading rate changes. In the meantime, as the loading rate increases, the failure mode of mudstone shows a transition law of the brittleness-ductility-brittleness[9−15]. He et al.[16] studied the effect of loading rate on rock. Using clay rocks as the test objects, they found the clay rock showed an approximately linear change trend with the increase of the uniaxial compression loading rate. Qi et al. [17] also studied the effect of rock loading rate, they found that the peak strength of some rock types did not increase as the loading rate increases such as dolomite, limestone, granite and basalt. They mentioned that only when the loading rate was in a specific state, that is, in the quasi-static loading state, these rocks would show obvious loading rate effects. Meng et al.[18] studied the loading rate effect of limestone in the range of 0.001–0.100 mm/s, and they found that as the loading rate increased, the damage extent of the limestone specimen became more serious. Ji et al.[19] conducted triaxial compression tests on the salt rock specimens under different confining pressures and different strain rates, and they divided the influence of loading rate on the triaxial strength of salt rock into three stages: an elastic stage without obvious effect, a plastic initial stage that was formed by the strength difference, and a strain hardening stage as the strength differences were maintained.

Based on the sandstone splitting tests under five loading rates, the effect of loading rates on the tensile strength and the influence mechanism were analyzed. While in the creep tests under different loading rates, as the loading rate increased, the greater the strain

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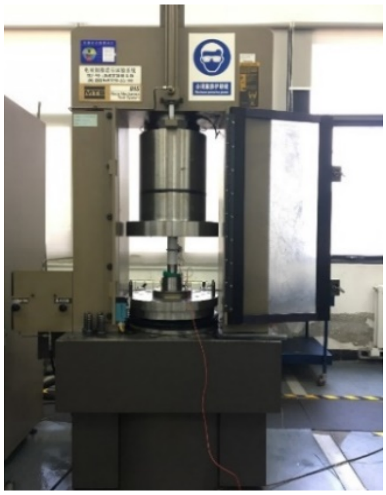
increment of the red sandstone creep attenuation, the smaller the strain increment of the constant velocity creep[20–22]. To examine the effect of loading rate on the brittle failure of granite based on an energy point of view, a series of uniaxial compression tests on granite was performed under four loading rate conditions. It was found that the stress-strain changes of the granite specimen with time were similar to the stress relaxation curve and creep strain curve[23-24]. Heap et al.[25] confirmed that the creep rate of basalt was closely related to the stress level during creep using triaxial compression tests. They found that when the stress of basalt specimen increased by 20%, the creep rate increased nearly 3 orders of magnitude. In the triaxial creep tests of siltstone, Hu et al.[26] found that the initial creep rate increased as the stress level grew, and the time required for the siltstone creep to enter into the steady-state stage also prolonged.

To sum, the loading rate has an obvious impact on the mechanical properties of rock. At present, the compression tests of the rock are mainly used to investigate the loading rate effect. However, the current studies are mostly focused on the influence of constant loading rate on the rock stress–strain relation, and less attention has been paid to the influence of different loading rates, especially the loading rate change on the rock deformation strength characteristics. The loading rate effect and its change effect are essentially an external reflection of the material's viscosity characteristics. No fully unified loading rate standard can be found in the current rock test specifications. Normally, the strain rate $\dot{\varepsilon}$ in the range of 10^{-6} – 10^{-4} s^{-1} is considered as low strain rate, $\dot{\varepsilon}$ in the range of 10^{-4} –10^{-2} s^{-1} is considered as medium strain rate, and when $\dot{\varepsilon}$ exceeds 10^{-2} s^{-1}, it is viewed as high strain rate[27]. At present, most of the research on the rock dynamic response is conducted under high strain rate condition. In the meantime, most of the research on the loading rate effect is conducted on hard and brittle rocks, and few studies are found on soft rocks such as mudstone. In this study, mudstone is taken as the research object, medium and low strain rates are used to conduct compression tests and hierarchical creep tests on mudstone specimens under uniaxial conditions. The deformation strength behaviour and creep deformation characteristics of mudstone are investigated with the change of loading rate. An elasto-viscoplastic constitutive model is built and used to better describe the effect of the loading rate change of mudstone under uniaxial compression, and the simulation is realized for the loading process.

2 Test summary

In the test, the mudstone specimen is a cylindrical sample with ϕ50 mm×100 mm and the bedding direction of the sample is all horizontal. The test device is the MTS815 electro-hydraulic servo rock test system, as shown in Fig.1.

(a) Mudstone specimens



(b) Test apparatus

Fig. 1 Uniaxial compression and creep tests of mudstone specimens

To reduce the influence of the rock sample discreteness on the test results, it is necessary to perform ultrasonic testing and analysis on the prepared standard rock specimens and obtain the corresponding wave velocity data. The rock specimens are then selected based on the wave velocity in the range of 2.0 –2.5 km/s. The selected rock specimens are finally used to conduct uniaxial compression test and graded creep test. To consider the influence of loading rate and its change on the characteristics of the deformation strength and creep deformation of mudstone, the test plan under uniaxial compression condition is as follows[28]:

The uniaxial compression tests include two test types: constant loading rate test and variable loading rate test. In the constant loading rate UCS tests, four loading rates are selected to compress the rock specimens, which are 0.005, 0.050, 0.500, and 3.000 mm/min. As for the variable loading rate UCS tests, which means that after loading at a constant rate for a certain period time, the loading rate is then suddenly changed to another constant rate when the stress reaches 50% of its peak strength, and then the loading is continued under the changed loading rate. In this study, three sets of mudstone specimens are tested with variable loading rates, and the loading histories are 0.005→0.05 mm/min, 0.05→0.5

mm/min, and 0.5→3 mm/min, respectively.

A graded loading method is adopted for the creep test. Considering the influence of the loading rate on the stress–strain characteristics of mudstone specimens, the relative stress level is used for grading in the test. First, the load level is classified according to the peak strength q_c obtained from the UCS test under different loading rates and the load levels are 35% – 40% of q_c (level 1), 60% – 65% of q_c (level 2), and 75% – 90% of q_c (level 3), respectively. During the actual test, the UCS tests are performed at four loading rates with 0.005, 0.05, 0.5, and 3 mm/min, respectively. When the compression load reaches the above-mentioned graded stress level, the creep loading test is then performed. The creep loading duration is maintained about 2 h for each stress level.

3 Effect of loading rate change

3.1 Effect of constant loading rate on deformation and strength characteristics of mudstone

Figure 2 shows the axial stress–strain relations of mudstone under uniaxial compression tests with different loading rates. The four loading rates are set as 0.005, 0.05, 0.5, and 3 mm/min, respectively. Table 1 presents the peak strength q_c values and the maximum strain ε_c (the strain corresponding to the peak axial stress) of mudstone under the corresponding loading rates. The test results show that the stress–strain curve changes accordingly with the loading rate change. The stress–strain curves of mudstone specimens have an obvious elastic stage and a failure stage, and a clear step-like decline phenomenon in the failure stage. As the loading rate increases, the peak strength of mudstone exhibits an increasing trend. Specifically, as the uniaxial compression loading rate increases from 0.005 mm/min to 3 mm/min, the peak strength of mudstone grows from 6.9 MPa to 12 MPa with a strength increase of about 74%.

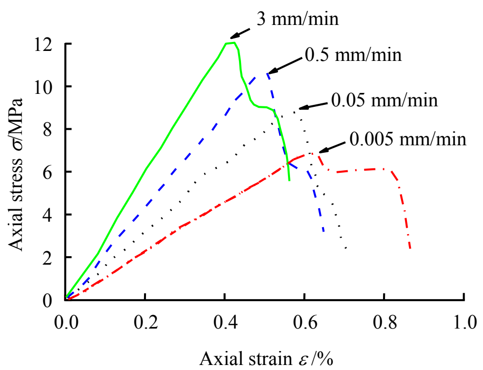


Fig. 2 Stress–strain relations of mudstone specimens at different loading rates

Table 1 The peak strengths and strains of mudstone under uniaxial compression tests

Loading rate v /(mm • min^{-1})	Peak strength q_c /MPa	Maximum strain ε_c /%
0.005	6.9	0.63
0.050	8.8	0.58
0.500	10.7	0.51
3.000	12.0	0.42

3.2 Effect of variable loading rate on deformation and strength characteristics of mudstone

Figures 3–5 depicts the stress–strain relations of three set mudstone specimens under the variable loading rate conditions in the UCS tests.

Figure 3 shows the stress–strain curve when the loading rate increases from 0.005 mm/min to 0.05 mm/min, and also presents the mudstone stress–strain curves under the constant loading rate in the UCS tests at the loading rate of 0.005 mm/min and 0.05 mm/min, respectively. At the beginning of the UCS test, the mudstone is loaded at a constant rate of 0.005 mm/min. When the strain is loaded to 0.3% (the stress is about 50% of its peak strength), the axial compression loading rate is then raised to 0.05 mm/min. The stress–strain curve has a clear upward change that arises from the loading rate increasing. Afterward, the load is continued at this loading rate, it is found that the stress–strain relation curve tends to be similar to the stress–strain relations of the UCS test performed at a constant loading rate of 0.05 mm/min.

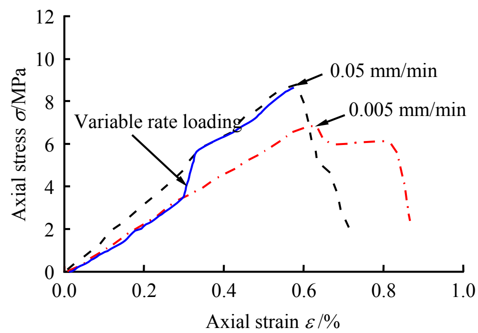


Fig. 3 Mudstone compression test at variable loading rate from 0.005 mm/min to 0.05 mm/min

The test results show similar observations for other variable loading rate UCS tests in this study, as shown in Fig.4 and Fig.5. It is found from these test results that during the mudstone UCS tests, when the loading rate changes suddenly, the stress–strain does not follow the initial stress–strain curve corresponding to that at constant loading rate, while it shows relatively high rigid and nearly elastic deformation behaviour. After the loading rate changes and as the uniaxial compression continues, the strain still maintains an increasing trend and the stress–strain curve after the sudden loading rate change gradually tends to follow the stress–strain curve shape at a related constant loading rate.

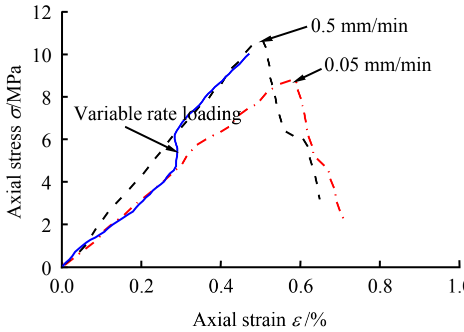


Fig. 4 Mudstone compression test at variable loading rate from 0.05 mm/min to 0.5 mm/min

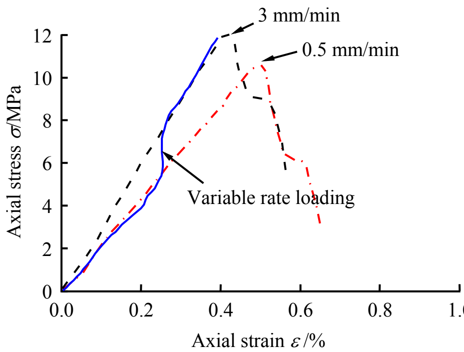


Fig. 5 Mudstone compression test at variable loading rate from 0.5 mm/min to 3 mm/min

The loading rate effect of geotechnical materials and its change effects are essentially one of the external manifestations of the viscous properties. Under the condition of changing loading rate, it can be seen from Figs.3–5 that the loading rate-related behaviours of mudstone are similar to that of soft clay, showing an isotach viscosity[29]. Specifically, during the variable loading rate UCS tests, the stress–strain relations change accordingly because of the sudden change of the axial compression loading rate, and the stress–strain relations after the sudden change of axial compression loading rate maintain the change rule. In other words, the change law is consistent with the stress–strain relation when a constant loading rate UCS test is performed at the desired sudden change rate, as shown in Fig.6. The results show that the effect of loading rate change on the mudstone stress–strain relation is permanent, which is different from the instantaneous viscosity characteristics of sand soil. It is known that the impact of loading rate change on the stress–strain relations of sand soil is kind of instantaneous with an ‘overshooting’ or ‘undershooting’ phenomenon [29].

3.3 Effect of loading rate on creep characteristics

3.3.1 Analysis of mudstone creep characteristics under different loading rates

Figures 7–10 show the stress–strain–time relations of mudstone under UCS tests with three-level creep loading under four loading rates at 0.005, 0.05, 0.5, and 3 mm/min, respectively. Under various creep stress levels (σ/q_c), mudstone shows obvious creep behaviours. It is seen from Figs.7 to 10 that when the specimen is reloaded after creep stage, similar to the variable rate loading situation described above, a high stiffness and approximate elasticity change trend is found herein. When the loading rate is 3 mm/min, the peak strength is 12 MPa, and the corresponding stress level during the third-level creep is 10.58 MPa, which is very close to its peak strength (88%). At this stress level, accelerated creep occurs (see Fig.10). It is therefore, safe to conclude that the mudstone is very prone to subject creep damage when the stress level is close to its peak strength during creep.

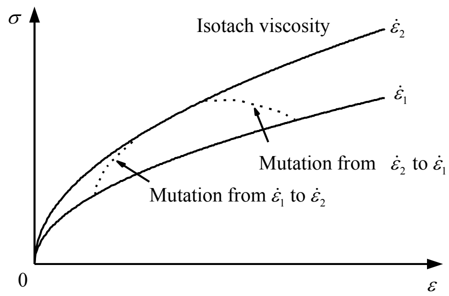
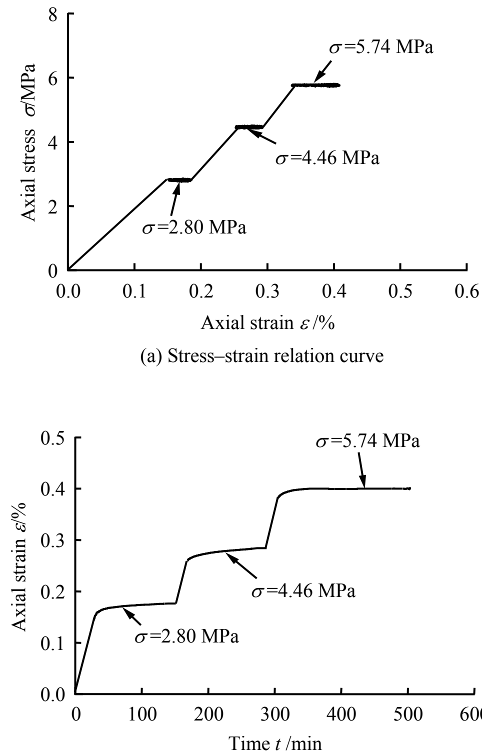


Fig. 6 Isotach viscosity



(a) Stress–strain relation curve

(b) Graded creep curve

Fig. 7 Graded creep test of mudstone at a loading rate of 0.005 mm/min

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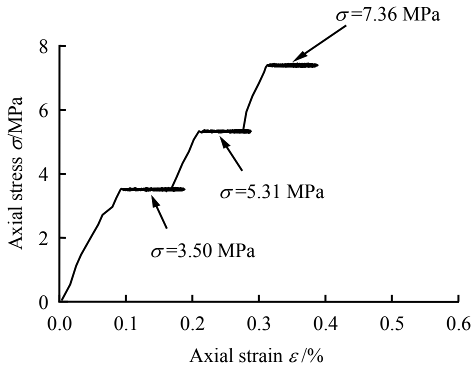
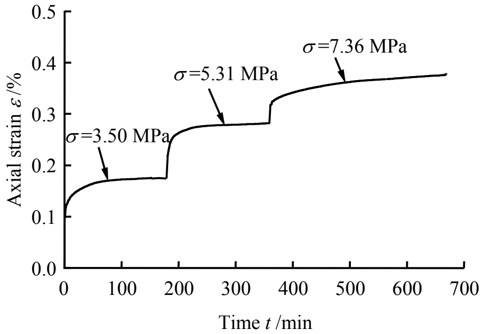
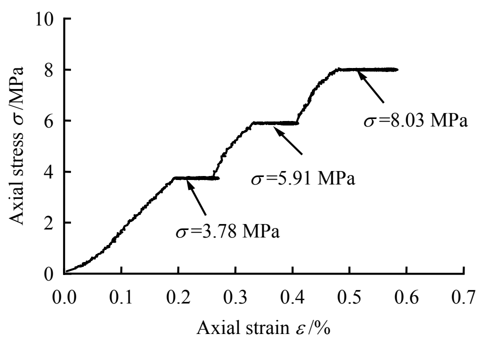


(a) Stress–strain relation curve

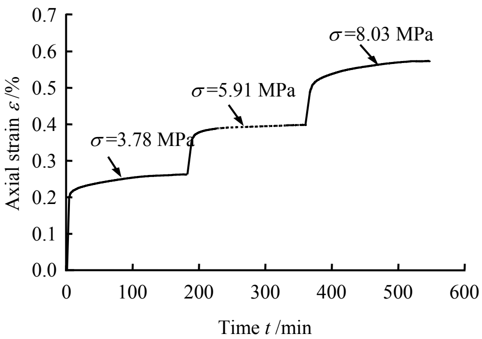


(b) Graded creep curve

Fig. 8 Graded creep test of mudstone at a loading rate of 0.05 mm/min

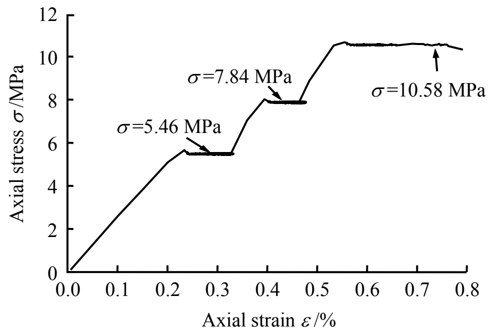


(a) Stress–strain relation curve

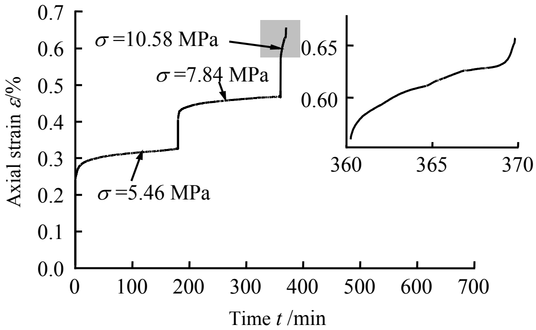


(b) Graded creep curve

Fig. 9 Graded creep test of mudstone at a loading rate of 0.5 mm/min



(a) Stress–strain relation curve



(b) Graded creep curve

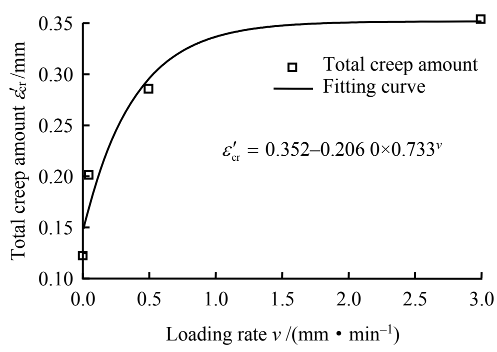
Fig. 10 Graded creep test of mudstone at a loading rate of 3 mm/min

In addition, when the loading rate is the same before creep, the higher the stress level during creep, the larger the creep amount, which is closely related to the shape of the stress–strain curve, that is, the stiffness of the stress–strain curve gradually declines as the loading progresses. On the other hand, when the stress level is the same during creep, the faster the loading rate before creep, the greater the creep amount. While as the stress level increases during creep, the effect of the loading rate before creep on the creep amount becomes smaller, and vice versa. It is seen that the stress level during creep and the loading rate before creep are two key factors that affect the creep behaviours. The influence mechanism of the stress level during creep on the creep of soft rock is the same as the existing study conclusions. The following sections will focus on the analysis of the influence of the loading rate before creep on creep characteristic, and the influence of the loading rate before creep and the stress level during creep on the creep rate, but the contribution portion of the two factors to the creep deformation and the mutual conversion mechanism still need further study.

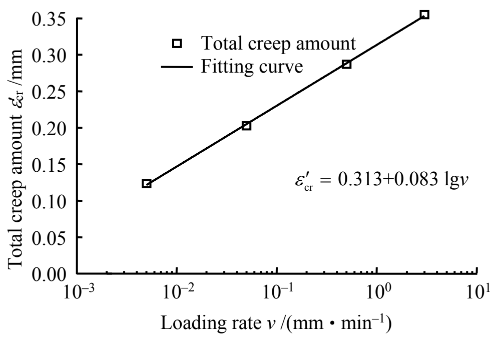
3.3.2 Effect of loading rate on creep amount

When compared with the creep amount of the creep test after loading with loading rate of 0.005 mm/min, for the first-level creep loading, the corresponding creep amount increases 170.72%, 231.08%, and 236.94%, respectively when the loading rate before creep is 0.05, 0.5, and 3 mm/min. For the second-level and third-level of creep loading, the creep amount has a similar growth trend compared with that of the first-level creep loading scenario. It is found that for the same level of creep loading, as the pre-creep loading rate rises, the creep amount gradually increases, however, the growth trend slows down gradually.

To obtain the total creep amount ε'_{cr} of mudstone for a total of 6 h under different uniaxial compression rates, the cumulative creep deformation is calculated during the creep loading test under various stress levels, and the result is shown in Fig.11(a). In the semi-logarithmic space, a linear relation is found between the creep amount and the logarithm of the loading rate, as shown in Fig.11(b). It is observed that with the increasing of the pre-creep loading rate, the total creep amount of mudstone shows an increasing trend with the gradual increase of the pre-creep loading rate, however, the increasing trend of the total creep amount shows the characteristic of slowing down gradually. For instance, when the axial loading rate increases from 0.005 mm/min to 3 mm/min, the total creep amount of mudstone rises from 0.123 4 mm to 0.202 5, 0.282 6, and 0.354 9 mm. The increased extent of the total creep is 64%, 40%, and 26%, respectively. The variation law of the total creep amount with the loading rate is basically the same as that of the creep amount under each stress level creep loading.



(a) ε'_{cr} -v relation



(b) ε'_{cr} -lg$v$ relation

Fig. 11 Relations between the total creep amount and the loading rate before creep stage

3.3.3 Effect of loading rate and stress level on creep rate

To study the effect of the pre-creep loading rate on the creep rate, the creep deformation under the same stress level can be analyzed under different loading rates. Hereafter, the first-level creep curve is used for analysis. Figure 12 shows the variation of the creep rate against time for the first-level creep under different loading rates. It should be noted here that the other two stress levels of creep loading show similar trends when compared with that from the first-level creep curve.

When the uniaxial compression loading rate decreases from 3 mm/min to 0.005 mm/min in pre-creep tests, the maximum creep rate of mudstone changes from 0.015 9 mm/min to 0.012 4, 0.007 6, and 0.004 9 mm/min, respectively. The creep rate evolution of mudstone with time can be divided into three stages under relative higher loading rate (such as 0.5 and 3 mm/min): (1) a linear decay stage: within five minutes of mudstone creep, the creep rate shows a linear and rapid decay; (2) a logarithmic decay stage: when the mudstone creep time is in the range of 5 – 50 min, the creep rate gives a logarithmic slow decay change rule; and (3) a stable stage: when the creep time surpasses 50 minutes, the decay of the creep rate becomes slow and will finally be stabilized. Due to the facts of low loading rate of mudstone before creep and the small maximum creep rate, when the loading rate is relatively small (such as 0.005 and 0.05 mm/min), the difference between the linear stage and the logarithmic stage of the creep rate decay process is not obvious compared that with the higher loading rate situations. The axial compression loading rate before mudstone creep has a large impact on the decay rate of the creep rate in the decay stage. The faster the loading rate is, the faster the creep rate decays, and vice versa. While regardless of whether the loading rate is fast or slow before creep, the corresponding creep rate will eventually enter into a stable state at stage (3).

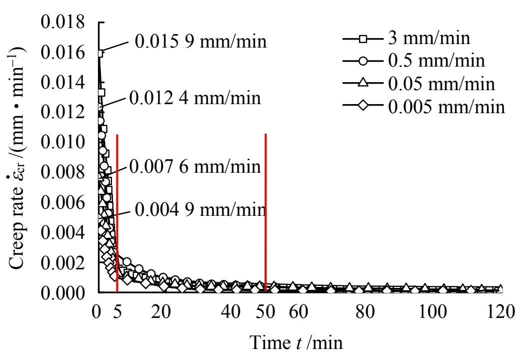


Fig. 12 Creep rates of mudstone at different loading rates

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The linear decay stage and the logarithmic decay stage of mudstone creep rate last for a short time (i.e., 50 min), and the cumulative amount of creep deformation caused by the two stages exceeds 70% of the total creep deformation. The maximum creep rate determines the amount of creep deformation in a short time. It is hence useful to use the maximum creep rate as an important indicator to analyze the characteristics of mudstone creep deformation. Figure 13 presents the relations between the maximum creep rate and the loading rate before creep under different stress levels. When the loading rate of mudstone before creep is the same, the maximum creep rate shows a decline tendency with increasing the stress level during creep, however, the decline trend is gradually strengthened as the loading rate prior to creep grows. When creeping under the same stress level, the maximum creep rate rises with the increase of the loading rate prior to creep.

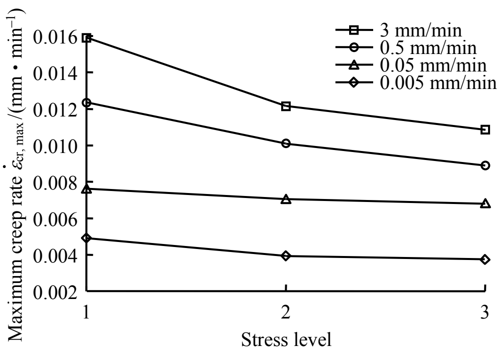


Fig. 13 Maximum creep rate of mudstone under different stress levels

4 Elasto-viscoplastic constitutive model and its verification

4.1 Elasto-viscoplastic constitutive model

In this study, a nonlinear three-component model is used to describe the elasto-viscoplasticity of mudstone. The three-component model can better depict the elasto-viscoplasticity of the rock and soil materials, especially for the rate-related viscosity characteristics, including the isotach viscosity and the instantaneous viscosity[29–31]. The nonlinear model consists of three components, namely elastic element *E*, viscous element *V*, and plastic element *P*, as shown in Fig.14.

The total strain rate and total stress can be obtained:

$$\dot{\varepsilon} = \dot{\varepsilon}^{e} + \dot{\varepsilon}^{ir}, \quad \sigma = \sigma^{f} + \sigma^{v} \tag{1}$$

where $\dot{\varepsilon}$, $\dot{\varepsilon}^{e}$, and $\dot{\varepsilon}^{ir}$ denote total strain rate, elastic strain rate, and unrecoverable strain rate, respectively; σ, σ^{f}, and σ^{v} stand for the total stress, non-viscous stress, and viscous stress, respectively.

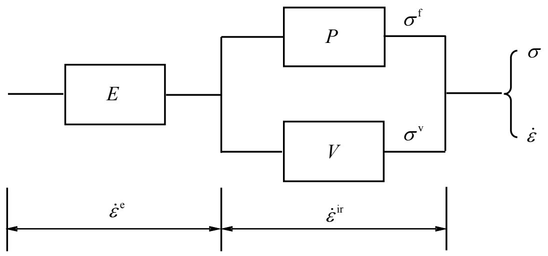


Fig. 14 Nonlinear three-component elasto-viscoplastic model

Under the uniaxial compression condition, the elastic component *E* of mudstone can be described by a sub-elastic model $\dot{\varepsilon}^{e} = \dot{\sigma}/E_{eq}$, where E_{eq} is the equivalent elastic modulus. The equivalent elastic modulus of mudstone is determined as 51.72 MPa using the cyclic loading and unloading test.

The relation between the non-viscous stress σ^{f} and the unrecoverable strain ε^{ir} is represented by component *P*, which is irrelevant with the uniaxial compression rate and corresponds to the stress–strain relation when the loading rate is zero. The plastic component *P* can be described by a conventional elasto-plastic constitutive relation or the plastic component *P* can also be expressed as any reasonable empirical equation such as a polynomial. Based on the mudstone test results under uniaxial compression, after fitting and analyzing the results of the constant rate test, the following 5th-degree polynomial can be used to denote the component *P* in the mudstone elasto-viscoplastic model:

$$\sigma^{f} = -0.035 + 8.05\varepsilon^{ir} + 35.99(\varepsilon^{ir})^{2} - 116.14(\varepsilon^{ir})^{3} + 138.83(\varepsilon^{ir})^{4} - 47.55(\varepsilon^{ir})^{5} \tag{2}$$

Based on the above analysis, mudstone exhibits isotach viscosity characteristics. In this consideration, the viscosity component *V* can be described by a rate-dependent constant-velocity viscosity model. In such condition, the viscous stress σ^{v} is a function of the irrecoverable strain ε^{ir} and its rate $\dot{\varepsilon}^{ir}$, and could have a certain proportional relation with σ^{f} [30]:

$$\sigma^{v} = \sigma^{v}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}) = \sigma^{f}(\varepsilon^{ir}) \cdot g_{v}(\dot{\varepsilon}^{ir}) \tag{3}$$

where the proportional coefficient $g_{v}(\dot{\varepsilon}^{ir})$ is a function that represents the material viscosity behaviours. For geotechnical materials, it can be assumed to be as

$$g_{v}(\dot{\varepsilon}^{ir}) = \alpha\{1 - \exp[1 - (\dot{\varepsilon}^{ir}/\dot{\varepsilon}_{r}^{ir} + 1)^{m}]\} \tag{4}$$

where α, $\dot{\varepsilon}_{r}^{ir}$, and *m* are all the positive material constants. According to the aforementioned variable loading rate UCS tests, the parameters in the viscosity function of mudstone are calculated as α=0.8, $\dot{\varepsilon}_{r}^{ir} = 1.0\times10^{-5}$ %/s and $m = 0.25$, respectively.

4.2 Model verification

In this section, the elasto-viscoplastic constitutive model is used to conduct a direct numerical simulation of the aforementioned mudstone UCS tests under various loading conditions, and the results are compared with the test results in order to verify the elasto-viscoplastic constitutive model of mudstone proposed in this study. The model parameters of mudstone in this study can be found in section 4.1. In the simulation, the load method is used to control the creep loading, and the displacement speed method is used to control the uniaxial loading. The displacement speed is determined based on the time history of the axial strain during each uniaxial loading test.

Figures 15 to 17 show the simulation results as well as the comparative results with the observations. Figure15 shows the result comparison of the uniaxial compression tests under different constant rates (see Fig.2). Figure 16 gives the comparison results of the uniaxial compression tests at variable loading rates (see Figs.3–5), and Fig.17 presents the comparison results of the graded loading creep tests (see Figs.7–10). From these comparison results, it is seen that the proposed elasto-viscoplastic model can describe the rate-related characteristics of mudstone before the peak strength. The model can simulate the whole process of loading and can better simulate the stress–strain relation of mudstone under different loading history conditions, including constant rate loading, variable rate loading and graded creep loading, especially in the following aspects:

(a) when the loading rate changes, the behaviour of high rigidity and approximate elasticity is observed when the creep continues to compress at the new loading rate; (b) characteristic of the creep amount increasing with increasing the stress level; and (c) feature of the faster the maximum creep rate, the larger the creep amount. In addition, the model parameters determined based on the variable rate loading test can be better used to simulate the effect of loading rate on the mudstone creep characteristics.

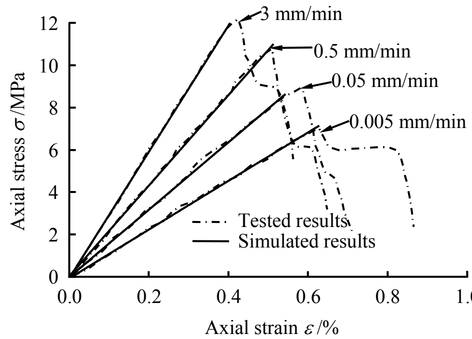
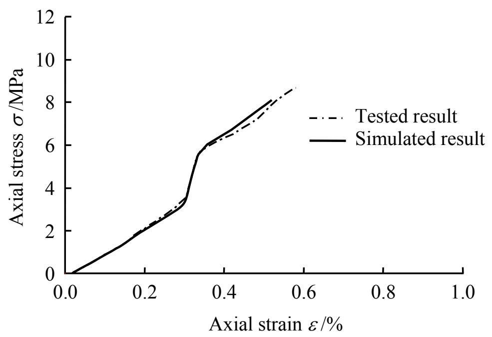
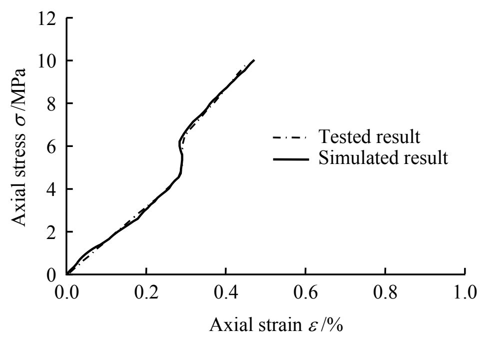


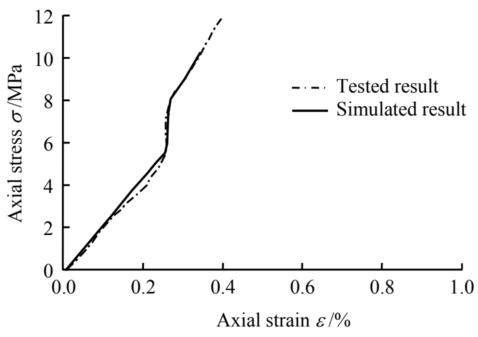
Fig. 15 Comparison between the tested and simulated results of uniaxial compression tests under different constant rate loading



(a) Loading rate changes from 0.005 mm/min to 0.05 mm/min

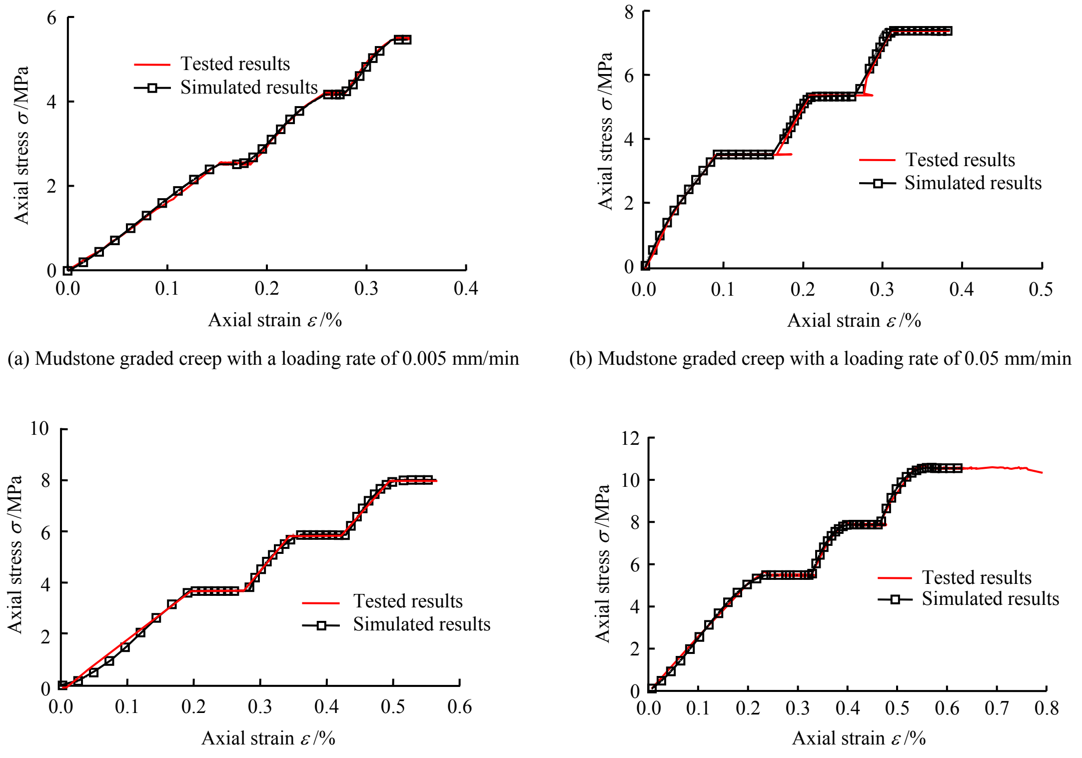


(b) Loading rate changes from 0.05 mm/min to 0.5 mm/min



(c) Loading rate changes from 0.5 mm/min to 3 mm/min

Fig. 16 Comparison between the tested and simulated results of uniaxial compression tests under variable rate loading



(a) Mudstone graded creep with a loading rate of 0.005 mm/min

(b) Mudstone graded creep with a loading rate of 0.05 mm/min

(c) Mudstone graded creep with a loading rate of 0.5 mm/min

(d) Mudstone graded creep with a loading rate of 3 mm/min

Fig. 17 Comparison between tested and simulated results of mudstone creep tests under graded loading considering loading rate effect

5 Conclusions

(1) An obvious effect of the loading rate change on the mudstone is observed in this study, that is, the stress–strain relation changes correspondingly with the different constant loading rates. Under the variable rate loading condition, the mudstone specimen exhibits an isotach viscosity characteristic.

(2) The loading rate before creep has a large effect on the creep amount of mudstone. Within the same creep time, the creep amount of mudstone rises largely with the loading rate increases, but the increasing trend of creep slows down gradually.

(3) The loading rate before creep has a greater influence on the creep rate of mudstone. It is found that the faster the loading rate before creep, the faster the corresponding creep rate.

(4) The creep rate decays rapidly within the first five minutes of creep. The process can be divided into three stages: a linear decay stage, a logarithmic decay stage, and a stable stage, however, the difference between the linear stage and logarithmic stage is not conspicuous when the loading rate is relatively low.

(5) Based on the nonlinear three-component model, an elasto-viscoplastic constitutive model of mudstone is developed in this study. The proposed model can better describe the effect of the loading rate change for mudstone under uniaxial compression, and can also better capture the behaviour of rate-dependent viscosity such as the effect of loading rate on creep characteristics.

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