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Review on the Fracture Mechanism of Mining-Induced Coal and Rock Mass

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Abstract: Coal mine is one of the important energy resources in the world, and the fracture mechanism of coal and rock mass has always been one of the important research issues in the field of mining engineering in the process of coal mining and transportation. It is of great significance to understand the fracture mechanism of mining coal rock mass to ensure the safe production of coal mines and improve the efficiency of coal mining. In this paper, the research on the fracture mechanism of mined coal and rock mass is reviewed, and the deformation and failure characteristics of coal and rock mass under different stress states, the law of rock mass fault evolution, and the application of numerical simulation and experimental research in the study of the fracture mechanism of mined coal and rock mass are discussed.

Keywords: Coal and rock mass; Fracture mechanism; Numerical simulation.

1. Introduction

The fracture mechanism of mining-induced coal and rock mass is one of the key issues in coal mining engineering [1]. Its investigation is of great significance for ensuring miners' safety, improving coal mine production efficiency, and protecting the environment. With the gradual depletion of coal resources and the continuous increase in mining depth, the problem of fracture in mining-induced coal and rock mass has become increasingly prominent, emerging as a critical technical constraint on coal extraction [2]. Studies conducted by scholars both domestically and internationally have revealed the deformation and failure characteristics of coal and rock mass under different stress states [3], as well as the evolution laws of rock mass fracturing. Through experimental studies, numerical simulations, and field observations, in-depth analyses of the fracture mechanisms of coal and rock mass have been carried out [4].

However, many unresolved issues still exist in this research field. For example, aspects such as multi-scale effects, complex geological conditions, and the integration of macroscopic and microscopic studies require further in-depth investigation [5]. Therefore, this review aims to provide a comprehensive overview of the current research status on the fracture mechanisms of mining-induced coal and rock mass both domestically and internationally, summarize previous research achievements and methodologies, analyze existing problems and challenges, and propose future research directions and development trends.

2. Study on Deformation and Failure Characteristics of Coal and Rock Mass

Under compressive stress, internal cracks within the coal and rock mass gradually close [17], leading to a stabilization of deformation; however, this process may still be accompanied by microscopic damage. Under tensile stress, the fracture behavior is mainly manifested by crack propagation and fragmentation of the rock mass [18]. Under shear stress, shear deformation occurs within the coal and rock mass, resulting in the formation of shear bands and fracture planes, and shear failure may take place.

In practical mining processes, coal and rock mass are often subjected to combined stress conditions, including compression, tension, and shear. In recent years, scholars both domestically and internationally have conducted more in-depth studies on the deformation and failure characteristics of coal and rock mass [19]. Zhang Qishuo established macro–micro mechanical models for dynamic impact failure of preloaded brittle rocks and for creep behavior under dynamic disturbances. The results indicate that with increasing axial pre-stress, the dynamic peak strength of the rock continuously decreases, while the corresponding peak strain, pre-crack length induced by axial pre-stress, and axial strain all increase[7].Chen Haoxiang et al. pointed out that traditional continuum mechanics theory fails to account for the structural characteristics and energy-bearing properties of rock masses, and therefore cannot adequately explain the unique nonlinear mechanical behavior of deep rock masses. From an energy perspective, combined with concepts from statistical physics, they provided an effective theoretical framework for analyzing the deformation and failure processes of deep rock masses under combined static and dynamic loading [14]. Yang Jianfeng et al. demonstrated that conventional linear elastic fracture theory is no longer applicable for characterizing the ductile fracture behavior of coal and rock mass. Through experimental studies and numerical simulations, they developed and validated a mixed-mode cohesive crack model for mudstone and coal based on the PPR potential function [10].

3. Fracture Evolution Law of Coal and Rock Mass

Under the action of stress, internal cracks within coal and rock mass gradually initiate, develop, and propagate. These cracks may originate from pre-existing fissures and joints or be newly generated under stress. The initiation and propagation of cracks ultimately lead to the fragmentation and failure of the coal and rock mass.

Fan Gangwei et al. analyzed the dissipative structure characteristics during the dynamic evolution of fracture systems in mining-induced overburden and pointed out that pore pressure entropy can be used to describe the “entropy reduction” phenomenon during the transition of the fracture system from a natural state to a mining-induced disturbed state [6]. Li Jianghua, through acoustic emission testing in rock mechanics, obtained the evolution characteristics of crack propagation and acoustic emission during the loading-induced deformation and failure of weathered rocks. A mechanical model was established to analyze the fracture characteristics of rock mass in close-distance coal seam mining and the load transfer effect of weathered rock. Numerical simulations further verified the influence of weathered rock on the failure of underlying strata. The results indicate that repeated disturbance occurs in close-distance coal seam mining, leading to superimposed damage of mining-induced fractures. The weathered zone acts as a connecting medium between upper and lower fracture systems, increasing the height of the water-conducting fracture zone, while water pressure promotes the propagation of fractures in weathered rock [11]. Zeng Ling et al. investigated the cracking characteristics of silty mudstone under thermo-hydro-mechanical coupling. They found that during cyclic coupling processes, humidity variations cause changes in the interlayer spacing of clay minerals, leading to particle breakage and pore expansion, thereby forming microcracks. Temperature cycling induces differential thermal stress and moisture redistribution, facilitating the initiation and coalescence of microcracks. Under loading, stress concentration at crack tips increases, eventually resulting in the formation of a crack network [15]. Zhang Kai et al. analyzed the relationship between damage degree and wave velocity, as well as the evolution of acoustic emission characteristics. They explored the acoustic emission response mechanisms of rocks with different damage levels and found that the internal crack density increases with increasing damage. This leads to a transition in failure behavior from progressive and stable failure to sudden and unstable failure during loading [16].

4. Application of Numerical Simulation in the Study of Fracture Mechanisms of Mining-Induced Coal and Rock Mass

Numerical simulation plays a vital role in the study of fracture mechanisms of coal and rock mass. By establishing mathematical models and performing computational simulations, it enables the analysis of fracture behavior under different stress conditions [20]. Numerical simulation can be used to reproduce the stress field distribution within coal and rock mass under loading conditions, as well as to simulate the initiation, propagation, and coalescence of internal cracks. It can also model the entire fracture evolution process, including the formation of fracture surfaces and the development of fracture zones [21]. Furthermore, numerical simulation allows for the evaluation of the stability of coal and rock mass, including the prediction of failure and collapse, analysis of safety under different working conditions, and optimization of mining schemes [22,31]. Liu Hongtao et al. employed a combined approach of theoretical analysis and numerical simulation to investigate the evolution law of the mining-induced stress field after the extraction of an upper coal seam. They conducted an in-depth study on the asymmetric deformation and failure mechanism of roadways in the lower coal seam, revealing that the extraction of the overlying coal seam alters the magnitude of principal stresses, the principal stress ratio, and the stress deflection angle at the roadway location. The variation of the stress vector was identified as the primary cause of asymmetric roadway failure [12]. Shuang Haiqing et al., focusing on the influence of roof-cutting gob-side entry retaining technology on the fracture distribution of overburden, combined physical similarity simulation with numerical simulation to analyze stress distribution in the goaf, overburden movement, and fracture evolution characteristics. Their results show that roof cutting changes the thickness of collapsed strata and the fracture mode of the roof, thereby affecting the development height of the fracture zone and the width of separation fracture zones within the control range of sub-key strata [9]. Meng Fanfei et al., based on the discrete element method (DEM), established numerical models of broken rock mass with different gradations under water immersion and lateral confinement compression conditions. They analyzed the deformation behavior and secondary fracture evolution characteristics of the broken rock mass. The results indicate that when there is a large disparity in particle size, the contact bond strain energy reaches a maximum while fracture energy increases slowly. Fractures are predominantly distributed in the contact regions between rock blocks and densely packed particles, whereas very few fractures occur in regions adjacent to voids [8].

5. Conclusion

By reviewing the current research status on the fracture mechanisms of coal and rock mass both domestically and internationally, it is found that experimental studies and numerical simulation methods have been widely applied in this field, providing important tools and technical support for a deeper understanding of fracture mechanisms.

(1) The fracture mechanism of coal and rock mass is influenced by multiple factors, including scale effects and temperature effects. Current studies are mostly focused on the macroscopic level, while the understanding of fracture mechanisms at the microscopic scale is still insufficient. Therefore, it is necessary to strengthen the integration of macro–micro scale research.

(2) Geological conditions vary across different regions, leading to differences in the fracture mechanisms of coal and rock mass. Existing studies are mainly concentrated on typical geological conditions, whereas research under complex geological settings remains relatively limited and requires further attention.

(3) Numerical simulation plays a significant role in the study of fracture mechanisms of coal and rock mass; however, the accuracy of model construction and parameter selection directly affects the reliability of simulation results. At present, there are still deficiencies in some numerical simulation models, which need further improvement and validation.

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However, several problems and challenges still remain, including multi-scale effects, complex geological conditions, and the integration of macroscopic and microscopic studies, all of which require further investigation and resolution.

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