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Regularity and mechanism of coal resistivity response with different conductive characteristics in complete stress–strain process

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ABSTRACT

The stress, strain as well as resistivity of coal during uniaxial compression process were tested based on self-built real-time testing system of loaded coal resistivity. Furthermore, the coal resistivity regularity and mechanism were analyzed at different stages of complete stress–strain process, which includes the two kinds of coal body with typical conductive characteristics. The results indicate that coal resistivity with different conductive characteristics has different change rules in complete stress–strain process. It is mainly represented at the densification and flexibility phases before dilatation occurs. The variation of resistivity can be divided into two kinds, named down and up. Dilatation of coal samples occurred between 66%σ_{max} and 87%σ_{max}. Because of dilatation, coal resistivity involves sudden change. The overall representation is shifting from reducing into improving or from slow improving into accelerated improving. Thus, coal resistivity always shows an increasing tendency at the plastic stage. After peak stress, coal body enters into failure stage. The expanding and communicating of macro fracture causes further improvement of coal resistivity. The maximum value of resistivity rangeability named λ reached 3.49. Through making real-time monitoring on coal resistivity, variation rules of resistivity can be deemed as precursory information so as to reflect the dilatation and sudden change before coal body reaches buckling failure, which can provide a new technological means for forecasting the dynamic disaster of coal petrography.

1. Introduction

The dynamic disaster, including coal and gas outburst as well as rock burst, is a severely natural threat to coal mine. In recent years, it shows multiple and increasingly severity of the dynamic disaster [1,2]. During the preparating and developing process of coal and rock dynamic disaster, there are many kinds of physical mechanics responses along with the deformation and damage of coal–rock mass [3]. In particular, resistivity is one of the important parameters. And the difference in resistivity is the physical property as a premise to do electrical prospecting [4,5]. Thus, studying variation rules of resistivity during coal loading process is beneficial to deeply knowing about the coal–rock mass deformation and evolutionary process of dynamic disaster. More importantly, it has great theoretical and practical significance for applying electrical prospecting technology to forecasting and predicting dynamic disaster.

The study of rock resistivity has a long history which mainly concentrated in the earthquake [6,7]. The precursory characteristics of resistivity were found in studying the change law of rock resistivity. The technology was applied to forecasting the earthquake. This kind of work was carried out by foreign scholars. However, most studies was done based on static testing of coal resistivity. For example, the variation of coal resistivity was studied by changing experimental conditions such as testing voltage, test frequency and temperature, as well as testing direction [8–10]. In fact, during excavating process, coal–rock mass is always under loading condition. The effect of stress leads to deformation and damage of coal–rock mass, thus changing the electrical characteristic of coal–rock mass [11]. To control dynamic disasters, some Chinese scholars have studied the electrical resistivity of coal body under load, and lay a foundation for the application of electrical prospecting technology into detection of mine dynamic disaster. Wen made the test on the resistivity of different coal samples at different stress levels, while Li made this kind of test under uniaxial compression on large-scaled coal body [12,13]. Liu made the contrastive analysis on the electrical resistivity of both dry and

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wet coal samples during uniaxial compress [14]. Wang studied the resistivity characteristics of briquette coal and raw coal under the condition of uniaxial compression [15,16]. Some tests were also done on the coal body with bump proneness under uniaxial compression [17]. Chen investigated the different coals in different orientations under different loading methods. And the mechanism of coal resistivity variation was illustrated in detail [18].

The previous studies mainly focus on the overall feature of coal resistivity variation, and do not further analyze the variation rules and the response mechanism of resistivity at different stages during the complete stress–strain process. Generally, it is deemed that "fracture" gives rise to resistivity variation. In fact, before the main fracture happens, qualitative change of coal–rock mass structure was made because the occurrence of dilatation has already caused.

This is the major manifestation before buckling failure of coal–rock mass [19]. As a result, it has great significance to investigate the resistivity response regularity caused by dilatation deeply. In this paper, resistivity real-time testing system for loaded coal was established so as to test and analyze the resistivity response and its mechanism regularity during complete stress–strain process and then to get the precursory information of resistivity variation caused by dilatation. It aims to lay a foundation for predicting and forecasting coal–rock mass dynamic disaster via resistivity method.

2. Experimental

The experimental system (Fig. 1) contains loading system, resistivity test system and deformation measuring system. Loading system employs WAW-600 Microcomputer-controlled electro-hydraulic servo universal testing machine which consists of host tester, servo oil sources, full-digital measure and control instrument and computer-control system, etc. Resistivity test system uses American Agilent U1733C LCR tester connected to PC and then collects data successively. Deformation measuring system is comprised of Epsilon 3542RA axial extensometer and Epsilon 3544 radial extensometer. By connecting the extensometer, full-digital measure and control instrument of the tester, the axial and radial deformation of coal–rock samples can be dynamically measured.

The coal samples used in the experiment were collected from Xinzhuang Coal Mine, Chengjiao Coal Mine in Henan province and Sijiazhuang Coal Mine in Shanxi province respectively. The coal chunk was processed in the cylinder with ∅50 mm × 100 mm. Then, both ends were rubbed down after sampling. The evenness error of both ends face is controlled within 0.02 mm. And, DDG-A efficient electric contact conductive paste was used between copper sheet electrode and coal end face to make coupling. Besides, the axial compression loading rate is 0.1 mm/min.

3. Results and discussion

3.1. Testing complete stress–strain curve of coal body

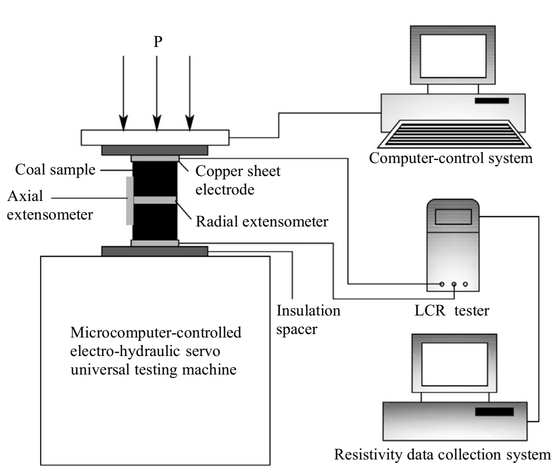
The underground coal–rock mass generally undergoes the impact of compressive load. The stress–strain curve can well describe the deformation and breakage of coal–rock mass [20]. According to elastic theory, the sum of linear strain should be equal to volumetric strain ($\varepsilon_x + \varepsilon_y + \varepsilon_z = \varepsilon_v, \varepsilon_x = \varepsilon_y = -\varepsilon_d, \varepsilon_z = \varepsilon_l$). Then, the relation between linear strain and volumetric strain under the uniaxial compression can be obtained as follows:

$$\varepsilon_v = \varepsilon_l - 2\varepsilon_d \qquad (1)$$

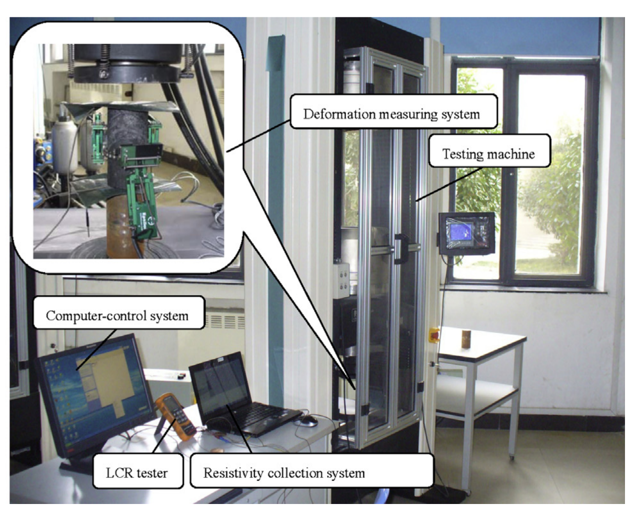
Fig. 2 shows the complete stress–strain curve of typical coal–rock mass. And ε_d, ε_l and ε_v refer to the radial strain, axial strain and volumetric strain, respectively. Based on the variation characteristics of stress–strain curve, the loading process can be divided into several stages with different properties. The stages from I to IV are densification stage (*OA*), elastic stage (*AB*), plastic stage (*BC*) and breakage stage (*CD*) respectively (Fig. 2). In $\varepsilon_l - \sigma$ curve, the slope of tangent at *B* deviates from curve and decreases gradually, denoting the deformation of coal body transits from elastic deformation into plastic deformation. At this moment, shear fracture of coal sample happened, indicating the state of specimen turns from volume compression to dilatation.

The radial strain and axial strain of experimental coal samples were tested by using deformation measurement system. And, its volumetric strain was calculated according to Eq. (1). Based on the typical complete stress–strain curve in Fig. 3, it can be seen that there exist differences between different coal samples. In terms of axial strain and compressive strength, Sijiazhuang coal sample is the biggest, followed by Xinzhuang coal sample, and Chengjiao coal sample is the smallest.

On the basis of characteristics of stress–strain curve, the stress level values corresponding to dilatation point of each experimental



(a) Schematic diagram



(b) Physical diagram

Fig. 1. Diagram of loaded coal resistivity real-time testing system.