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Research Article

Size Effect on Acoustic Emission Characteristics of Coal-Rock Damage Evolution

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Coal-gas outburst, rock burst, and other mine dynamic disasters are closely related to the instability and failure of coal-rock. Coal-rock is the assemblies of mineral particles of varying sizes and shapes bonded together by cementing materials. The damage and rupture process of coal-rock is accompanied by acoustic emission (AE), which can be used as an effective means to monitor and predict the instability of coal-rock body. In this manuscript, considering the size effect of coal-rock, the influence of different height to diameter ratio on the acoustic emission characteristics of coal-rock damage evolution was discussed by microparticle flow PFC^{2D} software platform. The results show that coal-rock size influences the uniaxial compressive strength, peak strain, and elastic modulus of itself; the size effect has little effect on the acoustic emission law of coal-rock damage and the effects of the size of coal-rock samples on acoustic emission characteristics are mainly reflected in three aspects: the triggering time of acoustic emission, the strain range of strong acoustic emission, and the intensity of acoustic emission; the damage evolution of coal-rock specimen can be divided into 4 stages: initial damage, stable development, accelerated development, and damage.

1. Introduction

Along with the increase of mining depth, the dynamic disasters related to the instability and failure of coal-rock are being more and more serious. The coal-rock mass is made up of different mineral particles with different sizes and shapes and is bonded together by a certain cementing material. Under the external load, the preexisting fissures in the coal-rock will evolve. As new fissures are produced and propagate, the damage of the coal-rock is aggravated, finally leading to rupture instability of the coal-rock [1]. The damage and rupture of the coal-rock is accompanied by acoustic emission (AE), which can be used to monitor and predict the propagation and penetration of microcracks in the coal-rock on a continuous, real-time, and effective basis. Thus the stability and rock burst of mines can be predicted [2–9].

The research of acoustic emission characteristics of coal-rock under the conventional standard scale (diameter 50 mm × height 100 mm) has obtained some interesting results. Shkuratnik et al. [10] studied the triaxial compression acoustic emission characteristics of anthracite samples and the features of acoustic emission parameters in various deformation stages are revealed and the physicomechanical properties of coal are estimated. Li et al. [11] carried out the uniaxial compression tests on rocks and analyzed the mechanical characteristics and acoustic emission characteristics of the whole process of rock failure. Wu et al. [12] performed acoustic emission tests on 48 specimens under uniaxial tension loading. The existence of Kaiser effect and the corresponding stress range in the concrete specimens under uniaxial cyclic tension loading and the factors that influence the Kaiser effect of the concrete specimens were systemically analyzed. Xu et al. [13], based on the independent development of mesoshear test equipment for coal-rock and PCI-2 acoustic emission detection analysis system, studied the acoustic emission features of sandstone with different saturation degrees of 0%, 50%, and 100% during shearing process and the relationship between evolution law of acoustic emission signal and cracking and extension of sandstone was discussed. These researches were helpful to understand the relationship between the compressive failure mechanism of coal-rock and the acoustic emission information. However, the actual mining scale is much larger than that of the laboratory scale. Considering the size effect, carrying on further research on the acoustic emission characteristics of coal-rock has practical significance for the stability monitoring of coal mine.

In situ or indoors acoustic emission test has the following disadvantages: one is that the coal-rock material including many joints or fissures and the different of sampling time and spatial positions result in great discreteness of physical and mechanical properties of coal-rock mass; this will inevitably lead to different acoustic emission characteristics of coal-rock sample of different height to diameter ratio; the other is that monitoring results of acoustic emission monitoring equipment cannot fully reflect the true characteristics of coal-rock damage AE information under the influence of the human factors, sensor monitoring factors, or the different monitor time and location. Therefore, in this paper, numerical method was used to study the size effect of acoustic emission characteristics of coal-rock damage evolution. Firstly, the coal-rock uniaxial compression was established by the platform of the microparticle flow software PFC^{2D}, and the physical mechanical parameters which were consistent with the laboratory experiment were obtained through the "trial and error" method [14]. Secondly, the influence of size effect on acoustic emission characteristics of coal-rock damage evolution was deeply analyzed. Finally, the damage evolution characteristics of coal-rock mass were discussed based on acoustic emission characteristics.

2. Uniaxial Compression Model for Coal-Rock

2.1. Particle Flow Code. Based on the discrete element method, Cundall and Strack [15] established the particle flow theory that provides a microscopic analysis of the mechanism of damage evolution of materials with good applicability. When used to simulate the damage of the bond between the particles, particle flow code (PFC) offers the bond model for 2 types of bond, namely, contact bond and parallel bond [16]. Contact bond refers to the bond between the particles and the force is generated upon relative displacement between the particles. However, the moment of force cannot be transmitted, and therefore the contact bond applies to granular material (e.g., soil mass). Parallel bond is the plane-to-plane bond and the moment of force can be transmitted. Therefore, parallel bond is applied to compact material such as coal-rocks. In this study, the uniaxial compression model for coal-rock specimen was built using the parallel bond.

2.2. Physicomechanical Parameters of Coal-Rock Specimen. Microscopic physicomechanical properties of the particles and the bond properties are required for running the simulation tests using the particle flow theory. However, these parameters cannot be directly acquired from laboratory tests. Therefore, before the numerical simulation, the microscopic parameters were first checked and corrected. During this process, a large number of numerical simulation tests with similar conditions as the laboratory tests or in situ field tests were first carried out. Then the numerical simulation results were compared against the results of laboratory tests or in situ field tests. The microscopic parameters were adjusted repeatedly by trial and error method until they satisfy the requirement of simulation analysis.

In view of the limitation of laboratory test condition, the parameters provided by Wang et al. [17] were used to carry out numerical test. In this manuscript, the mechanical parameters of uniaxial compression of standard coal-rock specimens in a certain mining area were selected as the reference basis for the particle flow program. Through the method of "trial and error" repeated check comparison, the physical mechanical parameters of Table 1 are close to the macroscopic mechanical parameters of the real coal-rock mass. The stress-strain curve (Figure 1) and the final failure characteristics (Figure 2) of PFC model are in good agreement with the laboratory tests of real coal-rock.

Table 1: Physicomechanical parameters of coal-rock specimen.

Parameter	Value
Minimum particle diameter/mm	0.3
Particle diameter ratio	1.66
Density/(kg/m^3)	1800
Contact modulus of the particle/GPa	1.0
Parallel bond deformation modulus/GPa	12
Porosity	0.1
Coefficient of friction	0.46
Parallel bond compressive strength/MPa	10
Parallel bond cohesive force/MPa	16

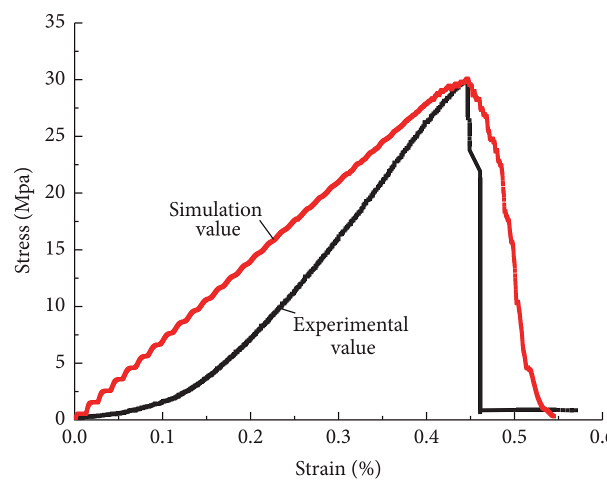


Figure 1: Stress-strain curves of coal-rock specimen.

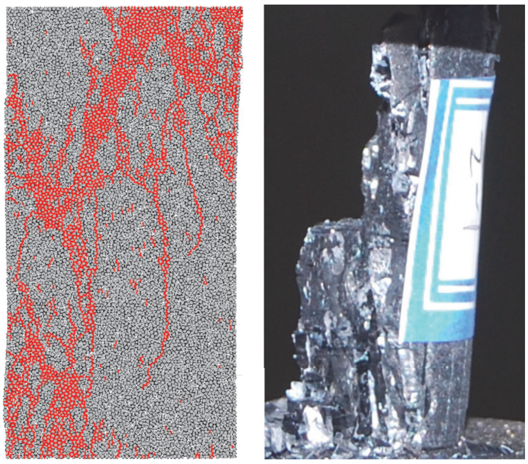


Figure 2: Failure mode of coal-rock specimen.

2.3. AE Simulation by PFC. During the loading process of BMP, the bond will fracture when the stress intensity transmitted between the particles exceeds the bonding strength between the particles, thus creating microcracks in the coal-rock specimen [18]. As the microcracks propagate in the coal-rock specimen, the damage energy is rapidly released as acoustic waves. This is the so-called AE phenomenon. When the compression of the coal-rock specimen was simulated with PFC, the program based on Fish language was used to monitor the number of fractured parallel bonds at each moment (each step). Thus the AE characteristics produced upon damage were analyzed.

To study the influence of size effect on the AE characteristics, five different ratios of height to diameter were selected for the model (Figure 3) with the diameter fixed as 50 mm. The height-diameter ratio K was 0.5, 1.0, 1.5, 2.0, and 2.5, respectively. The model neglects the influence of particle shape and distribution and uses the parameters of Table 1 uniformly, sufficient particles in the set area were generated by enlarging radius method to meet the porosity, and the total number of particles produced by each model was 2197, 4358, 6560, 8753, and 10946. The unbalanced force generated in this process was eliminated cyclically. Loading was performed by moving the wall on top at the same stress rate. To prevent the spill-out of the particles, the wall was lengthened appropriately. Loading was terminated when the residual stress was 0.01 times that of the peak strength by controlling the FISH language.

3. Influence of Size Effect on AE Characteristics

3.1. Relationship between Coal-Rock Size and Strength. Figure 4 shows the stress-strain curves of coal-rock specimen with different height-diameter ratio under the same diameter and Table 2 presents the mechanical parameters of coal-rock in all numerical schemes. The parameters of σ_p, E, and ε represent the uniaxial compressive strength, elastic modulus, and peak strain, respectively. It should be explained that the peak strain here refers to the average strain of the whole specimen, rather than the strain in the middle part under end constrained. It can be seen from Figure 4 and Table 2 that when height-diameter ratio is larger than 1, the uniaxial compressive strength of coal-rock gradually decreased and has an inverse relationship to the height-diameter ratio, which is consistent with the view of Hoek and Brown [19] and Pells [20]. However, when the height-diameter ratio is smaller than 1, it is no longer in compliance with this rule, and the postpeak mechanical properties are more complicated. This can be explained that when height-diameter ratio is less than 1, the coal-rock compression process will produce more of the cracks, the coal-rock is divided into a plurality of blocks, as shown in Figure 5(a), and the average stress of the wall of the FISH language recorded cannot reflect the real stress of the internal area of the coal-rock mass. With the increase of the height-diameter ratio, the peak strain of coal-rock decreases gradually, and the peak strain changes slightly when the height-diameter ratio is greater than 1.5. The elastic modulus increases with the increase of the height-diameter ratio. At the same time, it can be shown that the failure modes of coal-rock with different height-diameter ratio have different characteristics due to the friction effect generated in the particles or between the particles and the loading walls. When the height-diameter ratio is 2.5, the cracks of coal-rock are mainly generated on the ends of the specimen and distributed in parallel, which are approximately symmetrical to the center of the specimen. When the height-diameter ratio is 2, the cracks were distributed in splitting shape. When the height-diameter ratio is 1.5, the cracks of coal-rock are mainly generated at the nonloading end, and they extended upward with splitting shape. When the height-diameter ratio is 1.0, the cracks distributed in V shape, and when the height-diameter ratio is 1.0, the cracks distributed in String wave shape.

Table 2: Mechanical parameters of coal-rock with different height-diameter ratio.

Scheme	K	σ_p/MPa	E/GPa	ε/%
(1)	0.5	29.95	5.13	0.61
(2)	1.0	33.18	6.24	0.56
(3)	1.5	31.13	6.69	0.48
(4)	2.0	30.09	7.14	0.45
(5)	2.5	30.06	7.48	0.43

3.2. Influence of Coal-Rock Size on AE Characteristics. Figure 6 shows the AE characteristics with different ratio of height-diameter ratio; Figure 7 shows the AE characteristics-time curve with different height-diameter ratio. The AE characteristics with different height to diameter ratio are listed as follows:

(1) Initial compression stage: due to the fact that particle flow model established is of 2 dimensions, and without considering the initial damage of coal-rock, the compression AE characteristics of coal-rocks are not particularly distinctly,

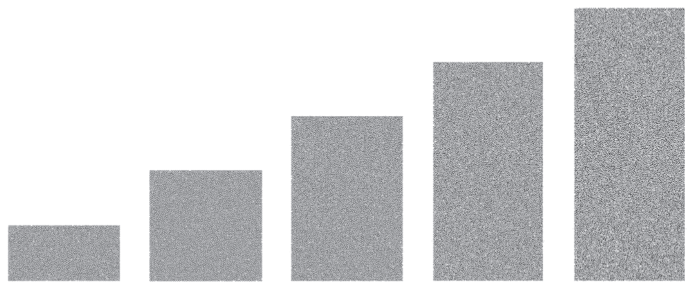


FIGURE 3: Coal-rock specimen with different height-diameter ratio.

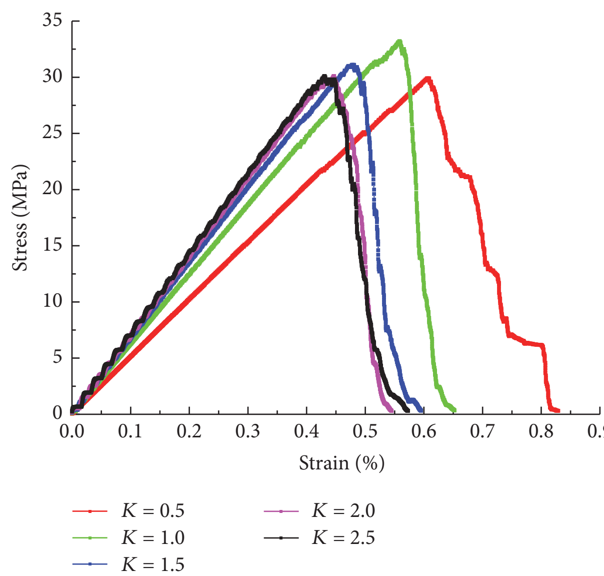


FIGURE 4: Coal-rock stress-strain curves with different high diameter ratio.

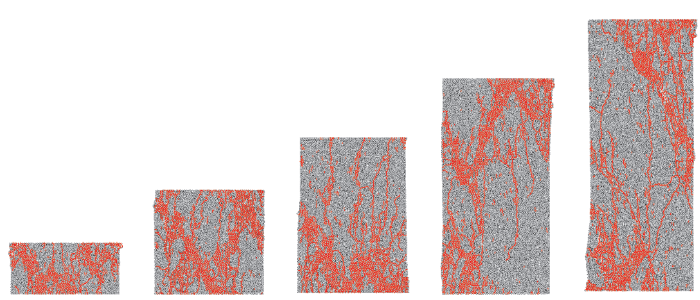
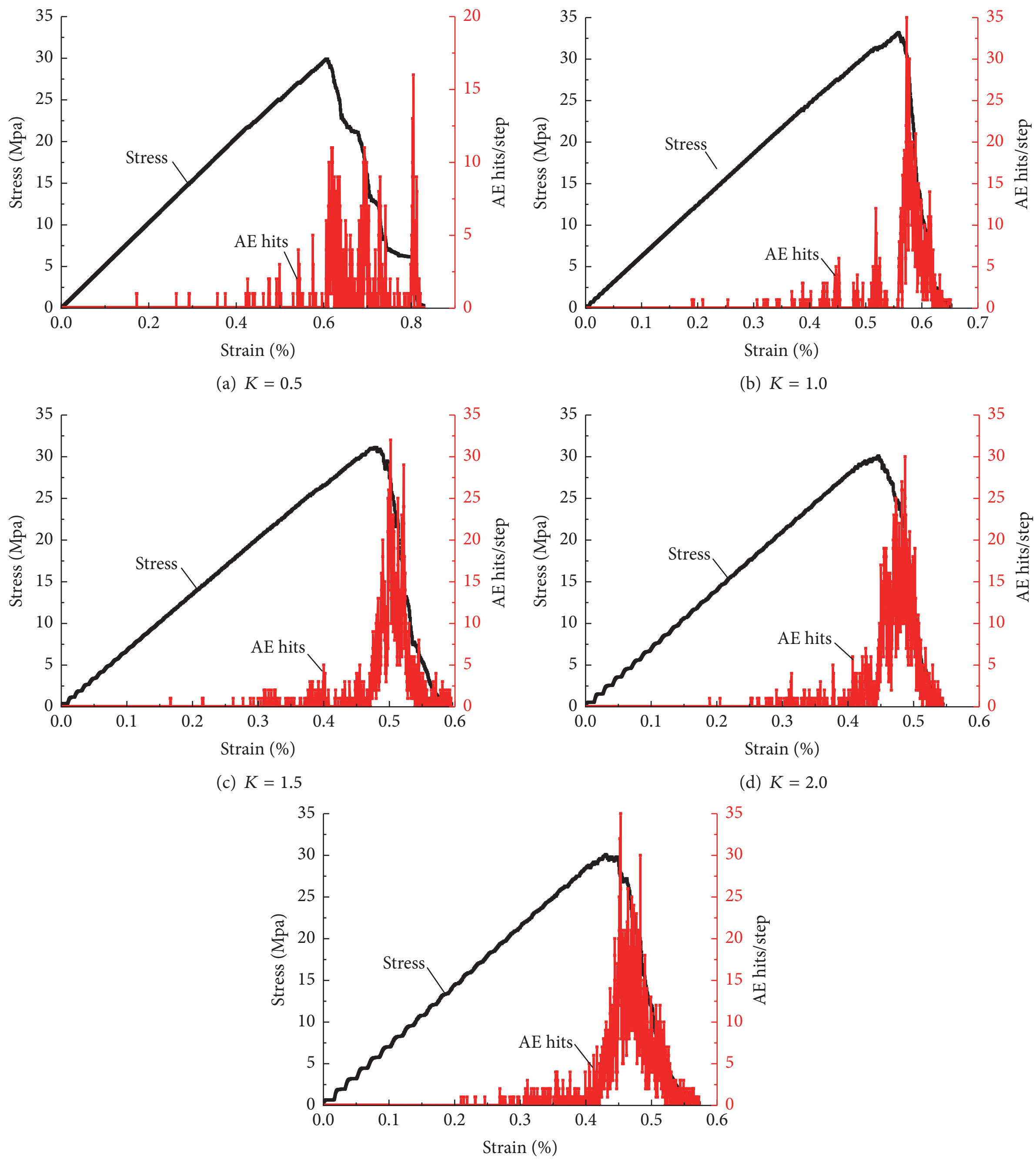


FIGURE 5: Compression failure mode of coal-rock specimens with different height-diameter ratio.

the acoustic emission hits strength and number are very little. At this stage, the size effect has little influence on the acoustic emission characteristics.

(2) Elastic compression stage: the microcrack of coal-rock specimen is gradually expanded, and the number of the acoustic emissions is increased, but the impact strength of the acoustic emission is small. During this stage, with the increase of the height-diameter ratio of the coal-rock samples, the acoustic emission impact strength increases correspondingly, and the acoustic emission occurred in advance.

(3) Pre and postpeak compression stage: a large number of AE signals are detected, and the number is more than many



(a) $K = 0.5$ (b) $K = 1.0$ (c) $K = 1.5$ (d) $K = 2.0$ (e) $K = 2.5$

Figure 6: Acoustic emission characteristic curves with different height-diameter ratio.

times that of other stages. The strain range in which the AE hits occurred reduced with the increase of height-diameter ratio, but the intensity of AE hits tended to increase.

(4) Residual plastic flow stage: the coal-rock specimen still possesses certain load-bearing capacity. As the microcracks propagate, acoustic emission impact signal decreased rapidly, and this trend is more obvious with the height-diameter ratio increases.

By comparing the stress-strain-AE characteristics curves and the AE hits-time curves under different height-diameter ratio, it can be inferred that the size effect has only limited impact on AE characteristics. Four stages as mentioned above of variation of AE are identified for different height-diameter ratio, and the effect of size on acoustic emission characteristics is mainly reflected in three aspects: (1) the larger the size of coal-rock specimen, the earlier the triggering time of AE; (2) the smaller the size, the larger the strain range in which the AE hits occurred; (3) the larger the size, the higher the intensity of AE near the moment of peak.

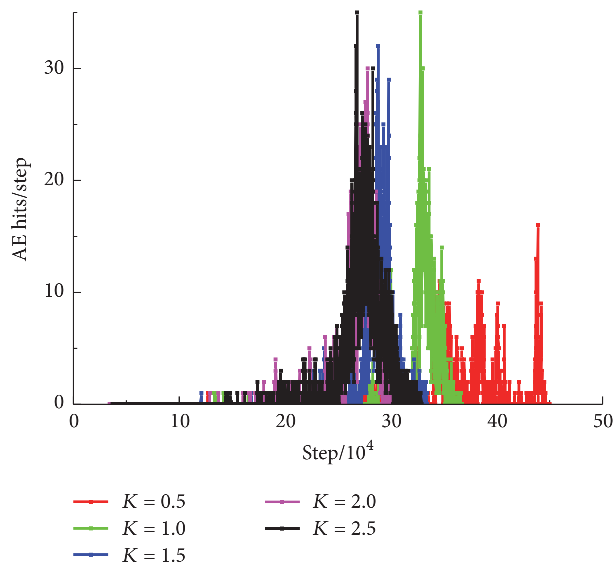


FIGURE 7: Acoustic emission and time characteristic curves with different height-diameter ratio.

3.3. Damage Constitutive Equation for the Coal-Rock Specimen Based on AE. Many studies have shown that the index of AE hits can reflect the changes of properties of the materials. This parameter is proportional to the dislocation of material and the strain produced due to fracture and crack propagation [21]. Hence the number of AE hits was used to characterize the damage evolution of the coal-rock specimen.

Kachanov [22], the scholar of the former Soviet Union, defines the damage variable as follows:

$$D = \frac{A_d}{A}, \tag{1}$$

where A_d is the cross-sectional area of damage and A is the cross-sectional area of the material without damage at the initial stage.

Suppose that the number of cumulative AE hits at the moment when the damage-free cross-sectional area A completely loses the load-bearing capacity is C_0. Then the number of cumulative AE hits for unit area of coal-rock specimen C_w is calculated by

$$C_w = \frac{C_0}{A}. \tag{2}$$

When the cross-sectional area of damage reaches A_d, the number of cumulative AE hits C_d is calculated by

$$C_d = C_w A_d = \frac{C_0}{A} A_d. \tag{3}$$

Thus,

$$D = \frac{C_d}{C_0}. \tag{4}$$

Since the coal-rock specimen is hard to achieve complete failure under the compression process, in this paper, considering the total number of AE hits at the moment, the residual stress that is 0.01 times that of the peak strength (load stop point) as the cumulative AE hits of coal-rock fails completely.

Based on the acoustic emission hit characteristics and strain equivalence principle [23], the damage constitutive model for the coal-rock specimen under uniaxial compression is established:

$$\sigma = E\varepsilon(1 - D) = E\varepsilon\left(1 - \frac{C_d}{C_0}\right). \tag{5}$$

Figure 8 shows the stress-strain curve fitted by the damage constitutive equation based on AE hits characteristics when the height-diameter ratio is 2.0. It can be seen that the fitted curve is consistent with the actual numerical curve.

3.4. Influence of Size Effect on Damage Evolution of Coal-Rock Specimen. Figure 9 shows the damage variable-strain curves at different height-diameter ratio. The damage evolution of the coal-rock specimen can be divided into four stages.

(1) Initial Stage. The damage variable is very small at this stage, and the specimen is gradually compacted. Since the fissures are closed initially, the size effect only has limited impact on the damage variable.

(2) Stage of Stable Evolution of Damage. The damage variable increases stably at this stage. The existing cracks begin to propagate, and new cracks are formed. The size effect has a small impact on the damage variable, but the impact on the damage strain is considerable. The smaller the height-diameter ratio, the larger the damage strain.

(3) Stage of Accelerated Damage Evolution. The damage variable increases dramatically at this stage, approaching the critical value of damage. The microcracks rapidly evolve into joints and fissures, giving rise to macroscopic damage. At this stage, the size effect has considerable impact on the damage variable. The larger the height-diameter ratio, the sharper the change of the damage variable and the lower the strain relief.

(4) Stage of Failure. The damage variable tends to be stabilized and the coal-rock specimen loses the load-bearing capacity at this stage. The failure mode is characterized by the propagation of fissures, and fewer new ruptures are generated. Size effect has limited impact at this stage.

4. Conclusions

(1) The coal-rock was simulated by the parallel bond model using the discrete element method, which can better reflect the mechanical properties of the coal-rock mass. And the program based on Fish language can be used to measure the AE characteristics during the process of damage evolution.

(2) When the height-diameter ratio is larger than 1, the strength is inversely proportional to the height-diameter ratio of the specimen. when the height-diameter ratio is smaller than 1, it is no longer in compliance with this rule, and the postpeak mechanical properties are more complicated. With the increase of the height-diameter ratio, the peak strain

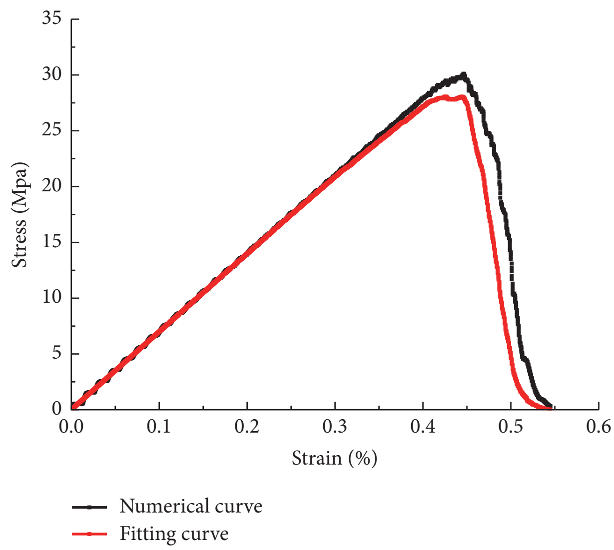


FIGURE 8: Stress-strain curves.

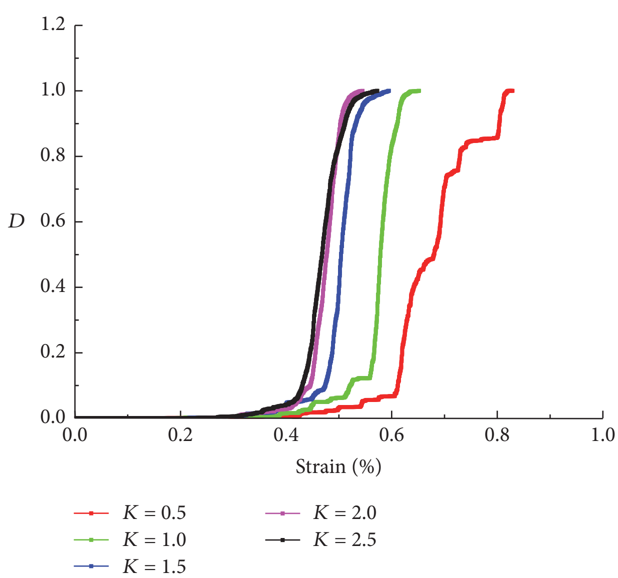


FIGURE 9: Damage variable-strain curve of coal-rock specimen with different height-diameter ratio.

of coal-rock decreases gradually, but the elastic modulus increased correspondingly.

(3) Size effect has limited influence on AE, and the changes of AE with the rock size can be summarized as follows: the larger the rock size, the earlier the triggering time of AE and the larger the strain range in which plenty of AE hits occurred; the larger the rock size, the greater the intensity of AE characteristics around the peak time.

(4) The damage evolution of the specimen can be divided into four stages: initial stage, stage of stable damage evolution, stage of accelerated damage evolution, and stage of failure. The size effect has limited impact on the damage variable in the first, second, and fourth stage; however, the impact of the size effect is higher in the third stage. The larger the height-diameter ratio, the sharper the change of the damage variable and the lower the strain relief.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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References

[1] C. D. Su and Z. H. Zhang, "Analysis of plastic deformation and energy property of marble under pseudo-triaxial compression," *Chinese Journal of Rock Mechanics and Engineering*, vol. 27, no. 2, pp. 273–280, 2008.

[2] A. Lavrov, "The Kaiser effect in rocks: principles and stress estimation techniques," *International Journal of Rock Mechanics and Mining Sciences*, vol. 40, no. 2, pp. 151–171, 2003.

[3] V. Rudajev, J. Vilhelm, and T. Lokajíček, "Laboratory studies of acoustic emission prior to uniaxial compressive rock failure," *International Journal of Rock Mechanics and Mining Sciences*, vol. 37, no. 4, pp. 699–704, 2000.

[4] T. Ishida, T. Kanagawa, and Y. Kanaori, "Source distribution of acoustic emissions during an in-situ direct shear test: implications for an analog model of seismogenic faulting in an inhomogeneous rock mass," *Engineering Geology*, vol. 110, no. 3-4, pp. 66–76, 2010.

[5] Katsuyama, *Application of AE Techniques*, Feng X., T., Translator, Metallurgy Industry Press, Beijing, China, 1996.

[6] Z. J. Wen, X. Wang, Q. H. Li et al., "Simulation analysis on the strength and acoustic emission characteristics of jointed rock mass," *Technical Gazette*, vol. 23, no. 5, pp. 1277–1284, 2016.

[7] W. Blake, *Microseismic Application for Mining: A Practical Guide*, Bureau of Mines, Washington, DC, USA, 1982.

[8] D. A. Lockner, J. D. Byerlee, V. Kuksenko, A. Ponomarev, and A. Sidorin, "Quasi-static fault growth and shear fracture energy in granite," *Nature*, vol. 350, no. 6313, pp. 39–42, 1991.

[9] X. D. Zhao, B. Chen, and F. X. Jiang, "Study of micro-seismic engineering applications," *Chinese Journal of Rock Mechanics and Engineering*, vol. 21, no. 2, pp. 2609–2612, 2002.

[10] V. L. Shkuratnik, Y. L. Filimonov, and S. V. Kuchurin, "Regularities of acoustic emission in coal samples under triaxial compression," *Journal of Mining Science*, vol. 41, no. 1, pp. 44–52, 2005.

[11] S. Li, X. Yin, Y. Wang, and H. Tang, "Studies on acoustic emission characteristics of uniaxial compressive rock failure," *Chinese Journal of Rock Mechanics and Engineering*, vol. 23, no. 15, pp. 2499–2503, 2004.

[12] S. X. Wu, S. X. Zhang, and D. J. Shen, "An experimental study on Kaiser effect of acoustic emission in concrete under uniaxial tension loading," *China Civil Engineering Journal*, vol. 41, no. 4, pp. 31–39, 2008.

[13] J. Xu, H. Wu, and L. F. Lu, "Experimental study of acoustic emission characteristics during shearing process of sandstone under different water contents," *Chinese Journal of Rock Mechanics and Engineering*, vol. 31, no. 5, pp. 914–920, 2012.

[14] Itasca Consulting Group Inc, *Manual of Particle Flow Code in 2-Dimension (Version 3.10)*, Itasca Consulting Group Inc, Minneapolis, Minn, USA, 2005.

[15] P. A. Cundall and O. D. Strack, "A discreate numerical model for granula assemblies," *Geotechnique*, vol. 29, no. 1, pp. 47–65, 1979.

[16] Itasca Consulting Group, *PFC2D (Particle Flow Code in 2 Dimensions) Fish in PFC2D*, Itasca Consulting Group, Minneapolis, Minn, USA, 2008.

[17] X. Wang, Z.-J. Wen, and Y.-J. Jiang, "Time-space effect of stress field and damage evolution law of compressed coal-rock," *Geotechnical and Geological Engineering*, vol. 34, no. 6, pp. 1933–1940, 2016.

[18] J. F. Hazzard, R. P. Young, and S. C. Maxwell, "Micro-mechanical modeling of cracking and failure in brittle rocks," *Journal of Geophysical Research*, vol. 105, no. 7, pp. 1978–2012, 2000.

[19] E. Hoek and E. T. Brown, *Underground Excavations in Rock*, vol. 27, no. 2, Institute Mining and Metallurgy, London, UK, 1980.

[20] P. J. N. Pells, *Uniaxial Strength Testing, Comprehensive Rock Engineering Principles, Practice & Projrcts*, Pergamon Press, Oxford, UK, 1993.

[21] X. W. Liu, J. Z. Lin, and Z. Y. Yuan, "Rrsearch on evaluation of material fatigue damage by acoustic emission technology," *China Railway Science*, vol. 18, no. 4, pp. 74–91, 1997.

[22] L. M. Kachanov, "Time of the rupture process under creep conditions," *Izvestia Akademii Nauk SSSR, Otdelenie Tekhnicheskich Nauk*, vol. 12, no. 8, pp. 26–31, 1958.

[23] J. Lemaitre, J. P. Sermage, and R. Desmorat, "A two scale damage concept applied to fatigue," *International Journal of Fracture*, vol. 97, no. 4, pp. 67–81, 1999.