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Evaluation research of the fracturing capacity of non-explosive expansion material applied to coal-seam roof rock

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ABSTRACT

Goaf caving is an effective measure to prevent disasters caused by large area roof weighting (LARW). This study uses non-explosive expansion material (NEEM) as a crack source to initiate goaf caving. To evaluate the fracturing capacity of NEEM, we prepared similar specimens with and without an included layer, and different numbers of slots were made along the radial direction of the hole. Acoustic emission and static strain gauge were adopted to monitor energy release and fracture strain damage. All the specimens displayed complex fracture phenomena, and there were positive correlations between fracture number and fractal dimension, fracture density, and the degree of faulting. The fractal dimension and fracture density of layer-bearing specimens were greater than those of specimens without a layer. The released cumulative energy was higher for specimens with two slots than for those with no slots, for specimens both with and without layers. Overall, compared to non-layer specimens, layer-bearing specimens showed a more concentrated energy ratio and a longer duration time of energy release. The relative cumulative energy curves showed several stable rising and abrupt rising patterns, which prolonged the action time of rock internal energy accumulation and accelerated the accumulation of internal damage.

1. Introduction

To reduce the destructive effect of huge shock loads generated from large area roof weighting (LARW) during the goaf caving process, the integrality of the goaf roof should be destroyed before it is subjected to pressure.[1] The common methods used to deal with roof problems are caving, filling, and pillar support,[2–5] with the methods used being selected with reference to the roof characteristics, coal seam thickness, and protection of the ground surface.[6,7] Caving method possesses the advantages of simplicity of operation, reliability, and low cost. This method involves removal of all the stands in the goaf space as the working face moves forward. In general, the soft rock of the immediate roof collapses under its own weight; in contrast, for a hard roof that is more coherent and has great thickness and strong self-bearing capacity, a large hanging arch without natural caving capacity forms after mining.[8] If free caving is not carried out for a long time or unreasonable pressure relief measures are adopted, shear failure will occur under high pressure, causing LARW that can induce a hurricane accident.[9] For instance, on March 23, 2016, a hurricane accident triggered by forced caving occurred at the 8117 comprehensive mechanized coal mining face, 5# floor, Anping Coal Company, Tongmei Group, Shanxi Province, China, which caused nineteen deaths. The forced caving was carried out by traditional deep-hole blasting which a large amount of mining explosive in the deep hole, and the hard roof was fractured by the high-pressure shock waves generated at the moment of blasting. LARW generation caused the air to be compressed in the goaf space, after which a hurricane formed, causing an accident.

In China, the occurrence conditions of coal seams are complicated. Approximately one-third of seams are hard–roof coal, which occurs in more than half of mining areas, such as No. 2, 3, 11, and 12 coal-seam roofs in Datong and 15 # coal-seam roof in Jincheng.[10,11] For hard-roof caving, methods such as high-pressure hydraulic fracturing [3,12,13] and deep-hole blasting [14–16] are adopted to reduce the length and weight of roof cantilevers. The caved loose rock fills the goaf space and supports the non-caved main roof from sinking sequentially, releasing the roof pressure and promoting safety in production. However, the existing caving methods have some limitations, for example, deep-hole blasting fractures the roof rock with an extremely short action time; thus, the generated high-pressure shock waves might induce a dynamic

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hazard and result in sudden LARW, which is not conducive to crack controllability of a large-area hanging arch. In addition, the open flame generated during deep-hole blasting might easily cause a goaf gas-explosion accident. Existing equipment that could provide a large flow and high pressure for high-pressure hydraulic fracturing occupies a large space, which causes inconvenience during operation. Its weakening effect is restricted by some factors, such as the permeability of internal rock, fracture distribution, and ground stress. In consequence, with the aim of mitigating the shortcomings of the existing roof crack methods, the non-explosive expansion fracture method (NEEFM) is proposed to achieve the weakening and fracturing while maintaining safety and control.

NEEFM works by thermal expansion, which causes the surrounding media to swell. The swelling force is generated from the chemical reaction between non-explosive expansion material (NEEM) and water. This material is stable, non-polluting, does not produce slungshot, and dose not require an open flame. NEEM is an optimization of a traditional static cracking agent, which greatly improves the fracturing capacity. Many studies of cracking agents have been carried out. Gambatese[17] studied the controllable fracture behavior of concrete on a small scale under the effect of a cracking agent. Hinze and Brown[18,19] investigated the influence of multiple factors on fracturing, such as the temperature, water to cement ratio, and borehole radius, finally concluding that temperature and water to cement ratio greatly affected the degree of fracturing, whereas borehole size had little effect on the swelling force at a specific temperature and water to cement ratio. Combining the above factors influencing the fracturing process, Guo et al.[20] established a structural model for a cracking agent and proposed a method for the addition of expansive agents to improve the swelling force. Tang et al.[21] confirmed the crack development process in concrete through initiation, growth, and final unstable extension using cracking agents by combining physical experiments and numerical simulation. Guo et al.[22] studied the formation of fracture networks in shale with different values of stiffness and brittleness under the action of cracking agents through dynamic monitoring of acoustic emission (AE) events, and proposed a new evaluation system for fracture networks. Li et al.[23] investigated the feasibility of fracturing hard coal and improving its permeability using cracking agents by combining an appropriate layout of boreholes. Lai et al.[24] carried experiments on specimen weakening and fracturing using AE and a fissure optical camera: the results had scientific significance in engineering applications and technology improvements for fracturing steep coal roofs. Hao et al.[25] studied the fracturing effect of cracking agents and attained a good industrial effect from forced caving in a highly gassy mine.

The use of NEEM can avoid the appearance of internal instantaneous high-stress concentration phenomenon appearing relied on its own stable response for a long time. Through stress compensation and continuous loading, NEEM continues to weaken the roof rock, thus producing internal tensile damage and inducing crack initiation. Crack initiation releases a fracturing signal that can be monitored using an AE system. Broadly speaking, AE is an instantaneous elastic-wave rapid-release phenomenon caused by local energy release in solid materials,[26–28] and also presents the stress transition process from an unsteady high-stress state to a lower-stress state because of the internal non-uniform stress distribution.[29,30] AE can be used to characterize fractures effectively, allowing evaluation of large internal failures in the medium to be monitored.[31] Compared with other non-contact test methods, such as ultrasonic and X-rays, the analysis of AE data has the advantages of being non-destructive and real-time.[32] This method can monitor both the internal transient fracturing process prior to overall complete failure of the solid, and the three-dimensional AE distribution, which represents the spatial distribution of micro fractures.[33,34]

By studying the relationships between the roof mechanical characteristics and formation of spatial cracks under the action of NEEM, the rules governing changes in rock porosity will be analyzed for different combinations of NEEM function and preexisting slots, allowing evaluation for the fracturing capacity of NEEM for coal-seam roofs. Fracturing of roof strata by NEEM is a complex kinetic process, and the key to the application of NEEM in engineering is being able to predict and control the dynamic process.

In this study, we used a simplified model of roof strata consisting of two kinds of specimens, with or without a layer, which agree with the strength of relevant roof rock.[35] Different numbers of slots were made around the hole to evaluate the directional fracture capacity of NEEM. AE and a static strain gauge (SSG) were adopted to monitor crack propagation, internal energy release process, and nonlinear deformation. Finally, the distribution of surface cracks was quantitatively characterized, and the complex fracture evolution process and fracture strain damage of different specimens were analyzed using the recorded data. Furthermore, issues that may be expected to arise when applying NEEM fracturing roof in the field were discussed.

2. Experimental methods

2.1. Specimen preparation

Considering the bearing capacity and borehole existence, the specimens with size of 300 mm×300 mm×300 mm were prepared to decrease the scale effect and boundary effect, as well avoid the shear failure during the loading process.[36,37] A ratio of cement to sand to gypsum to water of 2:1:2:2 was used to prepare similar specimens both with and without a layer, which was made of quartz and its thick was 30–40 mm.[35] A schematic diagram of both types of specimen is

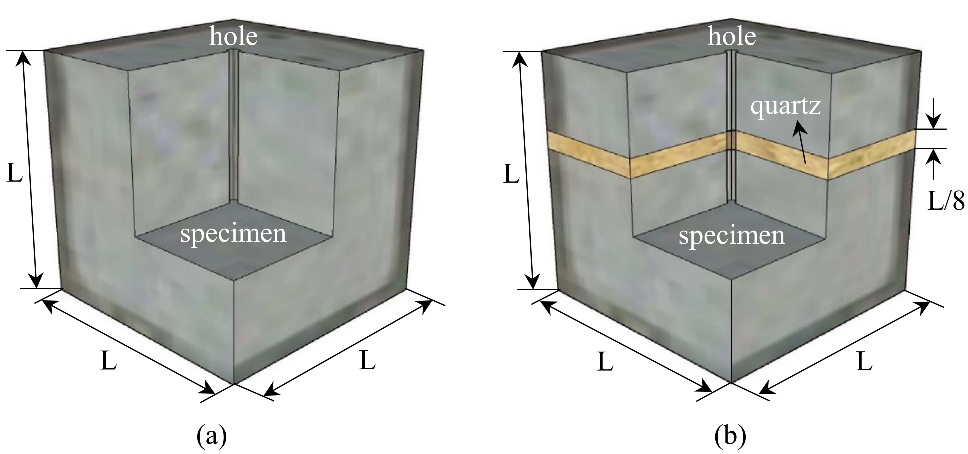

Fig. 1. Schematic diagram of two kinds of specimens: (a) specimen without a quartz layer; (b) specimen with a quartz layer.