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Scale Effect on Uniaxial Compressive Properties of the Outburst-Prone Coal

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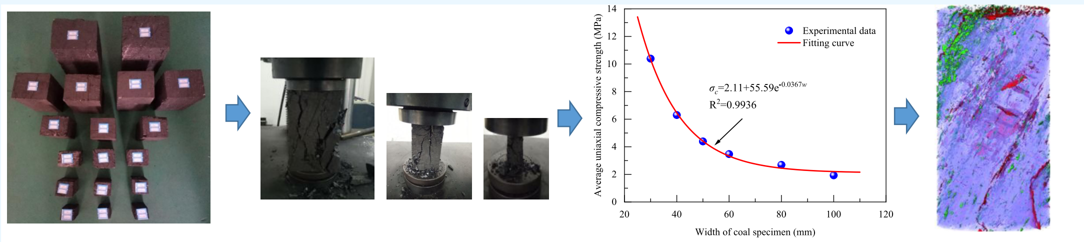

Prepared coal samples with different sizes. Ruptured coal samples with different scale sizes. Scale effect on the uniaxial compressive strength. Microstructures in coal sample.

ABSTRACT: Coal is a naturally discontinuous, heterogeneous, and anisotropic brittle material. The uniaxial compressive strength of coals is significantly affected by the sample size-dominated microstructure of minerals and fractures. The scale effect of the mechanical properties of coal is a bridge connecting the mechanical parameters of laboratory-scale coal samples and engineering-scale coal. The scale effect of coal strength is of great significance in explaining the fracturing law of the coal seam and reveal the mechanism of coal and gas outburst disaster. The uniaxial compressive strength of outburst-prone coal samples with different scale sizes was tested, the variation law of uniaxial compressive strength with increasing scale was analyzed, and the mathematical models of both were constructed. The results show that the average compressive strength and elastic modulus of outburst coal decrease exponentially with the increase in scale size, and the decrease rate is reduced. The average compressive strength of the tested coal samples decreased from 10.4 MPa for size 60 × 30 × 30 mm^3 to 1.9 MPa for scale 200 × 100 × 100 mm^3, which decreases by 81.4%.

1. INTRODUCTION

A coal and gas outburst is a kind of dynamic disaster occurring underground in coal mines, and the process of outburst is accompanied by a large amount of coal rock being broken and gas ejected, causing equipment damage and casualties.[1,2] Soft outburst coal is easy to cause coal and gas outbursts, so mastering the strength of outburst coal is the basis for revealing the causes of outbursts and preventing them.[3] However, as a brittle and semibrittle material, the strength of coal rock depends on the variation of the sample scale, namely, the scale effect.[4] Although large-scale field tests can accurately estimate the strength and deformation characteristics of coal rock around underground projects such as coal mining and tunneling, these tests are not always practical or economical considering the difficulty of conducting such tests or the time and economic costs that result.[5] A particularly promising alternative is to amplify the strength and elastic properties of laboratory-tested intact coal to match coal rock in practical engineering. At this point, a suitable scale effect model for outburst coal is critical.[6]

In general, the scale effect refers to the effect of sample size (i.e., diameter or width) on the mechanical properties, which is different from the shape effect (i.e., aspect ratio).[7] The scale effect depends on the deformation process and therefore it varies with loading conditions and testing methods. Many researchers have investigated the scale effect of concrete and rock under different stress states, including uniaxial compression, point loading, and triaxial compression experiments.[8,9] Under different stress conditions, a large number of scholars have been carried out on the scale effect of coal rock, including uniaxial compression, indirect tensile, point load, and triaxial compression tests. Four classical models of the scale effect were established based on statistics, fracture energy, and multifractal and mixed fractal theory with fracture energy.

Bieniawski et al.[10] tested the uniaxial compressive strength of cubic coal from 0.75 inches to 6.6 feet in the field and preliminarily established the relationship between coal strength and scale dimension. Gonzatti et al.[11] conducted laboratory tests to define the behavior of the uniaxial compressive strength of the Irapua coal seam and established a first approximation for the in situ strength of this coal seam. Wang

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(a) Microcomputer-controlled electro-hydraulic servo testing apparatus (b) Prepared coal samples

Figure 1. Apparatus and samples for scale effect tests of outburst-prone coal.

et al.[12] obtained the force−displacement curve for each small particle by the uniaxial compression of 1200 coal particles of sizes in the range of 0.2−7 mm. Medhurst et al.[13] tested the triaxial compressive strength of cubic coal with scales of 61, 101, 146, and 300 mm, obtained the intrinsic variable of the coal scale, and used this relationship to design the reasonable scale of coal pillar. Van der Merwe.[14] tested the scale effect of coal strength from different mining areas in the laboratory and found that the strength of coal specimens increases linearly with the diameter−height ratio and decreases exponentially with the specimen scale. Scholtès et al.[15] studied scale effects on the strength of coal using a discrete element model. Following that, Poulsen et al.[16] investigated the scale effect of coal strength by numerical simulations and pointed out that the uniaxial tensile strength of actual coal is much smaller than that of experimental specimens. Chen et al.[17] calculated the uniaxial compressive strength of coal with different scale sizes based on the Weibull distribution law. Song et al.[18] experimentally studied the scale effect of uniaxial compression of coal containing gas considering the adsorption of gas. Peng et al.[19] investigated the sensitivity of coal sample permeability to surrounding pressure and analyzed the influence of the scale effect on it. Song et al.[20−22] combined acoustic emission signal and primary wave velocity to analyze the variation law of compressive strength of coal samples with different scale sizes and bedding directions under uniaxial pressure and fitted the functional relationship between the scale, bedding angle, and uniaxial compressive strength. Wen et al.[23] considered the size effect of coal rock to investigate the influence of different height-to-diameter ratios on the acoustic emission characteristics of coal rock damage evolution.

The above studies are rarely focused on soft outburst-prone coal. In this paper, the uniaxial compressive strength of outburst-prone coal samples with different scale sizes will be tested, and the variation of compressive strength and elastic modulus with scale sizes will be analyzed to construct the uniaxial compressive properties of outburst coal. The mathematical model of scale sizes is expected to have a deeper understanding of the strength characteristics of outburst coal.

2. EXPERIMENTAL EQUIPMENT AND COAL SAMPLES

The uniaxial compression test of outburst-prone coals was carried out on the microcomputer-controlled electrohydraulic servo testing machine with a load capacity of 100 kN and an accuracy of ±0.5% in the mining engineering laboratory of Liaoning Technology University. The supporting equipment also includes the DH5929 dynamic signal test and analysis system, supporting load and displacement sensors, etc. The test was carried out at room temperature with displacement-controlled loading at a rate of 1mm/min. The testing apparatus is shown in Figure 1a.

The coal samples used were from Xintian Coal Mine in Guizhou Province. Large coal blocks were collected on-site, sealed with plastic wrap, transported to the laboratory, and cut into standard samples with a width-to-height ratio of 0.5 for uniaxial compressive strength testing. To ensure the accuracy of the experimental results, after the coal sample met the scale requirements, both ends of the cuboid coal sample were cut and ground to ensure flatness ±0.05mm and parallelism ±0.02 mm. The coal samples were cut into different scale sizes according to the size and quantity of the collected lump coal. Six groups of coal samples were used for testing. The sizes of the samples were 200 × 100 × 100, 160 × 80 × 80, 120 × 60 × 60, 100 × 50 × 50, 80 × 40 × 40, and 60 × 30 × 30 mm^3, respectively. To ensure the accuracy and rationality of the experimental results, three coal samples were tested in each group, and the results were averaged. It should be noted that one of the coal samples with a size of 200 × 100 × 100 mm^3 was partially broken during cutting and cut into the 160 × 80 × 80 mm^3 sample. The processed coal samples are shown in Figure 1b and Table 1.

Table 1. Statistics of Coal Samples

size of the sample (mm)	amount	identifier
200 × 100 × 100	2	M1, M2
160 × 80 × 80	4	M3, M4, M5, M6
120 × 60 × 60	3	M7, M8, M9
100 × 50 × 50	3	M10, M11, M12
80 × 40 × 40	3	M13, M14, M15
60 × 30 × 30	3	M16, M17, M18

3. EXPERIMENTAL RESULTS

The strength scale effect test of the outburst coal samples was carried out according to the experimental scheme. The coal samples after loading damage are shown in Figure 2. It can be seen that the fracture development of coal samples is roughly parallel to the loading direction regardless of the scale sizes, and the coal samples are damaged extremely unevenly, with serious local damages, mostly with vertical fractures, and obvious damages at the angles, indicating that the stress concentration is obvious. The large-scale coal samples rupture into a large number of irregular small prisms, and the surface of

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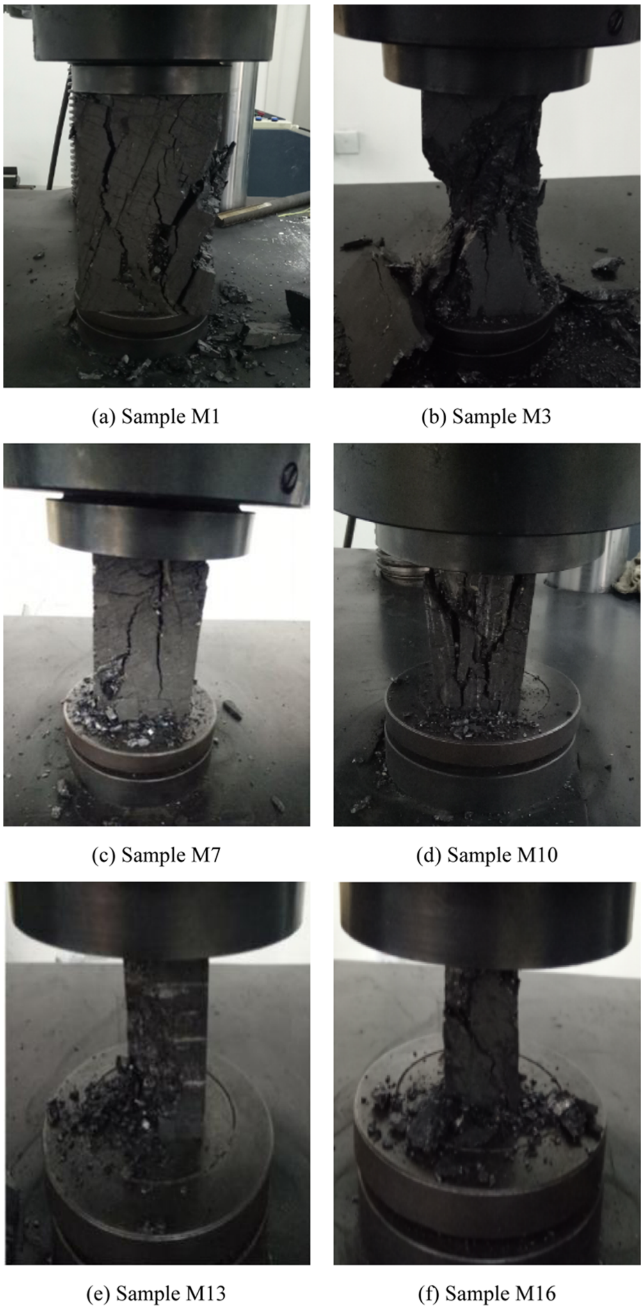
(a) Sample M1 (b) Sample M3 (c) Sample M7 (d) Sample M10 (e) Sample M13 (f) Sample M16

Figure 2. Photo of ruptured coal samples with different scale sizes.

the sample is obviously affected by tensile stress; the fractures are more developed, and many collapses occur.

After the coal sample is destroyed, it still has a certain residual strength, and if the loading continues, the irregular small pillars are crushed into powder, indicating that the residual strength of large-scale coal samples is maintained by the dissipation of surface energy. Under the action of an electrohydraulic servo universal testing machine, the fracture process of coal samples is generally an unsteady process, that is, from a steady state to instability. There is a complete bearing structure in the coal samples. The bearing structure begins to weaken when the strain reaches a certain value. At this time, the fracture is carried by friction and has reached the bearing limit of coal samples, that is, the peak stress. The internal fractures of large-scale coal samples are more developed due to the relative slip of the fracture surfaces so that the strain of the same stress increases. The damage development of large-scale coal samples is controlled by the internal pores, fractures, and other structures of coal samples. Under the same pressure, the stress distribution and stress concentration degree generated inside the coal samples is also different. Not only can new fractures be generated in the coal samples, but also the original fractures may also expand, and finally, they are always destroyed at a weaker position and release elastic energy.

In Figure 3, the smaller the scale of the coal samples, the faster the curve decreases after reaching the peak stress, and the higher the peak stress (compressive strength), indicating that the smaller the scale of the coal samples, the fewer fractures it contains internally, the greater the brittleness of the coal samples, and the greater the strength. The strain values corresponding to the peak stress of most stress−strain curves are between 0.01 and 0.015, but there is no obvious direct connection with the scale change.

The results of compressive strength and elastic modulus obtained from the experiment are summarized in Table 2. It can be found that with the increase of the coal sample scale, the compressive strength and elastic modulus are discrete, but the average compressive strength and elastic modulus both decreased gradually. For example, the average compressive strength of coal samples decreased from 10.39 MPa for size 60 × 30 × 30 mm^3 to 1.93 MPa for size 200 × 100 × 100 mm^3, which decreased by 81.4%. However, the elastic modulus decreased from 1.387 to 0.287 GPa.

The variation of uniaxial compressive strength and average compressive strength of coal samples with the width of coal samples is shown in Figure 4. The compressive strength of outburst coal is low, and when the width of coal samples is 30−100 mm, the compressive strength is in the range of 1.74−12.03 MPa. There is variability in the internal structure and fracture development of coal samples, and the compressive strengths of coal samples of the same scale are discrete points in the figure.

But overall, the larger the scale of the coal samples, the smaller the compressive strength. The average compressive strength of coal samples decreases exponentially with increasing the scale of the coal samples, and the rate of decrease slows down with increasing the scale of the coal samples, which can be expressed as follows[20]

$$\sigma_c = \sigma_M + (\sigma_0 - \sigma_M)e^{-k_1 w} \tag{1}$$

where σ_c is the uniaxial compressive strength of the coal samples stress section length w (width of the coal samples), MPa; σ_0 is the compressive strength of raw coal, that is, the uniaxial compressive strength of the coal samples when $w \to \infty$, MPa; σ_M is the compressive strength of coal, namely, the uniaxial compressive strength of coal when $w \to \infty$, MPa; and k_1 is a parameter related to the mechanical properties of the coal samples. When $w \to 0$, this is a limit case (actually meaningless).[24] At very small coal sample sizes, which can be considered as not containing any natural defects, the compressive strength of the sample is almost equal to the raw coal (coal skeleton) strength. σ_0, σ_M, and k_1 can be obtained by fitting the experimental data from uniaxial compression tests of coal samples of different scale sizes.

The first constant on the right side of eq 1 represents the uniaxial compressive strength of coal when $w \to \infty$, and the second term represents the increase in the strength of coal samples as the scale of coal samples decreases from ∞ to 0.

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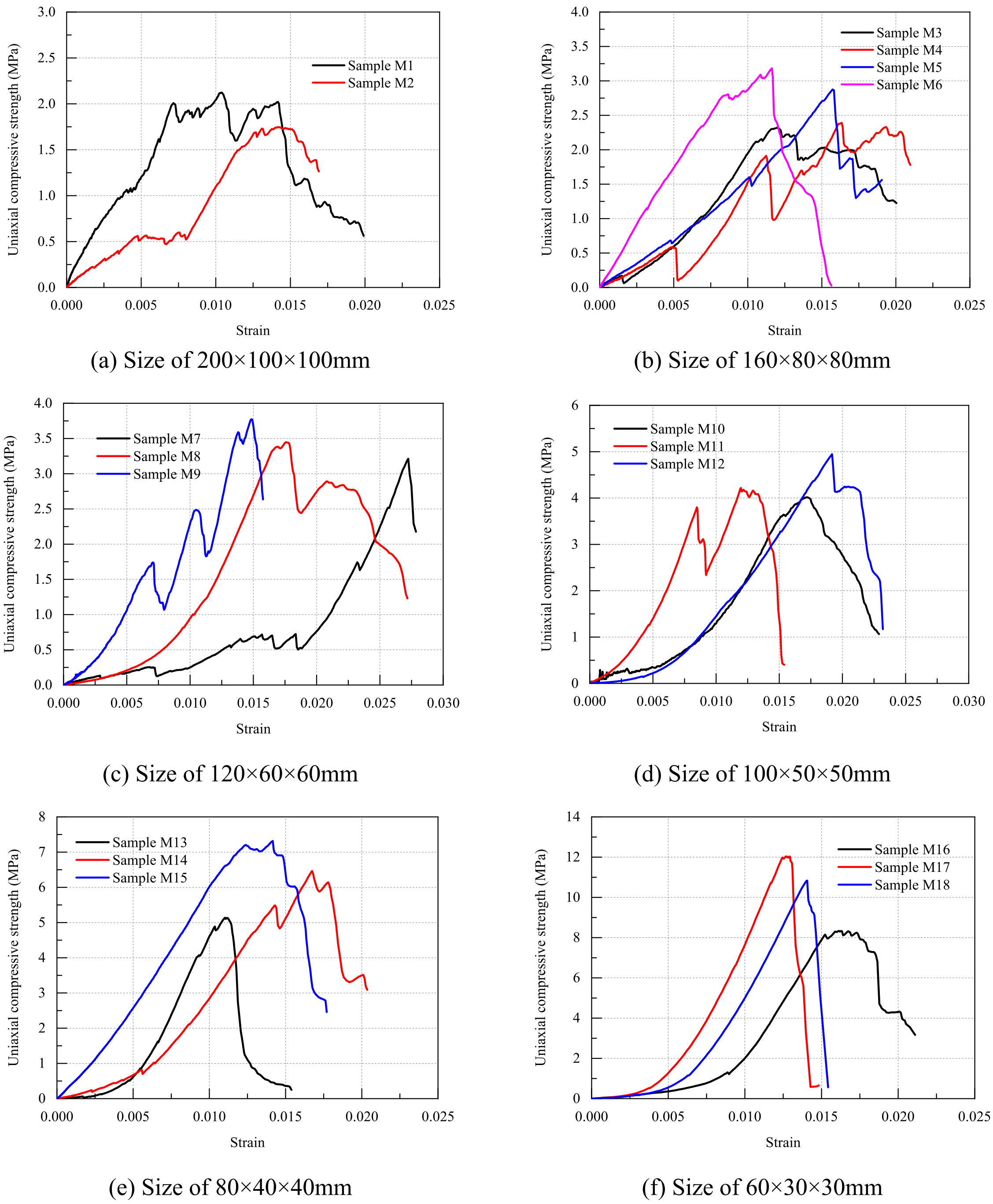

(a) Size of 200×100×100mm (b) Size of 160×80×80mm

(c) Size of 120×60×60mm (d) Size of 100×50×50mm

(e) Size of 80×40×40mm (f) Size of 60×30×30mm

Figure 3. Stress−strain curves of coal samples with different scale sizes.

The strength scale effect relationship equation of the coal samples is obtained by fitting the above equation

$$\sigma_c = 2.11 + 55.59e^{-0.0367w} \tag{2}$$

At this time, the compressive strength of raw coal σ_0 = 53.48 MPa, the compressive strength of coal σ_M = 2.11 MPa, the attenuation coefficient k_1 = 0.0367, and the fitting degree R^2 = 0.9936, indicating that this exponential form is suitable for fitting the relationship between the strength and scale. According to literature research,[24] with the enhancement of the integrity of rock, the attenuation coefficient k_1 decreases gradually.

4. DISCUSSIONS

The determination of mechanical properties such as the strength of coal at the field scale is critical to the design of the roadway support, top coal recoverability, and coal pillar as well as the occurrence mechanism of dynamic disasters such as rock bursts and coal and gas outbursts. The typical method for estimating rock strength and stiffness is to prepare rock samples, followed by laboratory tests and field tests. However, for coal, it is difficult to obtain complete samples of the required size for testing. The method of drilling cores to obtain samples is usually used during exploration but is rarely used during coal production. In addition, due to changes in temperature and humidity, after the coal samples are taken

Table 2. Mechanics Properties of Coal Samples with Different Sizes

identifier	size of sample (mm)	compressive strength (MPa)	average compressive strength (MPa)	elastic modulus (GPa)	average elastic modulus (GPa)
M1	200 × 100 × 100	2.12	1.93	0.319	0.287
M2		1.74		0.256	
M3	160 × 80 × 80	2.32	2.69	0.365	0.313
M4		2.39		0.305	
M5		2.87		0.257	
M6		3.18		0.323	
M7	120 × 60 × 60	3.21	3.47	0.416	0.473
M8		3.44		0.406	
M9		3.77		0.596	
M10	100 × 50 × 50	4.02	4.39	0.444	0.501
M11		4.21		0.677	
M12		4.94		0.381	
M13	80 × 40 × 40	5.13	6.3	0.936	0.737
M14		6.46		0.601	
M15		7.31		0.673	
M16	60 × 30 × 30	8.33	10.39	1.109	1.387
M17		12.03		1.645	
M18		10.83		1.407	

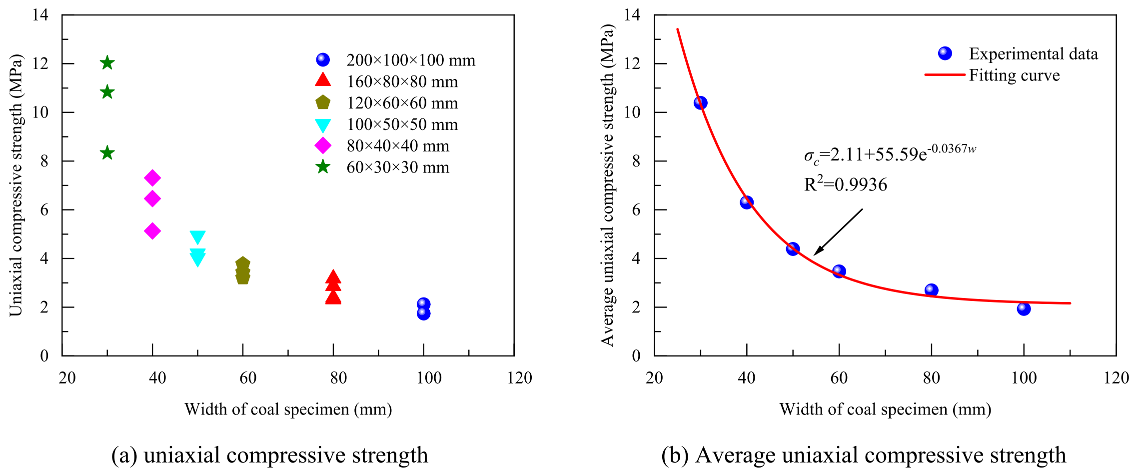

Figure 4. Scale effect on the uniaxial compressive strength of coal samples.

out of the mine, if no corresponding measures are taken, it will usually be quickly dehydrated and weathered, and the mechanical properties change greatly. Laboratory and field tests on coal mechanical strength show that the strength and stiffness decrease significantly with the increasing size of the coal samples, and the scale effect is obvious. The rate of strength reduction is more significant above a certain scale, but the strength changes more slowly for coal above that scale size, which is called the representative element volume (REV). The field test shows that the size of coal representative element volume is about 1.5−3 m.[25]

There are many fractures and other defects inside the coal samples, and if the size of coal is large enough, the internal fractures and other defects can be considered to be uniformly distributed. At this time, a small amount of fracture development will cause structural instability and failure, manifested as a brittle failure. Generally, under the requirement of engineering precision, the strength is considered to be constant, that is, the strength of coal remains unchanged after reaching the scale of the representative element volume. When the coal particles are small enough to contain no fractures in the coal matrix block with only uniformly distributed pores, the strength of the coal is considered to remain unchanged, that is, the strength of raw coal (coal skeleton) and the size at this time is the lower limit of the scale effect of coal. Therefore, scholars are concerned about the scale effect law of stage B in which the coal size is between the lower limit of the scale effect and the representative element volume (REV), and the heterogeneity caused by fracture development in this stage cannot be ignored. During the failure process of the B stage, a large number of fractures developed, expanded, and penetrated; stress was redistributed and it finally evolved into structural instability, showing quasi-brittle failure. In this stage, the scale effect of coal samples strength shows the exponential change law of eq 2, as shown in Figure 5. Through laboratory tests and field experiments, the physical change law of each coefficient of the exponential function is sought, their values are determined, and then the mechanical properties bridge between experimental scale coal samples and engineering-scale coal is built.

The scale effect is mainly due to various discontinuous fractures, beddings, and cleats observed in coal. The discontinuities result in coal with variability and anisotropy in strength and stiffness. In coal samples, the fracture length of randomly distributed splitting is usually longer than other splittings, although they have a lower fracture density. Using

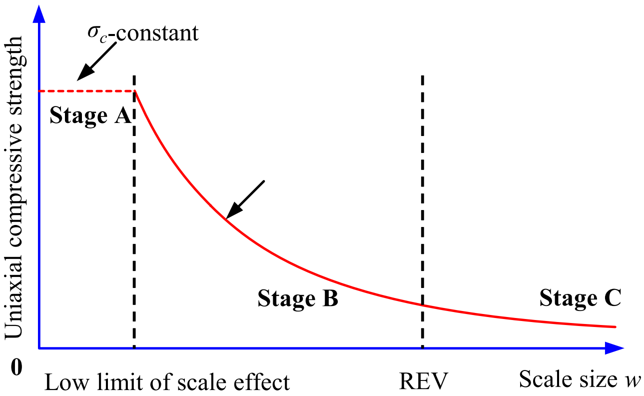

Figure 5. Relation between scale size and coal strength.

high-resolution X-ray micro-CT imaging technology,[20] a μCT scan three-dimensional reconstructed image of the variation of microscopic pore/fracture structure in coal samples with an increasing scale was obtained, as shown in Figure 6. It can be seen that with the increasing sample scale, the volume of mineral impurities increases, and the pre-existing fractures increase. As the diameter of the coal samples increased from 25 to 50 mm, the average volumes of initial fractures and mineral impurities increased from 14.52 and 219.31 mm^3 to 185.48 and 476.92 mm^3, respectively. At the same time, the average volume and volume change of mineral impurities within the coal samples of different sizes are greater than those of pre-existing fractures.

The important factors affecting the scale effect of coal mainly include the following aspects: coal properties, stress state, and structural plane.

Coal properties: Different properties of coal components, coal matrix particle size, quantity differences, and uneven distribution will enhance the heterogeneity of coal and increase the scale effect. In terms of the stress state, stress concentration and uneven stress distribution will cause obvious scale effects on coal samples. For example, the scale effect of coal samples under bending failure experimental conditions is more significant than that under compression failure experimental conditions, while the scale effect of the uniaxial compression experiment is more significant than that of triaxial compression.

Structural planes: Coal belongs to a geological body of structural planes containing a large number of structural planes. Large structural planes can be geological faults, and small structural planes can be fissures and fine fractures, pores, etc. Generally, the strength of coal is controlled by the structural weak plane, the large structural plane determines the strength of coal, and the small structural plane determines the strength of lump coal. The degree of concave and convex undulation or roughness of the structural surface inevitably affects the strength of the structural surface. Moreover, the structural plane can appear individually or in several strips or in large numbers in groups, some with obvious direction and some with random distribution in a haphazard manner. The fractures appearing in groups are called joints. The scale effect is significant when the density, length, shape, opening, surface roughness, and filling of joint fissures change greatly with the scale. In terms of stress gradient, it is usually assumed that the stress is uniformly loaded during the experimental test, while the actual stress may be highly inhomogeneous. The presence of defects in the coal samples will cause the stress gradient effect, and the test results will also affect the scale effect.

Stress state: The stress state of the coal sample will change its mechanical strength undoubtedly. Generally, the strength of coal samples under triaxial stress is higher than that under uniaxial stress. The higher the confining pressure, the greater the compressive strength of the coal sample. However, the scale effect of coal samples under triaxial conditions has not been revealed, which may be one of the directions in future research.

5. CONCLUSIONS

(1) The internal fractures in coal samples with large scale sizes are more developed than that with a small size. The

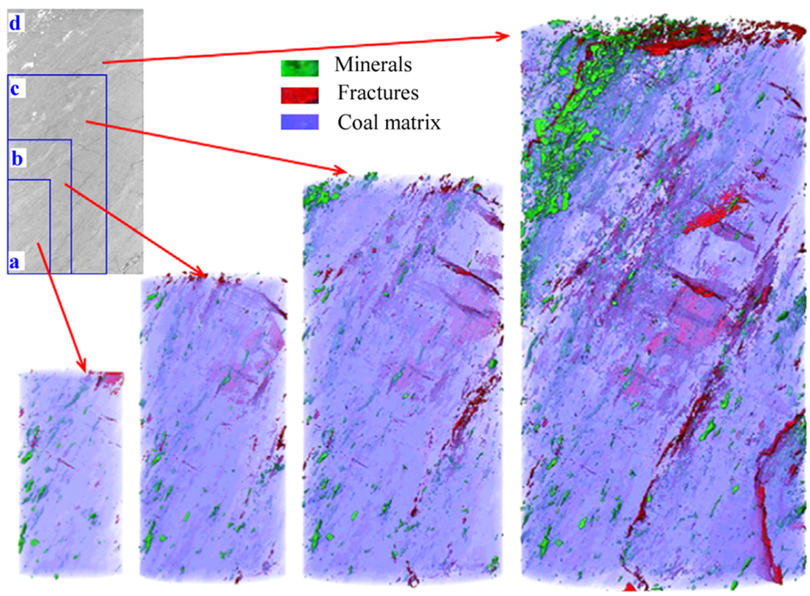

Figure 6. Variation of microstructures with increasing sample size: (a) diameter of 25 mm; (b) diameter of 38 mm; (c) diameter of 50 mm; and (d) diameter of 75 mm.

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smaller the scale of the coal sample, the faster the stress decreases after reaching the peak and the higher the compressive strength. This indicates that the coal samples with smaller sizes contain fewer internal fractures, which may result in greater brittleness of coals and enhanced mechanical strength.

(2) The average compressive strength and elastic modulus of outburst coal decrease exponentially with the increase of the scale. The average compressive strength of coal samples in this study decreased from 10.4MPa for size 60 × 30 × 30 mm^3 to 1.9 MPa for scale 200 × 100 × 100 mm^3, which decreased by 81.4%.

(3) The strength decreases significantly with the increasing size of the coal samples, and the scale effect is obvious. However, when the size of the coal samples reaches or exceeds the size of the representative element volume, the strength reduction rate of coal becomes slower or almost unchanged.

(4) The scale effect is mainly caused by various discontinuous fractures, bedding, and cleats observed in coal. The coal property, stress state, structural plane, and stress gradient have a great influence on the scale effect of coal strength.

The mathematical model of the scale effect in this work offers a useful medium to investigate the mechanism of coal and gas outbursts as well as the roadway support in the coal seam. Limited by the amount and type of coal samples, the mathematical model of the scale effect obtained can only represent the results of the tested coal samples. In the future, the scale effect on coal strength under the triaxial stress state will be studied.

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Notes

The authors declare no competing financial interest.

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