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Permeability and pressure distribution characteristics of the roadway surrounding rock in the damaged zone of an excavation

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ABSTRACT

Research on the permeability and pressure distribution characteristics of the roadway surrounding rock in the excavation damaged zone (EDZ) is beneficial for the development of gas control technology. In this study, analytical solutions of stress and strain of the roadway surrounding rock were obtained, in which the creep deformation and strain softening were considered. Using the MTS815 rock mechanics testing system and a gas permeability testing system, permeability tests were conducted in the complete stress-strain process, and the evolution characteristics of permeability and strain were studied over the whole loading process. Based on the analytical solutions of stress and strain and the governing equation of gas seepage flow, this paper proposes a hydro-mechanical (HM) model, which considers three different zones around the roadway. Then the gas flow process in the roadway surrounding rock in three different zones was simulated according to the engineering geological conditions, thus obtaining the permeability and pressure distribution characteristics of the roadway surrounding rock in three different zones. These results show that the surrounding rock around the roadway can be divided into four regions-the full flow zone (FFZ), flow-shielding zone (FSZ), transitive flow zone (TFZ), and in-situ rock flow zone (IRFZ). These results could provide theoretical guidance for the improvement of gas extraction and gas control technology.

1. Introduction

With the increase in coal mining depth and the development of intensive production, coal mine accidents occur frequently, especially gas accidents. Therefore, the gas accident is a difficult problem which needs to be solved in the safe production of a coal mine [1]. Engineering practices indicate that the underground excavation in coal mine production will lead to a large amount of gas emission. If the overflow and discharge of gas is not controlled effectively, it may threaten coal mine production and even lead to coal and gas outburst accidents [2,3]. Research on the spatial distribution characteristics of permeability and the gas flow law in an excavation damaged zone are of much significance to the development of the control and prevention technologies for roadway gas disasters.

The existence of an excavation damaged zone (EDZ) can seriously influence the stability of the roadway surrounding rock and lead to the potential safety hazard in practical engineering. Although scholars have carried out much research on the excavation damaged zone, the surrounding rock was usually regarded as an elastic material, and the influence of excavation damage was ignored when dealing with seepage problems [4,5]. Because the current permeability models are normally established based on the theory of porous elastic mechanics or the equivalent continuous medium, the effect of damage on permeability cannot be considered. However, the extent of fracturing in the excavation damage zone is obviously different from that of the undamaged zone, and the permeability of fractured surrounding rock is also significantly higher than that of the undamaged zone. It is the excavation damage zone that causes a variety of safety accidents. Therefore, ignoring the influence of the excavation damage zone may cause a large error.

In recent years, many scholars have simplified the surrounding rock as an elastic-plastic model or an elastic-brittle model, and obtain the analytical solutions of stress and strain of roadway surrounding rock. Brown et al. derived the analytical solutions of stress and strain in the surrounding rock during tunnel excavation based on the elastic-brittle model [6]. Yu et al. considered the plasticity of the surrounding rock when obtaining the analytical solutions of stress and strain, but ignored plastic softening and

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plastic volume dilatancy [7]. Ladanyi et al. analyzed the change law of stress and strain based on a visco-elastic model, but neglected the plasticity characteristics of the surrounding rock [8]. Zhang et al. regarded the rock mass as a viscoelastic and ideal ductile material and considered the influence of the plastic dilatancy effect, but ignored the strain softening of rock [9]. Based on previous studies, Lu et al. simplified the rock as a typical three step-wise model and analyzed the effect of plastic softening and plastic dilatancy, but this model did not consider the rheological properties of the rock mass [10].

In order to describe the gas seepage law in a coal seam, scholars have established various permeability models based on laboratory tests and field tests. Shi et al. proposed a linear elastic permeability model under a uniaxial strain condition, considering the effects of pore pressure and gas adsorption [11]. Zhang et al. proposed a coupled hydro-mechanical model which considers the effect of effective stress and gas adsorption [12]. Liu et al. proposed a typical dual-porosity and dual-permeability model containing a microporous matrix surrounded by macro-porous cleats/fractures, and analyzed the influence of coal deformation caused by gas adsorption on the gas flow characteristic [13]. Sun studied the gas injection technology of low permeability coal seams based on the study of the coupled relationship between the stress field and the temperature field [14]. Zhang et al. considered the transformation between adsorbed gas and free gas, and established a coupled coal deformation, gas flow and heat conduction model [15]. However, these permeability models were established based on the theory of porous elastic mechanics or the equivalent continuous medium, and the research on the gas flow law of damaged coal was relatively insufficient.

The excavation induces the emergence of the excavation damaged zone (EDZ) around the roadway. In deep and high stress mining practice, the rheological behavior of the surrounding rock occurs under the effect of geo-stress, so the range of the damaged zone will increase further with the passage of time. The excavation changes the stress state of the surrounding rock, and stress redistribution leads to permeability redistribution. Although scholars have carried out research on the permeability characteristics of the roadway surrounding rock [16–18], there is still no quantitative analysis of the permeability characteristics of surrounding rock.

In consideration of the inadequacy of these researches, this paper proposes a new research approach, the procedure for which is as follows:

(a) The change of effective stress (effective strain) affects the permeability of coal. The stress is redistributed after the roadway excavation, which seriously affects the permeability distribution. Therefore, the stress distribution of the surrounding rock and the range of the excavation damaged zone should be understood. The stress and strain distributions of the surrounding rock can be obtained with either an analytical solution or a numerical solution. Because the analytical solution can greatly reduce the computation workload, the analytical solution is adopted in this paper, and the stress and strain distribution of the surrounding rock is obtained based on a visco-elastic-plastic model.
(b) Because there is no effective permeability model for damaged coal, the relationship between permeability and strain is obtained in both the undamaged stage (elastic stage) and the damaged stage (plastic stage and residual state stage) based on permeability tests on coal samples. The corresponding relationship between permeability and strain of the surrounding rock is established.
(c) Based on the distribution of stress and strain of the roadway surrounding rock and the corresponding relationship between permeability and strain obtained by permeability tests, the permeability distribution of the surrounding rock is obtained in three zones.

In the calculation of the permeability of the roadway surrounding rock, the influence of the damage induced by excavation on the permeability is usually neglected in recent studies. The innovation of this paper is establishing a hydro-mechanical (HM) model based on the above procedure, in which the influence of the damage on the permeability of the roadway surrounding rock is considered. Then the permeability and gas pressure distribution characteristics of excavation damaged zone are obtained.

2. Viscoelastic-plastic analysis of fractured coal around a roadway

The excavation leads to stress redistribution around roadway. After excavation three zones are formed, which are: a viscoelastic zone, a strain softening zone and a residual state zone [8,19]. The mechanical properties of rock change noticeably, e.g. the surrounding rock becomes deformed, large numbers of fractures are produced and the permeability changes. Depending on the degree of disturbance, the residual state zone is regarded as the highly excavation damaged zone (HDZ), the strain softening zone is regarded as the excavation damaged zone (EDZ), and the viscoelastic zone is regarded as the undisturbed or undamaged zone [20].

It is assumed that the roadway is affected by hydrostatic pressure, and the initial stress in the rock mass is p_i.

The excavation of a roadway with a circular cross section is idealized as a cylindrical cavity. The excavation leads to stress redistribution around the roadway, and the strain softening zone and the residual state zone emerge in the surrounding rock. As shown in Fig. 1, the three zones are the residual state zone, strain softening zone and viscoelastic zone. R_0, R_b and R_p are the radii of the cavity, residual state zone and strain softening zone, respectively.

A typical three step-wise curve in Fig. 2 is widely used to describe the stress-strain relationship [6]. The viscoelastic strain is ε_1^e and the rock is usually regarded as a viscoelastic material at the pre-peak stage. After the peak point, the rock is in the plastic softening stage. The slope of curve k_s reflects the softening extent of rock. For an ideal elastoplastic rock, $k_s = 0$. For an ideal elastic, brittle rock, $k_s = \infty$. Plastic softening occurs in both the residual stage and strain softening stage. To simplify the calculation, it is assumed that the strength of the surrounding rock decreases linearly with the increase in strain in the plastic zone. When the coal is destroyed, the internal friction angle of coal is constant and the decrease of coal strength is caused by the decrease of the cohesive force of coal. After the coal reaches the peak strength, the maximum and minimum stresses in the surrounding rock satisfy the Mohr-Coulomb yield criterion in the plastic stage [19]:

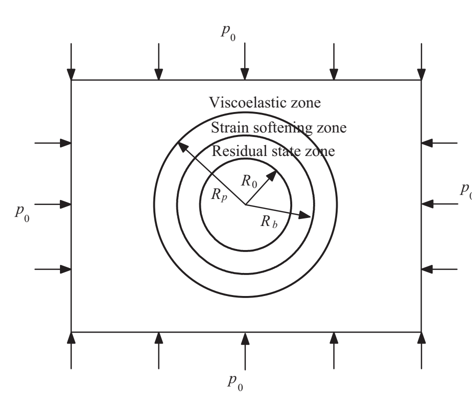

Fig. 1. Mechanical model of coal and rock mass around roadway.