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EXPERIMENTAL STUDY ON CREEP LOADING OF POROUS COAL UNDER DIFFERENT INFLUENCING FACTORS

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Abstract. *After the gas drainage borehole is formed in the coal seam, its stress deformation process is a creep process without the influence of mining. By arranging boreholes on coal samples and carrying out creep loading test of porous coal through rock mechanics testing machine, the creep process of boreholes in actual coal seams is simulated. The results show that the creep loading test results of drilled coal are quite different from those of conventional loading. Creep loading produces large deformation due to rheological and aging characteristics. Compared with non-porous coal, the yield of drilled coal occurs earlier and the yield platform is wider during creep loading. Also, the larger the borehole diameter, the deeper the borehole depth, and the lower the peak stress. The up dip angle is easier to destroy than the down dip angle. Compared with hard coal, soft coal produces greater deformation under smaller peak stress. The research results have guiding significance for drilling gas drainage in the soft coal seam.*

Key words: *Influencing factors, Porous coal, Creep, Destruction*

1. INTRODUCTION

Rheological properties and aging characteristics are the inherent mechanical properties of coal and rock. Under the action of continuous stress, there is still a strong time effect, resulting in large creep deformation [1, 2]. Li [3] has combined natural limestone and artificial samples, and conducted triaxial creep experiments on the combined samples to study the stress-strain curves of rocks under creep and stress relaxation. Time has a significant impact on the stress-strain curves. Creep and stress relaxation show different stress-strain curves. Based on the acoustic emission (AE) theory and Riemann - Liouville type fractional-order calculus operator theory, the creep loading test of salt rock was conducted, and the stress-strain dependence and damage of salt rock samples under

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uniaxial creep loading were studied. The creep curve and acoustic emission characteristic curve of salt rock were obtained. The theoretical curve was used to fit the test curve, and the predicted value could better describe the nonlinear accelerated creep stage [4]. In the process of gas drainage, the coal deformation, crack expansion and collapse around the borehole have a great impact on the gas drainage effect. There are methods based on elastic wave, acoustic emission, electromagnetic wave, microseismic and other methods used for monitoring fracture expansion. These methods are successful in monitoring large roadway deformation and rock burst, but they are not intuitive and cannot observe the specific form and process of fracture expansion [5-7]. However, for the gas drainage boreholes with small borehole diameter, there is often not enough time for prevention due to rapid deformation.

A constitutive model of creep deformation of rock materials is proposed by Shao et al. [8]. Starting from the elastic-plastic model describing short-term behavior, the deformation varying with time is described according to the evolution of microstructure, resulting in the gradual degradation of elastic modulus and failure strength of materials. For soft coal, creep leads to the reduction of the compressive strength of the material, but the deformation is increasing, which is why it is difficult to maintain the drilling in soft coal seam for a long time [9-11].

The defective rock material itself contains initial cracks, which has a great impact on crack propagation [12]. In triaxial compression creep tests, strain history has a certain impact on the initial deformation of damaged coal samples. The initial damage has a great influence on the creep time and peak stress during the creep failure [13]. The soft coal body, also known as the failure coal body, has experienced the compression failure of tectonic movement, which also explains why the soft coal body has rapid deformation and low peak stress [14, 15]. Unlike the accelerated creep stage of ordinary rocks, the accelerated creep stage of extremely soft coal rocks exhibits slowly accelerated deformation and instability, with a significant time process [16, 17]. In addition, research on mathematical models for creep deformation, damage, and crack evolution of materials such as rocks can grasp relevant laws [18-21].The creep process under cyclic loading can cause the accumulation of damage to coal and rock, ultimately leading to the failure of coal and rock. After the coal drilling ahead of the mining face undergoes the creep process, it is more likely to cause borehole collapse [22-23].

After the drilling of soft coal seam is completed, the continuous deformation occurs with the extension of time due to the influence of in-situ stress, which conforms to the creep characteristics. Therefore, it is necessary to study the creep characteristics of borehole coal. In this study, the creep loading test of drilled coal was carried out by using RMT-301 rock mechanics test system, and the creep loading tests of hard coal and soft coal were carried out respectively. The effects of borehole diameter, borehole depth and borehole inclination on creep were investigated, and the test results were analyzed.

2. TEST SCHEME

RMT-301 rock mechanics test system is composed of doorframe rigid host, dynamic loading system, control cabinet and computer. The device can realize uniaxial and triaxial compression and mechanical tests under different loading and unloading conditions. Its dynamic loading system adopts servo control, with high control accuracy and stability. The creep-loading test of drilled coal is carried out on RMT-301 rock mechanics testing machine, which can control the loading stress to a certain level and keep it unchanged, with good stability.

The creep loading test of borehole coal is divided into two categories: hard coal and soft coal. Both hard coal and soft coal are compared with a test without a hole as the control. The creep loading test of borehole coal considers the influence of the borehole diameter, borehole depth and borehole inclination on deformation and failure. The test scheme is presented in Table 1. The borehole diameter takes values 5 mm and 10 mm. The drilling depth is 25 mm and 50 mm. The dip angles of boreholes are +30° and -30°. The coal sample is of cylindrical shape with a diameter of 50 mm and length of 100 mm. Creep refers to the property that the deformation of an object increases as time propagates under the condition of constant stress or small increase of stress. According to the method for determination of creep of coal and rock under unidirectional compression, the initial load stress is about 20% of the uniaxial compressive strength of the specimen. When the deformation difference does not exceed 0.001 in continuous 2h, the next stage of loading can be carried out.

Table 1 Creep loading test scheme of borehole coal

Classification	Test name	No.	Drilling depth (mm)	Borehole inclination (°)	Loading rate (MPa/s)	Borehole diameter (mm)
Hard coal	No hole	R1	-	-	0.5	-
	Borehole diameter	R2	25	0	0.5	5
		R3	25	0	0.5	10
Soft coal	Drilling depth	R4	25	0	0.1	5
		R5	50	0	0.1	5
	Borehole inclination	R6	25	+30	0.1	5
		R7	25	-30	0.1	5

3. Analysis of Test Results

Firstly, the creep loading test of the non-drilled specimens is carried out. Compared with the conventional loading test, the uniaxial creep test of coal shows that the strength decreases during the creep loading, and a strong time effect appears under the action of continuous stress, resulting in large creep deformation. It can be seen from Table 2 that with the increase of stress, the initial deformation increases rapidly, then decreases, and then increases rapidly in the later stage.

Table 2 Creep graded loading process of undrilled coal

Classification	Time t (min)	Stress σ (MPa)	Deformation ε (mm)	$\Delta\varepsilon/\Delta\sigma$ (mm/MPa)	$\Delta\varepsilon/\Delta t$ (mm/min)
1	37	2.8	0.1560	0.055714	0.004216
2	70.4	5.5	0.2438	0.032519	0.002629
3	275.1	8.1	0.3182	0.028596	0.000363
4	435.7	11.0	0.4182	0.03450	0.000623
5	528.9	13.1	0.4822	0.030476	0.000687
6	601.6	16.2	0.6150	0.042823	0.001826

To facilitate the analysis, the rate of change in deformation of the specimen with respect to the change of stress, $\Delta\varepsilon/\Delta\sigma$, is introduced. The creep rate, $\Delta\varepsilon/\Delta t$, is the rate of change of deformation with respect to time. According to the development of these two quantities, the whole process can be divided into three stages. In the first stage, the deformation per unit stress $\Delta\varepsilon/\Delta\sigma$ and the creep rate ($\Delta\varepsilon/\Delta t$) show a decreasing trend with time. In the second stage, the deformation per unit stress $\Delta\varepsilon/\Delta\sigma$ and the creep rate remain nearly constant, and, hence, the trend of change is represented by nearly a straight line. Finally, in the third stage, the deformation per unit stress $\Delta\varepsilon/\Delta\sigma$ and the creep rate increase with time.

Fig. 1 also shows the three stages. The creep loading peak stress of non-porous hard coal is 18.23 MPa and the corresponding deformation is 0.7162 mm, as shown in Fig. 1. Compared with the conventional loading without holes, the peak stress decreases, but the strain increases. From Fig. 2, it can be seen that the time before yielding (plastic deformation, manifested as nonlinearity) accounts for a large proportion of the entire loading process, and an obvious yield platform is generated after yielding. The yield platform prolongs the creep loading strain process and increases the strain. Under conventional loading, the failure of coal samples is relatively simple, with obvious tensile shear fracture surface, while under creep loading, the coal samples are broken to a large extent, mostly in debris shape, and the failure form is complex.

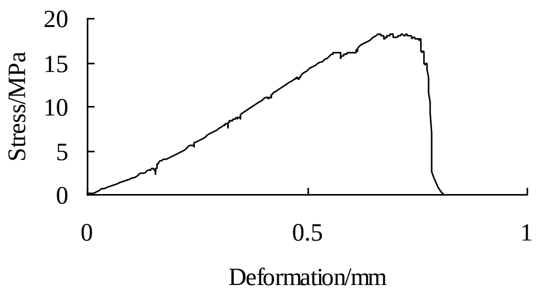

Fig. 1 Stress- deformation curve (R1)

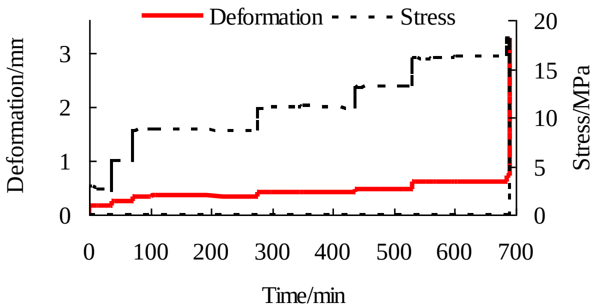

Fig. 2 Variation of stress and deformation with time (R1)

3.1. Effect of Borehole Diameter on Creep Loading

Similar to the creep loading of non-drilled coal, there is no obvious peak stress in the creep process of drilled coal. When there is no hole, the initial yield stress is about 18.2 MPa and the corresponding deformation is about 0.66mm. When the platform drops rapidly, the stress is about 17.58 MPa and the corresponding deformation is 0.75mm. The width of the platform is 0.09 mm. When the borehole diameter is 5 mm, as shown in Fig. 3 and Fig. 4, the initial yield stress is about 16.31 MPa and the corresponding deformation is about 0.55mm. When the platform drops rapidly, the stress is about 13.98 MPa and the corresponding deformation is 0.74mm. The width of the platform is 0.19 mm. When the borehole diameter is 10 mm, as shown in Fig. 5 and Fig. 6, the initial yield stress is about 13.29 MPa and the corresponding deformation is about 0.53mm. When the platform drops rapidly, the stress is 11.81 MPa and the corresponding deformation is 0.79mm. The width of the platform is 0.26 mm. Hence, the larger the borehole diameter, the lower the yield platform stress, and the larger the borehole diameter, the wider the yield platform.

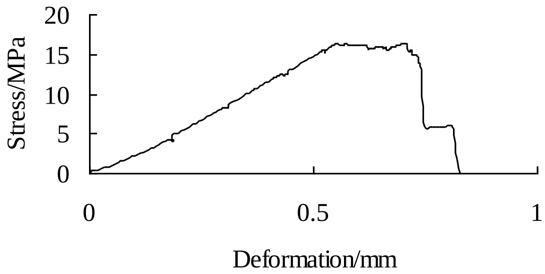

Fig. 3 Stress- deformation curve (R2)

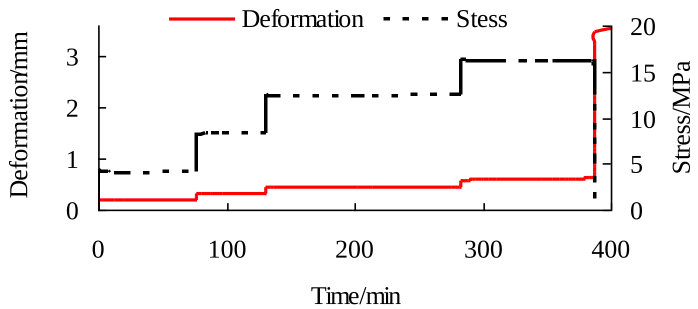

Fig. 4 Variation of stress and deformation with time (R2)

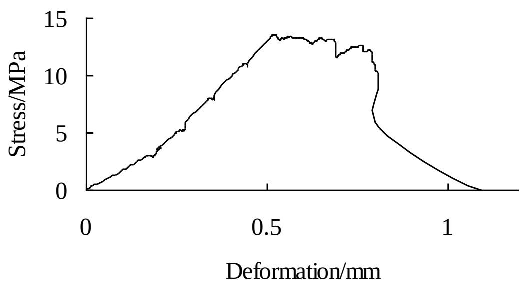

Fig. 5 Stress-deformation curve (R3)

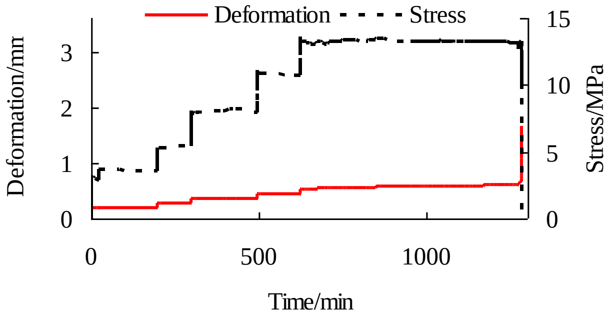

Fig. 6 Variation of stress and deformation with time (R3)

In engineering practice, the larger the diameter of the borehole, the larger the exposed area of the coal body, which is more conducive to gas drainage. From the test results, although the creep peak stress decreases with the increase of the diameter of the borehole, the yield platform widens and the peak deformation increases, indicating that the larger the diameter of the borehole, the more deformation time is required. Therefore, in the practice of gas drainage engineering, we should increase the borehole diameter as much as possible and expand the exposed area of coal in the borehole, which is conducive to extracting more gas. Of course, we should also consider the difficulty and cost of borehole construction and comprehensively consider to select the appropriate borehole diameter.

3.2. Effect of Drilling Depth on Creep Loading

The influence of drilling depth on creep loading of soft coal is shown in Figs. 7-10. When the drilling depth is 25 mm, the peak stress is 6.09 MPa and the corresponding deformation is 0.9183 mm. When the drilling depth is 50 mm, the peak stress is 6.09 MPa and the corresponding deformation is 1.2561 mm. The deeper the borehole is, the larger the failure surface of coal is, and the peak creep stress decreases. Due to the presence of borehole, the yield is more pronounced and the yield platform is wider compared to then case without the borehole.

From the point of view of peak stress and deformation, with the increase of drilling depth, the peak stress decreases, but the peak deformation increases, that is, smaller stress produces greater deformation, which means that the plasticity of coal body increases. In engineering practice, the deeper the drilling depth is, the larger the exposed area of the coal

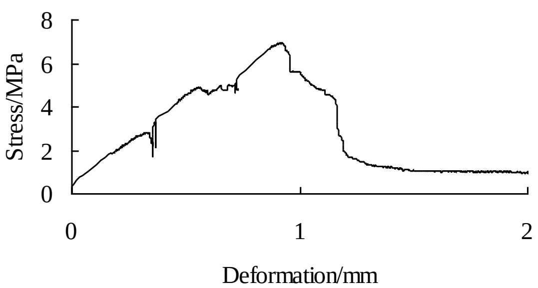

Fig. 7 Stress- deformation curve (R4)

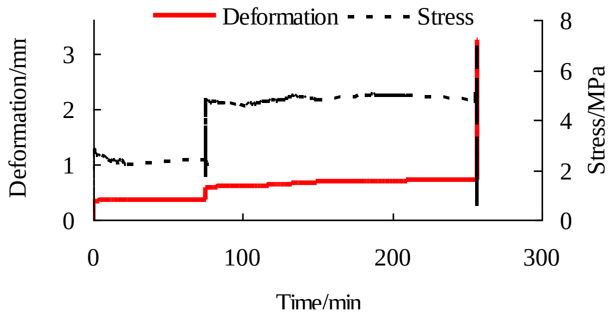

Fig. 8 Variation of stress and deformation with time (R4)

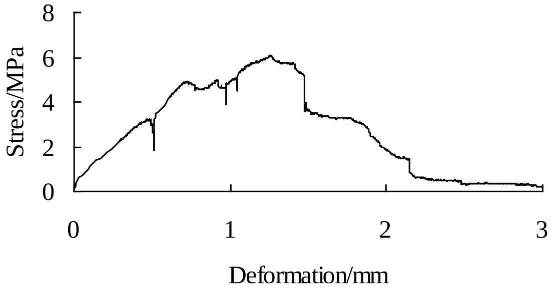

Fig. 9 Stress- deformation curve (R5)

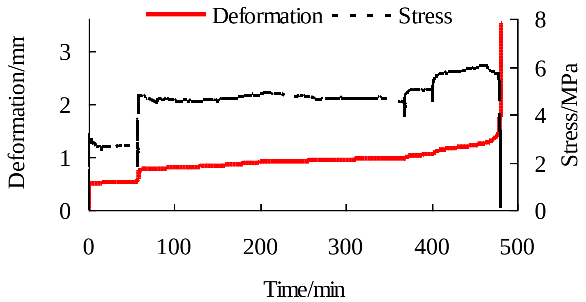

Fig. 10 Variation of stress and deformation with time (R5)

around the drilling hole is, which is again more conducive to gas drainage. Therefore, in the practice of gas drainage engineering, the drilling depth should be increased as much as possible to ensure that the drilling depth meets the drainage requirements and avoid blind areas, resulting in excessive local residual gas and large gas emission.

3.3. Influence of Borehole Inclination on Creep Loading

As shown in Figs. 11-14, when the borehole inclination is +30°, the peak stress is 6.81 MPa and the peak deformation is 0.75 mm. When the borehole inclination is -30°, the peak stress is 7.32 MPa, while the peak deformation is 0.79 mm. Compared with the horizontal drilling, the peak deformation is greatly reduced in both up- and down-dip angles. Compared with the down-dip angle, the peak stress and deformation of the up-dip angle borehole are smaller when coal is loaded, indicating that the up-dip angle borehole is easier to be damaged. Regarding damage, when the drilling angle is +30°, the upper part of the coal sample is broken more severely compared to the lower part, as there are more cracks and those are characterized by a wider crack width. With the drilling angle of -30°, the situation is opposite.

The borehole inclination has a great impact on the peak stress and deformation. Compared with the horizontal borehole, the peak stress and deformation are greatly reduced. Therefore, in the practice of gas drainage engineering, the borehole should be kept horizontal as far as possible. However, in the process of practical application, the borehole construction is generally consistent with the coal seam trend, so it is necessary to consider comprehensively the coal seam inclination and horizontal borehole. Drilling along the dip angle of the coal seam makes the borehole longer and the gas extraction effect better. For example, the up dip angle is more likely to reduce the peak stress and deformation of the coal body. For coal seams with a certain inclination angle, drilling from one direction to form a borehole is referred to as upward inclination angle borehole, while drilling in the opposite direction is referred to downward inclination angle borehole. Therefore, if conditions permit, the down dip angle drilling should be longer (deeper) and the up dip angle drilling should be shorter (shallower) as much as possible.

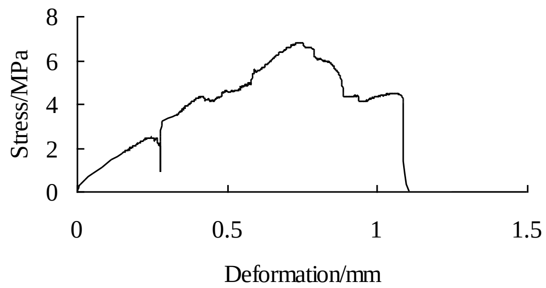

Fig. 11 Stress- deformation curve (R6)

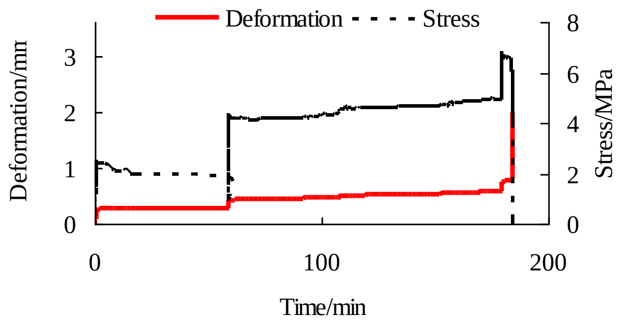

Fig. 12 Variation of stress and deformation with time (R6)

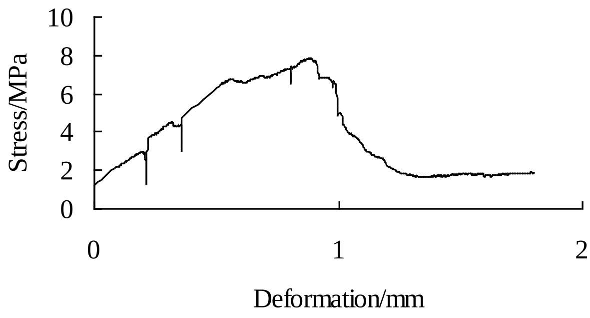

Fig. 13 Stress- deformation curve (R7)

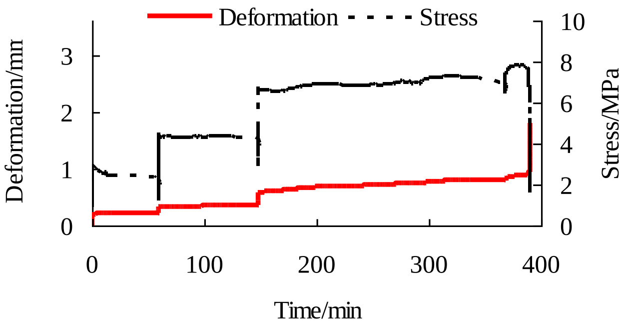

Fig. 14 Variation of stress and deformation with time (R7)

4. CONCLUSION

Creep is the process of continuous deformation of materials under constant stress. Through the creep loading test of porous coal, the deformation and failure law of porous coal is further understood. The experiment studied the influence of borehole diameter, borehole depth, and borehole inclination angle on creep loading, analyzed the relationship between the stress and strain, and the process of their variation over time. The conclusions are as follows:

- The creep loading test results of drilled coal are quite different from those of conventional loading. Creep loading produces large deformation due to rheological and aging characteristics. Compared with non-porous coal, the yield of drilled coal occurs at lower stress and the yield platform is wider during the creep loading.
- The larger the borehole diameter is, the larger the exposed surface of the coal around the borehole is, and the peak stress decreases in the creep process. In terms of strength, it is easier to damage, but the deformation increases and the plasticity range increases with the increase of the borehole diameter.
- With the increase of drilling depth, the degree of integrity damage of coal body is greater, thus resulting in the decrease of the peak stress of coal body. This is similar to the effect of drilling diameter on creep loading of coal. Although the peak stress decreases, the peak deformation increases. From the perspective of stress and strain, a deeper drilling depth does not imply a weaker coal resistance.

- Compared with horizontal boreholes, boreholes with a certain dip angle are easy to be damaged. From the point of view of the peak stress and deformation, the up dip angle is easier to be damaged than the down dip angle, so the down dip angle boreholes are more conducive to maintaining the boreholes for a longer time. Compared with a hard coal, soft coal produces greater deformation under smaller peak stress.

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