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Mechanical and acoustic emission characteristics of rock: Effect of loading and unloading confining pressure at the postpeak stage

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A B S T R A C T

The disturbance caused by excavation to surrounding rock structures during underground mining under complex geological conditions at great depth induces rock failure due to the effect of stress concentration and unloading. Therefore, the design, construction and maintenance of structures (i.e., pillars, drifts, chambers) are based not only on peak strength, but also on postpeak behavior and, subsequently, residual strength of rocks. Therefore, better understanding the characteristic features of rock at the postpeak stage is of paramount importance for underground construction and ground support design activities. Argillaceous limestone specimens loaded to the residual phase in the conventional triaxial compression test under different initial confining pressures were continuously loaded by loading and unloading cycles. Analysis of the variation characteristics of stress and strain were complemented with acoustic emission (AE) monitoring for investigating the effects of the confining pressure and the loading and unloading cycles on the mechanical properties of the rock in the residual phase. Besides, the yielding premonition information about the rock in the loading confining pressure stage was analyzed and calculated. The results show that because the deformation during the axial loading mainly comes from the sliding between the fracture planes, the bearing capacity is related to not only the confining pressure, but also the unloading path; the elastic modulus in the axial elastic deformation stage is larger than the corresponding elastic modulus of the prepeak stage, and the axial deformation presents good feature of elastic–plastic deformation; the bearing capacity of rock in the residual phase was provided by the frictional sliding between the elastic rock block under confining pressure. The precursor information about the rock yielding to plastic deformation in the loading confining pressure test of the failure rock could be confirmed based on the evolution characteristics of the AE amplitude.

1. Introduction

Rock can be broken by both loading and unloading stress, and the strength and deformation properties of broken rock depends on the rock block and in its discontinuity. The disturbance caused by excavation to surrounding rock structures during underground mining under complex geological conditions at great depths induce rock failure due to the effect of stress concentration and unloading. Therefore, during the application of underground engineering methods, the plastic or failure zone would inevitably be produced in the surrounding rock that directly threatens the stability of the rock structure. Therefore, the design, construction, and maintenance of structures (i.e., pillars, drifts, and chambers) are based not only on peak strength, but also on postpeak behavior and, subsequently, residual strength of rocks. In underground coal mining, especially while mining the underlying protective layer, the aforementioned concept holds true because (a) the protective layer of rock in which coal mine openings are excavated usually have relatively weak strength, and (b) these surrounding rock structures usually bear mining-induced stresses that can reach up to 6.0 times the overburden stress (Gao and Kang, 2016). As shown in Fig. 1, mining-induced stresses are so high that the surrounding rock of the bottom gas drainage lane will unavoidably fail, yielding considerable plastic deformation and reaching its residual strength. Therefore, when rock failure occurs, coal mine engineers' main concerns are the residual strength and support methods needed to maintain the residual strength.

The residual strength is the stable bearing capacity that a broken rock can sustain while the strain increases under a given confinement condition after its peak strength has been surpassed. For an

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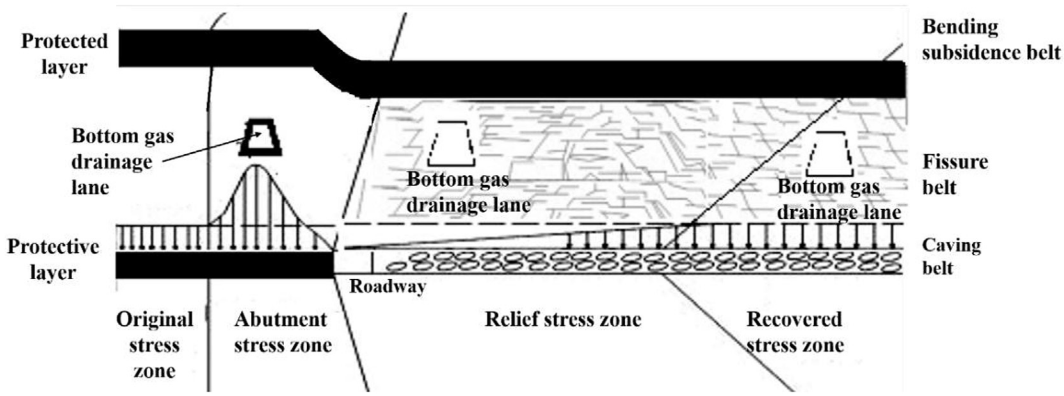

Fig. 1. The surrounding rock of the bottom gas drainage lane broke while excavating the protective layer.

intact rock specimen, however, after the peak strength at any given confinement is reached, damage to the specimen increases such that its load resistance decreases. The damage continues to occur until eventually a rough fracture surface ensues with some shearing of rough asperities or until a stable residual strength is established. For any further increase of strain, the residual strength remains constant. If the rough asperities were ground to a smooth surface, a base strength would be achieved. The residual strength could largely affect the yielding zone around the tunnel, as demonstrated by (Cai et al., 2007a). Even if the peak strength is the same for different residual friction angles and cohesions, the yielding zones are drastically different. Therefore, better understanding of the character of rock in the postpeak state is of paramount importance for underground construction and ground support design.

Residual strength is not an inherent characteristic of rock materials, but rather it is the carrying capacity presented by the integral structure that affects the rock block and fracture plane under confining pressures. Previous studies on the peak mechanical properties of rock materials have been systematic, but only limited studies are available on the postpeak phase characteristics of rock materials. For studying the residual strength of rock, researchers conducted tests mainly on rock samples with artificial joints or natural failure surfaces produced by stress. One advantage of using samples with artificial joints is that the space of the joints could be easily accessed and controlled, and another is that replicas allow studying the effect of one specific factor on the shear mechanism of the joints while the remaining factors remain constant. For example, Jafari et al. (2004) tested identical saw-tooth replica joints to study the effect of the number, frequency, and stress amplitudes of the prepeak (load-controlled) cycles on the residual shear strength of artificial rock joints and found that the residual shear strength of the samples would be nearly constant even after multiple cycles. Postpeak modulus of physical models of a rock mass in triaxial and true triaxial stress conditions was estimated by Tiwari and Rao (2006). Tests on artificially jointed granitic rock specimens revealed that the residual strength envelopes were practically equal to those of corresponding intact specimens (Arzua et al., 2014). Fathi et al. (2016) prepared rectangular joint replicas by pouring nonshrinking cement mortar on a fresh joint surface of an artificially split granite block and performed prepeak cyclic loading shear tests under different number of cycles. Their results showed that the low number of cycles did not change the residual shear strength of joints. There exists great difference in the surface topography, spatial shape, geometry size, etc. between the artificial fracture plane and the natural fracture plane, and therefore, the test results of artificial fracture plane samples cannot adequately represent the postpeak mechanical properties of rock.

Another method to study the postpeak mechanical properties of rock is by obtaining the complete stress-strain curve of intact rock loaded to destruction by axial load or lateral loading or unloading stress (Zhang et al., 2015). Stiff compression machines are necessary to obtain the postfailure curve of rocks, and displacement-controlled testing is important for detecting the postfailure part of the stress–strain curve. To detect postfailure regions of stress–strain curves, especially for brittle rock types, slower rates are necessary, and the circumferential displacement rate can be used as the controlling feedback mechanism (Yang et al., 2012). Arzúa and Alejano (2013) estimated the residual strength as the lowest principal strength value observed in each test from the stress–strain plots, and found that residual strength test results better fitted to Mohr–Coulomb than to Hoek–Brown failure criteria. The axial strain control and lateral strain control of the test control mode could also affect the postfailure behaviors of the rock and coal specimens (Mishra and Nie, 2013). Relations between prefailure rock parameters and postfailure strength and deformability parameters in unconfined (Tutluoglu et al., 2015) and confined compression tests (Walton et al., 2015) were discussed and the results were found to be consistent with a cohesion-weakening-friction-strengthening model for yield. The rocks displayed a sharp decrease in sample stiffness shortly after crack damage, which eventually reached a roughly constant residual value. Zhang et al., (2015) indicated that a small amount of postpeak strain is required to initiate macroscopic slip surfaces, and the friction angle decreases with further postpeak strain as the macroscopic slip surfaces in the rock become well established. Mohamadi, M. and R.G. Wan (Mohamadi and Wan, 2016) pointed that the characteristics of postpeak response of rock were in the form of localized deformations and the postpeak deformations of sheared samples could be portrayed by constant-rate dilation. These studies basically focused on the stress reduction section (strain softening stage) and on the relationship between residual strength and peak strength under the broken confining pressure of the intact rock after the rock damage; however, under many actual engineering practice circumstances, the surrounding rock suffers loading and unloading stress during the destruction state, and therefore, it is necessary to further study the mechanical properties of rock in the postpeaking phase under the condition of loading and unloading confining pressures.

Conventional stress and strain measurements are not sufficient to describe the postpeak feature of rock, and the crack initiation, propagation, and coalescence in rocks subjected to loading could be monitored by acoustic emission (AE). AE is a transient elastic wave generated by the rapid release of energy within a material, and it can be used to monitor the development of microcracks and the