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Experimental study on creep characteristics of infiltrated coal-rock under load

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Abstract: For the water-rich zone in the coal tunnel rock body perennial suffer from water infiltration destabilization destruction problem. In this paper, the influence of stress level and infiltration time on the creep properties of coal-rock was systematically studied after the water infiltration test, scanning electron microscope (SEM), water content test, uniaxial compressive strength test and creep mechanical properties test. The whole process of coal-rock creep is described by Hooke's body, Kelvin body and damage elastic-plastic body, and the total damage variable was introduced to show the weakening effect of the coupling effect of stress and water infiltration on the creep properties of coal-rock. A creep constitutive model of coal rock damage considering the weakening effect of water infiltration was established, besides, the influence law of stress level and infiltration time on creep parameters of coal rock was analyzed. The study shows that coal rocks underwent a process from surface drying and shrinkage to water absorption and swelling to

water-filled infiltration damage in the infiltration test. With the increase of infiltration time, the water content of coal-rock tended to increase and eventually stabilizes, while the uniaxial compressive strength gradually decreased. With the increase of stress level and infiltration time, the stable creep strain of coal-rock kept increasing which accelerated creep advance, and its internal damage continued to accumulate and eventually led to destabilization damage. At the same stress level, the creep parameter E_0 showed a tendency to increase and then decreased with the increase of infiltration time, while E_1 , η_1 , t_F , E_2 and ν continued to decrease. Combined with the microstructural changes of coal rocks in the water infiltration process, the change law of mechanical properties of infiltrated coal-rock and the intrinsic softening mechanism were revealed. Comparing the theoretical model of infiltrated coal rock creep with the experimental data, the model developed in this paper reflected the whole process of infiltrated coal-rock creep deformation and damage, and can characterize the influence of infiltration time and stress level on coal-rock creep properties, which verified the reasonableness of the model.

Key words: coal-rock creep; stress level; wetting time; experimental research; constitutive model

1 Introduction

Since the depletion of shallow resources and underground space, how to use deep resources and space more efficiently, safely, scientifically, and rationally has attracted widespread attention from scholars all over the world. In the process of

44 construction of deep underground projects, the appearance of groundwater will affect
45 the stability of the project, the influence of groundwater infiltration become
46 significantly. In coal mining, watertight isolated coal pillars are always in the state of
47 groundwater infiltration and subjected to long time effect of roof pressure, resulting in
48 creep phenomenon. With the extension of infiltration time, the creep effect of coal
49 pillar will become more and more obvious, which will lead to the instability of coal
50 pillar and cause safety accidents.

51 At present, researchers worldwide have gotten fruitful results on creep
52 mechanical properties of coal-rock under the effect of stress level, water content and
53 other influencing factors. Baud^[1] et al. analyzed by experimental results that changing
54 the stress levels can influence the rate of strain change and creep of coal-rock.
55 Kurita^[2], Ngwenya^[3] et al. and Heap^[4-6] et al. studied the relationship between stress
56 levels and creep mechanical properties of coal rocks, mainly in terms of effects on
57 creep rate and accelerated creep damage. Schoenball^[7] et al. used Abaqus to apply
58 time-dependent brittle creep to a wellbore damage mechanics model to explain the
59 cause of “V” fracture in situ tests. Brijes^[8] et al. conducted uniaxial and triaxial creep
60 tests on coal-bearing shales to investigate the causes of failure of coal-rock with time
61 under complex stress conditions. Mao^[9] et al. performed creep pre-damage on coal
62 samples using the SAW-2000 rock servo test system and conducted uniaxial
63 compression damage tests to analyze the relationship between the degree of damage
64 and peak strength and elastic modulus. Hadiseh^[10] et al. tested the creep properties of
65 salt rocks and found that the creep deformation is more intense and the creep rate

increases faster as the axial stress increases. Trzeciak^[11] et al. conducted long-time creep tests on shale and showed that the rock exhibited a significant time dependence under constant loading, with the creep strain in shale reaching more than half of the instantaneous strain after two weeks with the extension of loading time.

The above creep test results of coal-rock offer a foundation for the construction of creep models of coal-rock. In recent years, Tan^[12] et al. performed a micro-rheological analysis of the deformation properties of rocks and concluded that creep and confining stress are two fundamental factors in the mechanical properties of rocks, whereby the intrinsic equations of rocks under the action of confining stress, creep and dilation were established. Wang^[13] used the internal variable damage factor and its corresponding rheological deformation to characterize the macroscopic features of the creep-damage continuum of rock salt and developed a new constitutive model of creep damage in rock salt. Yang^[14] et al. developed a nonlinear short-term creep damage constitutive model for coal under triaxial compression conditions based on elastic-plasticity theory combined with damage evolution equations and validated it by experiments. Kang^[15] et al. considered the relationship between viscoelastic-plastic properties of coal-rock and damage, described the creep properties of coal with a fractional-order nonlinear model, and verified the validity of the model by uniaxial creep tests with different axial stresses applied. Wang^[16] et al. considered different degrees of initial damage as well as new damage caused by loading of coal-rock in creep constitutive model. Yuan^[17] et al. analyzed the effect of changing stress levels on strain-time curves under different surrounding pressures by triaxial

consolidation creep tests. Choens^[18] et al. performed creep tests on sandstone specimens from the Zenifim strata by low to medium confining pressure divisions, and developed a continuous damage pore-elastic constitutive model for sandstone considering the effect of gradual accumulation of rock damage.

With the depth of research, some scholars introduced the effect of water on coal-rock into the creep constitutive equation. Wang^[19] et al. studied the mechanical properties of soft rocks under water corrosion and concluded that the fracture effect of soft rock damage under water action is time-dependent. He^[20-21] investigated the creep-percolation coupling effect, and established a creep damage criterion based on the maximum tensile stress theory. Huang^[22] et al. established a rock damage constitutive model considering variable water content by combining the results of experimental studies on creep of muddy siltstone under different water content states. Wang^[23] et al. conducted triaxial creep tests with oil shale as the research object, introduced the nonlinear relationship presented by the damage inside the rock into the model, and constructed a creep constitutive model of oil shale under different water content change rates. Chen^[24] et al. approximated the internal water content of the rock as a switch, while introduced creep damage thresholds into the rock creep constitutive model. Yang^[25] et al. conducted triaxial creep tests on soft rocks under different water-bearing states to analyze the effect of changes in water content on the creep properties of rocks and their damage mechanisms, and obtained an improved nishihara model. Xu^[26] et al. studied in depth the creep change mechanism under different stress levels and water content, and established an time- effect creep damage

model. Hashiba^[27] considered rock strength and creep life theory under the influence of moisture, and obtained the relationship between rock strength and creep life under dry and wet conditions. Zhang^[28] et al. subjected the filling body of the goaf to graded loading creep tests under different water pressures. The results showed that the mechanical properties of the filling body decreased with increasing water injection pressure.

In general, most of the studies on creep properties of rocks in the above results take different stress levels and different water content conditions as influencing factors, while relatively few studies on creep properties of coal-rock under the combined effect of different stress levels and infiltration time. In fact, the change of water content after saturation of coal rock infiltration is weak, but with the increase of infiltration time, the cumulative effect of damage is obvious, and the friction coefficient of its internal structural particles decreases after the continuous lubrication effect of water, which will further aggravate the deterioration of coal rock body and lead to the decrease of bearing capacity. Therefore, this paper studies the creep mechanical properties of coal-rock under the combined action of stress level and infiltration time, analyzes the creep law of infiltrated coal-rock, and reveals the mechanism of creep deformation of coal-rock. To provide some theoretical basis for the prevention and control of soaked coal pillar instability.

2 Model development

In order to describe the whole process of coal-rock creep deformation under load,

the Hooke's body, Kelvin's body and damage elastoplastic body are used to describe the instantaneous stage, decelerating creep stage and the accelerated creep stage of coal-rock, respectively. The total strain ε of coal-rock consists of the instantaneous strain ε_0 of coal-rock simulated by the spring, the viscoelastic strain ε_{ve} simulated by the Kelvin body, and the plastic strain ε_p simulated by the damaged elastic-plastic body, and the schematic diagram is shown in Fig.1.

Fig.1 Creep constitutive model of infiltrated coal-rock

The total strain of the infiltrated coal-rock can be expressed as

$$\varepsilon = \varepsilon_0 + \varepsilon_{ve} + \varepsilon_p \quad (1)$$

The instantaneous strain ε_0 expressed by the Hooke body is

$$\varepsilon_0 = \frac{\sigma_0}{E_0} \quad (2)$$

Where, σ_0 is the stress on the coal-rock; E_0 is the instantaneous modulus of elasticity.

The viscoelastic strain expressed by Kelvin body is

$$\varepsilon_{ve} = \frac{\sigma_0}{E_1} (1 - e^{-\frac{E_1 t}{\eta_1}}) \quad (3)$$

Where, E_1 is the viscoelastic modulus also called the deceleration stage elastic modulus; η_1 is the viscous hysteresis coefficient; t is the creep time.

Taking the damage elastoplastic micro-unit, assuming that the total area S of the micro-unit is composed of damaged and undamaged materials, whose areas are S_1 and S_2 respectively, then there is

$$S = S_1 + S_2 \quad (4)$$

According to the characteristics of the damaged elastoplastic body, stress level of coal-rock σ_0 is greater than the yield strength of the damaged body σ_s before starting work, the actual damage to the elastic body of the stress needs to overcome the yield strength of coal-rock, $\sigma_0 - \sigma_s$, set the force on the undamaged part of the coal-rock to .It can be obtained by the balance principle of force

$$(\sigma_0 - \sigma_s)S = \sigma_1 S_2 \quad (5)$$

Based on the relationship between the damaged area and the total area of coal-rock, the total damage variable is defined as $D_m = 1 - S_2 / S$, which gives

$$\sigma_0 - \sigma_s = \sigma_1 (1 - D_m) \quad (6)$$

The stress-strain relationship obeys Hooke's law, defining the strain of the micro-unit and the undamaged part as ε_p and ε_{p1} . E_2 as the deformation modulus of the damaged elastoplastic body, which called the modulus of elasticity in the accelerated phase, then

$$\sigma_1 = E_2 \varepsilon_{p1} \quad (7)$$

According to the coordination principle of internal deformation of coal-rock, we can get

$$\varepsilon_p = \varepsilon_{p1} \quad (8)$$

Thus, simultaneous Eqs. (7) and (8)

$$\sigma_1 = E_2 \varepsilon_p \quad (9)$$

Substituting Eq. (9) into (6), we can get

$$\sigma_0 - \sigma_s = E_2 \varepsilon_p (1 - D_m) \quad (10)$$

Eq. (10) is the damage elastic-plastic stress-strain relationship of coal-rock

subjected to water infiltration and stress.

There exists creep damage of coal-rock under stress, the Kachanov expression is

$$\frac{dD}{dt} = C \left(\frac{\sigma_0}{1-D} \right)^v \quad (11)$$

Where C and v are both the inherent properties of the coal-rock material which are called coal-rock material parameters. Solving Eq. (11) yields the expression for the creep damage variable D under stress^[29] as

$$D = 1 - \left(1 - \frac{t}{t_F} \right)^{\frac{1}{v+1}} \quad (12)$$

Where, t_F is the creep life, also known as coal rock creep damage time.

When the stress is less than the yield strength σ_s , the coal-rock don't produce damage, and vice versa, produce damage, the model is expressed as follows

$$D = \begin{cases} 0, & \sigma_0 < \sigma_s \\ 1 - \left(1 - \frac{t}{t_F} \right)^\alpha, & \sigma_0 \geq \sigma_s \end{cases} \quad (13)$$

Where, $\alpha = 1/(v+1)$.

In the creep process of the infiltration coal-rock, in addition to the role of stress, there also exists the infiltration of water, which will lead to the softening of coal-rock. In general, the softening coefficient n is used to represent the infiltration effect of water on coal-rock.

$$n = \frac{R_w}{R_d} \quad (14)$$

Where, R_w is the uniaxial compressive strength of the coal-rock specimen in the infiltrated state; R_d is the uniaxial compressive strength of the coal-rock specimen in the dry state.

Define the creep damage variable of coal-rock under infiltration is

$$D_w = 1 - n \quad (15)$$

Combining the relationship between the total damage variable and the sub-damage variables derived in the literature^[30] the total damage variable of coal-rock under stress-infiltration can be written as

$$D_m = D + D_w - DD_w \quad (16)$$

Substituting Eqs. (13), (15) and (16) into Eq. (10), the constitutive model of the damaged elastic-plastic body under stress-infiltration is obtained as

$$\varepsilon_p = \begin{cases} 0, & \sigma_0 < \sigma_s \\ \frac{\sigma_0 - \sigma_s}{E_2} \left[\left(1 - \frac{t}{t_F} \right)^\alpha (2-n) + n - 1 \right]^{-1}, & \sigma_0 \geq \sigma_s \end{cases} \quad (17)$$

Substituting Eqs. (2), (3) and (17) into Eq.(1), we can obtain the damage creep constitutive model of coal-rock considering infiltration time and stress level

$$\varepsilon = \begin{cases} \frac{\sigma_0}{E_0 n} + \frac{\sigma_0}{E_1 n} \left(1 - e^{-\frac{E_1 t}{\eta_1}} \right) & \sigma_0 < \sigma_s \\ \frac{\sigma_0}{E_0 n} + \frac{\sigma_0}{E_1 n} \left(1 - e^{-\frac{E_1 t}{\eta_1}} \right) + \frac{\sigma_0 - \sigma_s}{E_2} \left[\left(1 - \frac{t}{t_F} \right)^\alpha (2-n) + n - 1 \right]^{-1} & \sigma_0 \geq \sigma_s \end{cases} \quad (18)$$

Where E_0 , E_1 and E_2 correspond to the instantaneous modulus of elasticity, the modulus of elasticity in the deceleration creep phase and the modulus of elasticity in the acceleration creep phase, shown in Fig.1, respectively; α is a coefficient on the material parameters of the coal-rock; η_1 is the coefficient of coal-rock viscosity; t_F is the creep life of coal-rock.

3 Overview of the experiment and analysis of results

3.1 Specimen preparation and test protocol

The fresh coal blocks retrieved from the mine site are processed into

214 $\Phi 50\text{mm} \times 100\text{mm}$ cylindrical international standard rock samples according to ISRM
215 recommendations, after core sampling from the set of holes and cutting and grinding
216 processes. The specimens with obvious defects are removed before the test, and then
217 the specimens with similar wave speed are selected for the test by ultrasonic detector,
218 so as to reduce the influence of coal-rock discreteness on the test results.

219 In order to study the creep law of coal-rock under the long time action of water
220 infiltration and stress, the following test procedure is designed:

221 (1) The specimens were subjected to a water continuous infiltration test, and the
222 specimens were taken out without infiltration, saturated with infiltration and after 120
223 days of infiltration for SEM to obtain their mesoscopic structural features.

224 (2) Three specimens were selected for uniaxial compression tests to obtain the
225 average compressive strength value σ_c of the coal-rock, which was then used to
226 classify the stress levels for uniaxial creep tests as $30\%\sigma_c$, $40\%\sigma_c$, $50\%\sigma_c$, $60\%\sigma_c$,
227 $70\%\sigma_c$ and $80\%\sigma_c$, respectively.

228 (3) Put the coal-rock specimens in the natural state into the drying oven, and to
229 ensure that the coal samples are completely dried, remove the coal samples from the
230 oven every 0.5 hours and weigh them on a high-precision balance until the mass no
231 longer changes; measure the mass of the specimens under different infiltration times,
232 and obtain the water content of the specimens with infiltration times of 0, 1, 3, 7, 15
233 and 30 days, respectively.

234 (4) Uniaxial creep tests with stress levels of $30\%\sigma_c$, $40\%\sigma_c$, $50\%\sigma_c$, $60\%\sigma_c$,
235 $70\%\sigma_c$, and $80\%\sigma_c$ were performed simultaneously on specimens infiltrated for 0, 1, 3,

7, 15, and 30 days.

3.2 Mesoscopic structural properties of infiltrated coal-rock

The coal-rocks under vacuum were scanned using COXEM EM-30 Plus SEM in dry condition, natural water absorption saturated condition and after 120 days of infiltration water with a magnification of 500 times. The results are shown in Fig.2.

As can be seen in Fig.2, it can be seen that the mesoscopic structure of coal rocks has been greatly changed under the action of water infiltration. As shown in Fig.2(a), the clay particles in the dry state are cemented together to form a larger lamellar structure. The units are assembled into larger particles with fine particles, and the pores are relatively uniformly distributed between the particles. As shown in Fig. 2(b), water is infiltrated in coal-rock and the open pores and fissures is filled by water body. The reason is that a large number of clay minerals absorb water and swell, resulting in the narrowing of the pores between the coal-rock. While in Fig. 2(c), the connection between coal rock particles became looser after 120 days of infiltration, and the initial tight, high-strength structure was gradually transformed into a porous, loose structure by the infiltration time. Meanwhile, more larger pores can be detected in the coal rock, and flocculent material can be seen locally, and the mineral particles are basically distributed in a flaky or flocculent structure.

(a)

(b)

(c)

Fig.2 Mesostructure of coal rock;(a) Uninfiltrated state,(b) Natural water absorption saturation state,(c) State after 120 days of infiltration

Scanning electron microscopy results show that water infiltration causes internal damage to coal-rock. The kerogen undergoes a process from surface drying and shrinkage to water absorption and swelling to water-saturated infiltration damage during the infiltration process. In the dry state, the surface of coal-rock is rough and prone to dry shrinkage, and the micro-features show that the microstructure of internal minerals is sharp and angular. After infiltration and water absorption, the minerals

swell with water, and the surface bulges minerals especially so, so that the original cemented skeletal structure becomes softened and full, and the surface of coal-rock is more rounded and smooth. As the infiltration time continues to increase, the cement gradually dilutes, the internal volume of the coal-rock expands, the pores increase and new cracks are created, and the infiltration action continues to accumulate damage to the coal-rock.

3.3 Influence of infiltration time on water content and strength of coal-rock

The results of water content of the specimens and their uniaxial compressive strength under the influence of infiltration time, as shown in Fig.3.

Fig.3 Influence curve of water content and uniaxial compressive strength of coal with infiltration time

From Fig.3, it can be seen that the infiltration time increased from 0 to 1 day and the water content of coal-rock increased from 0 to 6.375% with an increase of 100%. The infiltration time increased from 1 to 3 days and the water content of coal-rock increased from 6.375% to 8.258%, an increase of 29.96%. The infiltration time increased from 3 to 7 days and increase in coal-rock water content from 8.258% to 8.481%, an increase of 2.70%. The infiltration time increased from 7 to 15 days and

the water content of coal-rock increased from 8.481% to 8.492%, an increase of 0.13%.The infiltration time increased from 15 to 30 days, and the water content of coal rock increased from 8.492% to 8.518%, an increase of 0.31%.It can be seen that, with the increase of infiltration time, the water content of coal rock is increasing but its change rate gradually decreases and stabilizes, and the water content of coal rock is 8.481% at 7 days of infiltration, compared with the water content of 8.518% at 30 days of infiltration, almost no change occurs.

It can be seen that, with the increase of infiltration time, the water content of coal-rock is increasing but its change rate gradually decreases and stabilizes, and the water content of coal-rock is 8.481% at 7 days of infiltration, compared with the water content of 8.518% at 30 days of infiltration, almost no change occurs.The analysis shows that with the extension of infiltration time, the water content after infiltration saturation, although maintaining the same but the uniaxial compressive strength of coal rock decreases, and the mechanical properties continue to weaken.As shown in Fig.2, the prolonged infiltration of water molecules in coal rock fissures reduces the cohesion between coal-rock particles, causing its overall structure to become porous, loose and soft, which leads to the weakening of the overall macroscopic mechanical properties.Therefore, the infiltration time is an important influence factor for the mechanical properties of coal-rock.

3.4 Influence of infiltration time and stress level on creep mechanical properties of coal-rock

There are two main factors that affect the creep properties of coal-rock. Under the action of water infiltration for a long time and stress level, the original pores and cracks existing inside the coal-rock, which will extend to cause new damage. Therefore, it is important to study the influence of infiltration time and stress level on creep mechanical properties of coal-rock for theoretical guidance of engineering.

The creep test result curves of coal-rock at different infiltration times and different stress levels were obtained from the uniaxial creep test of infiltrated coal-rock, and the results as shown in Fig.4 and Fig.5.

321

322

(e) $t=15d$

(f) $t=30d$

Fig.4 Uniaxial compression creep curves of coal under different infiltration times

(a) $\sigma_1=11.1MPa$

(b) $\sigma_1=14.8MPa$

(c) $\sigma_1=18.5MPa$

(d) $\sigma_1=22.2MPa$

326

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328

329

Fig.5 Creep curves of coal under uniaxial compression under different stress levels

It's easy to see from Fig.4 and Fig.5, it can be seen that when the stress levels are 11.1 MPa, 14.8 MPa, and 18.5 MPa, respectively, the creep curves go through the deceleration creep phase, the isokinetic creep phase, but there is no accelerated creep phase. This is due to the fact that the strain in the stable creep phase increases with the prolongation of infiltration time, but when the stress level acting on the coal rock specimen is low, the accumulated damage is not enough to cause damage to the coal-rock. Its deformation eventually tends to a stable value, so the coal-rock does not produce an accelerated creep phase. When the coal-rock stress level is equal to 22.2 MPa and 25.9 MPa, an accelerated creep phase appears in part of the creep curve; when the coal-rock stress level is equal to 29.6 MPa, an accelerated creep phase appears in each of the creep curves. It can be seen that when the applied stress is close to the ultimate stress of the coal-rock, the specimen undergoes a short period of stable creep or even directly enters the accelerated creep phase and undergoes rapid fracturing.

When the infiltration time is fixed 0 days, and stable creep strain reaches 4.85×10^{-3} at a stress of 11.1 MPa and 5.46×10^{-3} at a stress of 14.8 MPa, with an

increase of 12.57%, 6.00×10^{-3} at a stress of 18.5 MPa, with an increase of 9.90%,
 7.48×10^{-3} at a stress of 22.2 MPa, with an increase of 24.67%, 8.88×10^{-3} at a stress of
25.9 MPa, with an increase of 18.72%, 11.67×10^{-3} at a stress of 29.6 MPa, with an
increase of 31.42%. For the same infiltration time, there is an overall increasing trend
of stable creep strain with increasing stress level. At 29.6 MPa, the coal-rock produces
an accelerated creep phase and eventually breaks down. Therefore, the stress level is
an important factor affecting the creep curve trend.

When the infiltration time is fixed 22.2 MPa, the stable creep strain reached
 7.48×10^{-3} at 0 days of infiltration, reached 10.91×10^{-3} at 1 day of infiltration, with an
increase of 31.44%, reached 11.70×10^{-3} at 3 days of infiltration, with an increase of
7.24%, reached 12.01×10^{-3} at 7 days of infiltration, with an increase of 2.65%,
reached 17.06×10^{-3} at 15 days of infiltration, with an increase of 42.05%, reached
 17.60×10^{-3} at 30 days of infiltration, with an increase of 3.17%. At the same stress
level, the overall trend of stable creep strain increased with the increase of infiltration
time, and the accelerated creep stage appeared at 15 and 30 days of infiltration under
this stress level. It can be seen that the infiltration time is also another important factor
affecting the creep curve.

In summary, the generation of total creep process in coal rocks depends on the
nature of coal-rock themselves on the one hand, and is closely related to the
environment in which coal-rock is stored on the other hand. Both stress level and
infiltration time can change the creep mechanical properties of coal-rock. According to
the scanning electron microscope results, the coal-rock is transformed from an initial

relatively dense, high strength flaky and dense structure to a loose and porous flocculent and crumbly structure under the long time infiltration of water, and the infiltration of the water body makes the internal damage of the coal-rock accumulate continuously. When the infiltration time and stress level reach a specific value, the combination of both causes the accumulation of damage inside the coal-rock to increase and the deformation to intensify, which eventually makes the coal-rock destabilized and ruptured. Compared with the infiltration time, the coal-rock reflects more sensitive to the stress level and has more significant effect.

4 Validation of damage creep constitutive model

In order to analyze the variation law of coal-rock creep constitutive model parameters with different stress levels and infiltration time, the parameters of the test model were identified by the least squares method, the results as shown in Table 1.

σ_0 /MPa	Time /d	E_0 /GPa	α	E_1 /GPa	η_1	E_2 /GPa	t_F /min	σ_0 /MPa	Time /d	E_0 /GPa	α	E_1 /GPa	η_1	E_2 /GPa	t_F /min
11.1	0	5.25	0.1002	4.10	82.99	/	1440	22.2	0	9.80	0.1010	4.31	95.61	/	1440
	1	5.24	0.1021	4.09	80.50	/	1440		1	5.28	0.1111	4.15	93.05	/	1440
	3	7.92	0.1054	3.55	69.73	/	1440		3	9.00	0.1201	3.20	91.00	/	1440
	7	6.76	0.1087	3.20	69.42	/	1440		7	13.99	0.1254	2.92	89.45	/	1440
	15	6.54	0.1112	3.14	65.49	/	1440		15	8.46	0.1321	2.52	88.45	7.34	691
	30	5.95	0.1142	2.42	64.99	/	1440		30	8.13	0.1385	2.42	86.46	6.95	177
14.8	0	7.80	0.1005	4.16	93.00	/	1440	25.9	0	9.38	0.1062	4.27	100.90	/	1440
	1	9.89	0.1026	4.05	88.80	/	1440		1	8.26	0.1156	3.12	90.99	/	1440
	3	17.97	0.1065	3.55	84.07	/	1440		3	13.98	0.1214	2.66	88.91	7.98	927
	7	14.50	0.1111	3.35	79.92	/	1440		7	15.50	0.1311	2.60	88.49	7.12	787
	15	13.09	0.1153	3.51	78.97	/	1440		15	13.47	0.1421	2.52	78.63	6.34	612
	30	6.95	0.1182	2.15	75.50	/	1440		30	7.14	0.1455	1.95	76.49	6.01	120
18.5	0	9.62	0.1001	4.46	101.90		1440	29.6	0	6.33	0.0435	4.29	100.50	8.45	1320

1	8.40	0.1021	4.16	95.90	/	1440	1	7.06	0.0535	4.13	94.16	7.89	1134
3	9.84	0.1023	4.00	93.49	/	1440	3	14.09	0.0842	2.94	87.51	7.08	824
7	15.17	0.1123	4.35	92.01	/	1440	7	10.58	0.0958	3.05	85.49	6.88	650
15	13.32	0.1158	3.85	88.00	/	1440	15	6.92	0.1298	3.14	72.22	5.86	324
30	7.53	0.1205	2.87	80.48	/	1440	30	5.19	0.1326	1.98	70.33	5.09	112

Table 1 Coal and rock creep constitutive model parameters after different infiltration times under six sets of stress levels

Based on the results of parameter identification in Table 1, different parameter curves were plotted with infiltration time for six stress levels.

(c)

(d)

(e)

(f)

Fig.6 Variation of various parameters with infiltration time under different stress, (a) Change curve of instantaneous modulus of elasticity E_0 , (b) Change curve of elastic modulus E_1 in deceleration stage, (c) Change curve of viscosity coefficient η_1 , (d) Change curve of creep life t_F , (e) Change curve of coefficient α , (f) Change curve of elastic modulus E_2 in acceleration phase

From Fig.6, it can be seen that the instantaneous modulus of elasticity of coal-rock first increases and then decreases with the increase of infiltration time, and the peak point appears in the infiltration time of 3-7 days. A schematic diagram of the internal tectonic changes of the infiltrated coal rock is drawn in combination with SEM results, as shown in Fig.7.

Fig.7 Internal structure change process after coal infiltration, (a) Uninfiltrated coal-rock, (b) Coal-rock after infiltration for a period of time, (c) Saturated coal-rock, (d) Long-infiltrated coal-rock

It is analyzed that with the increase of infiltration time, water continuously dissolves the colloid between coal particles, and the salt solution flows freely between coal particles, which makes the internal structure of coal-rock damaged. At the early stage of infiltration, the pores inside the coal-rock are not penetrated by the water body, and the water is not discharged in time during the test. Due to the incompressibility of the water body, the water and the coal rock structure share the external load, and the macroscopic expression is the increase of the instantaneous elastic modulus. And with the extension of infiltration time, the internal structure of coal-rock is connected by the water body through and through, and it can be extruded through the connecting pores. Therefore, it is again manifested as a decrease in the instantaneous modulus of elasticity.

Under the same stress level, the modulus of elasticity in the decelerating creep phase and the modulus of elasticity in the accelerating creep phase of coal-rock decrease gradually with the extension of infiltration time. As shown in Fig.7, due to the softening and dissolution of the cementing material, it shows a decreasing trend of the viscosity coefficient, and the creep life of the coal-rock becomes shorter and

shorter, making the accelerated destruction time earlier. As shown by the coefficient $\alpha=1/(\nu+1)$, the coal rock material parameter ν decreases with the increase of infiltration time.

The theoretical curve of coal-rock creep constitutive model was obtained based on the experimental data and equation (18), and compared with the experimental curve as shown in Fig.8. As can be seen from Fig.8, the overall agreement between the theoretical curve of the creep constitutive model of coal-rock and the experimental curve is good, which can reflect the whole process of creep deformation and damage of infiltrated coal-rock. The influence of stress level and infiltration time on creep properties of coal-rock can also be characterized, thus verifying the rationality of the creep constitutive model of coal-rock developed in this paper.

(a) $\sigma_1=11.1\text{MPa}$

(b) $\sigma_1=14.8\text{MPa}$

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Fig.8 Comparison of creep test curves and theoretical curves of infiltrated coal at different times under different stress conditions

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5 Conclusions

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This paper reports a creep damage model for the combined effect of stress level and infiltration time, and validates it using experimental results on coal-rock specimens.

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Creep tests of coal-rock were conducted at six infiltration times and six stress levels, respectively. The results show that the higher the stress level, the greater the amount of stable creep and the more likely to have an accelerated creep phase. The longer the coal-rock is infiltrated, the greater the amount of stable creep, and the accelerated creep phase will appear earlier at low stress levels. Coal-rock creep is more sensitive to the magnitude of stress levels compared to the length of infiltration time.

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According to the results of parameter identification, at the same stress level, E_0 increases and then decreases with the extension of infiltration time, showing a

decreasing trend in general. E_1 , η_1 , t_F , E_2 and v show a general decreasing trend. The analysis shows that water infiltration has a weakening effect on the creep properties of coal-rock.

Describing the whole process of coal-rock creep by connecting Hooke's body, Kelvin body and damage elastic-plastic body in series. The total damage variable is used to represent the weakening effect of the coupling effect of stress and water infiltration on the mechanical properties of coal-rock, and a creep constitutive model of coal-rock under the stress-infiltration effect is established. The model can better reflect the deceleration creep stage, equal creep stage and accelerated creep stage of coal-rock. The reasonableness and feasibility of the model were verified by comparing and analyzing the theoretical curve with the experimental curve.

However, it must be noted that the present model does not account for the size effect that exists during localization of damage, and so the parameters obtained for tests on specimens of one single size cannot be expected to be valid for specimens of whole sizes. This size effect will need to be incorporated into future extensions of our creep model.

6 Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest.

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8 Data Availability Statement

The [DATA TYPE] data used to support the findings of this study are available from the corresponding author upon request.

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