Research Article

Study on the Mechanical Properties of Coal Weakened by Acidic and Alkaline Solutions

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Received 13 June 2020; Revised 31 July 2020; Accepted 22 September 2020; Published 10 October 2020

Academic Editor: Elhem Ghorbel

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A novel method for fracturing coal is presented in this paper. A chemical solution is injected into coal under high pressure, whereby the coal is fractured and subsequently weakened by chemical erosion over time to produce an anti-impact soft structure. In this study, the mechanical properties of coal under chemical erosion were investigated, and the fracturing design parameters were optimized. The uniaxial compression test and the split Hopkinson pressure bar (SHPB) test were used to determine the dynamic and static mechanical properties of coal after 20 days of immersion in different chemical solutions. After chemical solution erosion, the dynamic and static compressive strengths and elastic modulus of the coal decreased according to an exponential power law in the damage variable. The chemical treatment increased the duration of the pore compaction stage and decreased that of the elastic deformation stage, while decreasing the brittleness and increasing the ductility of coal. The acoustic emission (AE) curve of the immersed coal samples consisted of four stages corresponding to those of the stress-strain curve: pore compaction-closure, a slowly rising linear elastic regime, steady-state prepeak crack propagation, and unsteady crack propagation at the peak strain. The increase in the damage variable of the coal sample from chemical erosion led to a lower dissipated energy, a higher fractal dimension, and a more fragmented coal sample. The effect of the investigated chemical solutions on weakening the coal mechanical properties decreased in the following order: alkaline solution > acidic solution > NaCl solution > distilled water. The experimental results provide a reference for weakening fractured coal seams.

1. Introduction

The severity of a rockburst disaster increases with the mining depth of a coal seam [1]. Current rockburst prevention and control measures mainly involve changing the stress distribution in coal rock to transfer high stresses in the coal and installing anti-impact components on the support to passively absorb rockburst energy [2, 3]. The primary level of protection is weakening the downhole impact source. However, the high horizon of the downhole impact source and the difficulty of accurately determining the impact source point make it generally difficult to achieve this level of protection [4]. A secondary level of protection is to construct a soft structural layer in the rock surrounding the roadway in

the propagation path of the impact wave [5]. A final level of protection involves the installation of anti-impact energy-absorbing components on the support in the propagation path [6–9]. Failure at this level of protection can be catastrophic for the downhole production system. Therefore, it is most effective and straightforward to construct an anti-impact soft structural layer in the rock surrounding the roadway.

At present, anti-impact soft structures are mainly built using methods such as high-pressure fracturing [10, 11] and drilling-blasting [12–14]. These methods break the coal structure using only mechanical forces, such as high water pressure and blasting shock waves produced by explosives. The construction of a soft structure in the rock surrounding the roadway envelope occurs immediately after fracturing or blasting and is consequently

often inadequate. Therefore, an alternative construction method is urgently required. The use of a novel acidic or alkaline fracturing fluid can erode coal after high-pressure mechanical fracturing, creating a secondary weakening effect.

The use of chemical solutions in rock erosion has been extensively studied over the past decade. Li et al. [15, 16] investigated the porosity change, microscopic damage, and macroscopic mechanical properties of limestone samples under the action of chemical solutions and established a coupled stress-permeability mechanical model of limestone subjected to chemical erosion. Xu et al. [17] conducted chemical erosion and freeze-thaw coupling experiments on barite, showing that chemical erosion significantly affected the propagation of microcracks. Wang et al. [18] examined the influences of environmental factors, such as the stress difference, temperature, and chemical solution pH, on the creep characteristics of deep shale. Callahan et al. [19] investigated the effect of the chemical environment on the fracture toughness and subcritical fracture growth index of silicified fault rocks and found that chemical conditions can promote fissure propagation. Schimmel et al. [20] mitigated the compaction effect in a reservoir by injecting a supercritical fluid or acidic solution into a gas well. Peng et al. [21] studied the effect of chemical erosion on the mode-I fracture factors of sandstone. Ao et al. [22] investigated the effect of supercritical CO₂ on the physical structure (porosity, deformation, and mechanical properties) and chemical structure (mineral composition) of shale. Cai et al. [23] studied the effect of water saturation on the mechanical behaviour of different types of rocks and explained the mechanism underlying the differences between rock sensitivities to water. The studies above have mainly focused on rocks, whereas the soft structure for a roadway is typically constructed in a coal seam. Relatively few studies have been conducted on using chemical erosion to weaken the mechanical properties of a coal seam, and even fewer studies have been conducted on dynamic coal mechanical properties under erosion. Therefore, the study of the mechanical properties of a coal seam after erosion by chemical solutions has considerable reference value for designing novel coal fracturing parameters and fracturing fluid compositions.

In the present study, static compression and dynamic impact mechanical tests were carried out on coal samples immersed in an alkaline solution, an acidic solution, a NaCl solution, and distilled water. The static and dynamic mechanical properties and the acoustic emission (AE) patterns of coal samples subjected to chemical solutions of different pH values were investigated. The energy dissipation patterns, fractal geometry, and fragmentation characteristics of the coal samples under dynamic impact loading were analysed. The results provide good support for the construction of anti-impact soft structures.

2. Materials and Methods

2.1. Material Preparation. The test coal samples were obtained from the Xiaozhuang coal mine in the Binchang mining area. To eliminate interference factors and ensure the reliability of the test results, all the samples were obtained

from intact coal seam blocks with high integrity and uniformity. Cylindrical samples of $\Phi 50 \times 100$ mm were selected following the International Society of Rock Mechanics standard. The sample ends were polished to ensure that the surface roughness of the ends did not exceed 0.2 mm and that the nonparallelism did not exceed $\pm 0.1\%$. Each sample had a 2:1 length:diameter ratio. The samples were divided into two sets, one for the static mechanical test and the other for the dynamic mechanical test.

The water used in coal seam fracturing comes from downhole. This water is not pure and has a highly complex chemical composition, including ions such as Na⁺, K⁺, Ca²⁺, H⁺, Cl⁻, SO₄²⁻, and HCO₃⁻, making it very difficult to fully simulate groundwater solutions. In this study, a 0.1 mol/L NaCl solution at pH 7 was prepared to simulate groundwater. The mechanical properties of coal samples were tested under the action of different acidic and alkaline chemical solutions. An acidic solution at pH 3 was prepared by adding an HCl solution to the NaCl solution, and an alkaline solution at pH 11 was prepared by adding an NaOH solution to the NaCl solution. The samples were divided into five groups (A, B, C, D, and E), which consisted of samples immersed in the acidic solution, the NaCl solution, the alkaline solution, and distilled water and the original dry rock samples, respectively.

2.2. Test Procedure. The following test procedure was used in the experiment. (1) Preparation of coal samples: The mass and fissure distribution standard cylindrical samples were compared, and the samples were divided into five groups (A, B, C, D, and E), with six samples per group. (2) Preparation of chemical solutions: An acidic solution at pH 3, a NaCl solution and distilled water at pH 7, and an alkaline solution at pH 11 were prepared. The samples in groups A, B, C, and D were immersed for 20 days in the acidic solution, the NaCl solution, the alkaline solution, and distilled water, respectively, and then dried. (3) Mechanical properties and AE tests: A static compression test was performed on the samples labelled 1, 2, and 3 in each group, and the split Hopkinson pressure bar (SHPB) test was carried out on the samples labelled 4, 5, and 6 in each group.

2.3. Static and Dynamic Load Tests

2.3.1. Static Mechanical Test. The static compression test was carried out on an MTS-C64.106 electrohydraulic servo control test machine, using a displacement control mode with a displacement loading rate of 0.01 mm/s. The test system is shown in Figure 1.

The AE monitoring was performed using a PCI-2 AE system with a threshold value of 35 dB, a peak definition time of 50 μ s, a hit lockout time of 300 μ s, and an AE sensor operating frequency range of 100 to 400 kHz. The sampling frequency was 2 MHz, and the preamplifier was set to 40 dB. Vaseline (petroleum jelly) was applied between the AE sensor and the coal sample for coupling treatment. The loading process and the AE were monitored at room temperature until the sample failed in compression.

FIGURE 1: Test system for static mechanical properties of coal samples.

2.3.2. Dynamic Mechanical Test. The dynamic load test was carried out on an SHPB test system. Figure 2 is a schematic of the system, which consisted of a specially shaped striker, an incident bar, a transmission bar, and a damper [24]. The incident bar and the transmission bar were both made of 48Cr steel with a longitudinal wave velocity of 5400 m/s, a density 7850 kg/m³, and an elastic modulus of 210 GPa. Two strain gauges were installed on the incident bar and the transmission bar to measure the strain. The data were stored in the dynamic strain gauges and then sent to the data processing system.

Assuming one-dimensional stress wave propagation, the stress-strain relation of a sample can be expressed as follows [25].

$$\begin{aligned}\varepsilon &= \frac{V_0}{L_s} [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)], \\ \varepsilon &= \frac{V_0}{L_s} \int_0^t [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] dt, \\ \sigma &= \frac{A_0}{2A_s} E_0 [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)],\end{aligned}\quad (1)$$

where V_0 , A_0 , and E_0 represent the wave velocity, the cross-sectional area, and the elastic modulus of the bars, respectively. A_s and L_s are the original area and length of the specimen, respectively. $\varepsilon_i(t)$, $\varepsilon_r(t)$, and $\varepsilon_t(t)$ are the incident strain, reflected strain, and transmission strain, respectively.

3. Mechanical Properties of Coal under Different Solution Concentrations

3.1. Static Mechanical Properties of Coal Samples. For the unimmersed raw coal sample, the prepeak stress-strain curve was smooth. Figure 3 shows that, upon reaching the peak strength, the coal exhibited brittle failure, and the AE counts were significantly concentrated in the peak failure stage. Figure 4 shows that, for the coal sample that was immersed in distilled water, the prepeak stress-strain curve

did not fluctuate significantly, and the coal sample exhibited brittle failure beyond the peak. The coal strength was slightly lower than that of the raw coal sample, indicating that distilled water softened the coal but did not improve the internal microstructure. Figure 5 shows that, for the coal sample that was immersed in NaCl solution, the prepeak stress-strain curve fluctuated, but the coal sample still exhibited brittle failure beyond the peak. This result indicated that the NaCl solution underwent ion exchange with the chemical constituents of the coal, resulting in some interior coal damage [26]. Figures 6 and 7 show that, for the coal samples that were immersed in the acidic and alkaline solutions, respectively, multiple stress reductions occurred in the prepeak stress-strain curve, and AE peaks appeared at the stress reduction positions. These findings indicated that chemical damage occurred in the form of microjoint fissures, and the interior pores expanded after coal erosion by the acidic or alkaline chemical solutions. Under stress, microjoint fissures were initiated and propagated, corresponding to multiple fluctuations in the stress-strain curve. Moreover, the coal sample immersed in the alkaline solution showed a prepeak stress that fluctuated with an amplitude reaching 3.6 MPa, indicating that the solution caused large damage to the sample interior and significantly transformed the microstructure.

A statistical comparison was performed for the coal mechanical parameters before and after the samples were immersed in the chemical solutions. All the results below are referenced to the raw coal samples. For the samples immersed in the acidic solution, the uniaxial compressive strength decreased by 29.6%, the elastic modulus decreased by 42.8%, and the peak strain increased by 34.6%. For the samples immersed in the alkaline solution, the uniaxial compressive strength decreased by 37.3%, the elastic modulus decreased by 60.9%, and the peak strain increased by 41.7%. For the samples immersed in distilled water, the uniaxial compressive strength decreased by 9.7%, the elastic modulus decreased by 9.4%, and the peak strain increased by 13.5%. For the samples immersed in the NaCl solution, the uniaxial compressive strength

FIGURE 2: SHPB experimental device.

FIGURE 3: Stress-strain curve and acoustic emission monitoring curve of unimmersed raw coal sample.

decreased by 19.3%, the elastic modulus decreased by 31.9%, and the peak strain increased by 23.1%. Therefore, the effect of the chemical solutions on weakening the static mechanical properties of coal decreased in the following order: alkaline solution > acidic solution > NaCl solution > distilled water. After erosion by the different chemical solutions, the duration of the pore compaction stage of coal samples increased, whereas that of the elastic stage decreased, and significant increases in the corresponding peak strain of the samples and the ductility of the postpeak stress-strain curve were observed.

Four stages were identified in the cumulative AE curve of the samples after immersion in the chemical solutions, as shown in Figure 8. Stage I corresponded to pore compaction-closure (OA) with weak AE activity. During stage II, linear elastic deformation (AB) occurred, with no significant crack propagation and almost no AE activity. Stage III was characterized by the stable development of fissures (BC), rupture initiation, and intensified AE activity. During stage IV (CD), the crack that formed in section BC propagated, the critical stress state was reached, unsteady crack propagation occurred, the AE activity increased rapidly, and the sample finally ruptured. The variation pattern of the AE activities of

the coal samples basically corresponded to the stress-strain curve and could be approximately divided into the following stages: pore compaction-closure, a slowly rising linear elastic regime, precrack steady-state crack propagation, and unsteady crack propagation at the peak strain.

After the coal samples were chemically eroded, internal microcrack pores appeared and propagated. As the chemical solutions dissolved a portion of the coal, the sample mass was reduced. A mass damage variable S was defined to reflect the degree of damage to the sample from chemical erosion as follows:

$$S = \left(1 - \frac{M_t}{M_0} \right) \times 100\%, \quad (2)$$

where M_0 and M_t are the masses of the dried sample before and after immersion in the chemical solution, respectively.

The masses of the coal samples before and after immersion in chemical solutions were statistically analysed, as shown in Table 1. The chemical damage to samples immersed in the acidic solution, the alkaline solution, distilled water, and the NaCl solution was 2.5%, 3.15%, 1.11%, and 1.78%, respectively. Thus, the degree of damage to the coal samples from the chemical solutions decreased in the

FIGURE 4: Stress-strain curve and acoustic emission monitoring curve of coal sample after immersion in distilled water.

FIGURE 5: Stress-strain curve and acoustic emission monitoring curve of coal sample after immersion in NaCl solution.

FIGURE 6: Stress-strain curve and acoustic emission monitoring curve of coal sample after immersion in acidic solution.

FIGURE 7: Stress-strain curve and acoustic emission monitoring curve of coal sample after immersion in alkaline solution.

FIGURE 8: Cumulative curve of acoustic emission during coal sample failure.

following order: alkaline solution > acidic solution > NaCl solution > distilled water.

Figure 9 shows fitted correlations in the form of exponential power laws that describe the decrease in the static compressive strength and elastic modulus as a function of the damage variable for the samples under the action of different solutions.

3.2. Dynamic Mechanical Properties of Coal Samples

3.2.1. Analysis of Dynamic Mechanical Parameters.

Figure 10 shows the dynamic stress-strain curves of samples immersed in different chemical solutions under high-speed impact loading. There was no clear pore compaction stage and only an elastic stage, a plastic yielding stage, and a postpeak stage were observed. The peak strengths and elastic

moduli differed significantly among samples immersed in different chemical solutions. The following results are referenced to the raw coal sample. For the samples immersed in the acidic solution, the dynamic compressive strength decreased by 40.1%, the dynamic elastic modulus decreased by 45.5%, and the peak strain increased by 22.5%. For the samples immersed in the alkaline solution, the dynamic compressive strength decreased by 48.7%, the dynamic elastic modulus decreased by 61.7%, and the peak strain increased by 29.7%. For the samples immersed in distilled water, the dynamic compressive strength decreased by 14.2%, the dynamic elastic modulus decreased by 17.5%, and the peak strain increased by 5.7%. For the samples immersed in the NaCl solution, the dynamic compressive strength decreased by 25.9%, the dynamic elastic modulus decreased by 32.3%, and the peak strain increased by 15.6%. Thus, the effect of the chemical solutions on weakening the dynamic mechanical properties of the coal samples decreased in the following order: alkaline solution > acidic solution > NaCl solution > distilled water. The chemical solutions weakened the sample strength significantly more under dynamic loading than under static loading.

In the dynamic loading tests, the damage to the samples after immersion in the alkaline solution, the acidic solution, the NaCl solution, and distilled water was 3.09%, 2.38%, 1.60%, and 1.16%, respectively (Table 2). The decrease in the dynamic compressive strength and dynamic elastic modulus of the samples immersed in the chemical solutions as a function of the damage variable were fitted by an exponential power law (Figure 11).

3.2.2. Energy Analysis of Dynamic Impact Test.

The frictional dissipation energy between the sample and the bar during the loading process of the SHPB test was neglected. The incident energy W_i , the transmitted energy W_t , the reflected energy W_r , and the dissipated energy W_d on the pressure bar

TABLE 1: Mass parameters of coal samples under static load tests.

Specimen group	Number	Dry mass of raw coal sample (g)		Dry mass of immersed coal sample (g)		Mass change of coal sample (g)		Damage variable S (%)	
		Tested	Average	Tested	Average	Tested	Average	Tested	Average
Acidic solution	A1-3	229.6	230.57	223.8	224.80	5.8	5.77	2.53	2.50
	A2-3	231.5		225.7		5.8		2.51	
	A3-3	230.6		224.9		5.7		2.47	
NaCl solution	B1-7	231.2	230.50	226.9	226.40	4.3	4.10	1.86	1.78
	B2-7	229.8		225.5		4.3		1.87	
	B3-7	230.5		226.8		3.7		1.61	
Alkaline solution	C1-11	231.6	230.80	224.5	223.53	7.1	7.27	3.07	3.15
	C2-11	232.1		224.9		7.2		3.10	
	C3-11	228.7		221.2		7.5		3.28	
Distilled water	D1-7	233.5	231.03	230.8	228.47	2.7	2.57	1.16	1.11
	D2-7	229.5		227.1		2.4		1.05	
	D3-7	230.1		227.5		2.6		1.13

FIGURE 9: Relationship between static mechanical parameters and damage variables for samples immersed in chemical solution.

from the beginning of loading to unloading can be calculated as follows [27]:

$$\begin{aligned}
 W_i &= \frac{A_0 V_0}{E_0} \int_0^t \sigma_i^2(t) dt = A_0 E_0 V_0 \int_0^t \varepsilon_i^2(t) dt, \\
 W_r &= \frac{A_0 V_0}{E_0} \int_0^t \sigma_r^2(t) dt = A_0 E_0 V_0 \int_0^t \varepsilon_r^2(t) dt, \\
 W_t &= \frac{A_0 V_0}{E_0} \int_0^t \sigma_t^2(t) dt = A_0 E_0 V_0 \int_0^t \varepsilon_t^2(t) dt, \\
 W_d &= W_i - (W_r + W_t),
 \end{aligned} \tag{3}$$

where $\sigma_i(t)$, $\sigma_r(t)$, and $\sigma_t(t)$ are the stresses of the incident wave, the reflected wave, and the transmitted wave, respectively.

The samples immersed in different chemical solutions were impacted by an air pressure of 0.15 MPa, and the relationship between the reflected energy, the transmitted energy, and the dissipated energy of the samples was analysed, as shown in Figure 12. As the erosion damage to a sample increased, the dissipated energy decreased and the transmitted energy increased. From a microscopic point of view, large erosion damage is accompanied by extensive crisscrossed crack pores in the sample. Under the impact load, the crystalline particles inside the sample slip along the direction of these cracks, such that considerably lower energy is consumed by the relative movement of the crystalline particles inside the sample than is required for a sample to fail in the absence of erosion damage.

FIGURE 10: Dynamic stress-strain curves of specimens immersed in different chemical solutions.

That is, the energy consumed by crack propagation is significantly lower than that consumed by crack initiation. Therefore, a sample with relatively low damage has a reasonably intact structure, such that more energy is required for the sample to fissure and eventually fail along the fissure. By comparison, for a sample with relatively high damage, cracks develop in the interior, and as crack propagation is much easier than crack initiation, less energy is dissipated, and hence more energy is transferred to the transmission bar.

3.2.3. Particle Size Analysis of Fragmented Coal. Fractal geometry can be used to process fragmented and extremely irregular shapes. The mass-equivalent size is often used to calculate the fractal dimension of a rock fragmentation distribution [28]:

$$D = 3 - b, \quad (4)$$

$$b = \frac{I_g(M_R/M)}{I_g R}, \quad (5)$$

where D is the fractal dimension of the fragment, b is the slope of the straight line of $(M_R/M) - R$ plotted in a double-logarithmic coordinate system, M_R is the cumulative mass of fragments with a diameter below R , and M is the total sample mass.

The coal fragments after the impact test were collected and sieved using standard coal sample sieves of 0.5, 1, 10, 20, and 30 mm, respectively, for statistical analysis. Figure 13 and Table 3 show the fractal dimension of the fragments in the failure test which was calculated using equations (4) and (5).

Figure 14 shows that, after the sample was impacted, the larger the damage variable was, the greater the fractal dimension was, and the more fragmented the sample was. The effect of the chemical solutions on the fragmentation level of the sample decreased in the following order: alkaline solution > acidic solution > NaCl solution > distilled water.

4. Engineering Applications

The Xiaozhuang coal mine is located in the Binchang mining area, Shaanxi province, China, where coal seam #4 is currently being mined. This seam has a burial depth of 531 to 731 m, poses a low rockburst hazard, and is rich in hydrogen sulfide (H_2S). During the mining of working face 40309, multiple rockbursts occurred in the return airway, and the instantaneous H_2S concentration reached 80 to 100 ppm, severely affecting the production of the working face. To ensure safe mining of the working face, high-pressure fracturing in the return airway was performed using the aforementioned alkaline fracturing fluid to weaken the strength of the coal and hence construct an anti-impact soft structure. The alkaline fracturing fluid was also employed to absorb H_2S from the coal to improve the operational environment of the working face.

Primary fissures in the coal at the working face propagated under high-pressure fracturing. New fissures were initiated, and the chemical solution permeated and diffused into the open fissures and pores of the coal along the fractured fissures under osmotic pressure, as shown in Figures 15(a) and 15(b). After fracturing, the secondary fissures and microfissures in the coal closed. The chemical solution was enclosed in the fissures and pores eroded the coal, such that the fissures and pores connected into a fissure network, forming an effective anti-impact soft structure under the stress of the surrounding rock, as shown in Figure 15(c). Outside the influence area of mining stress, borehole peeping on this anti-impact soft structure was carried out in the field by fracturing + injection of the coal rock in the return airway, as shown in Figure 16. Figure 16(a) shows that the coal exhibited good integrity before fracturing and did not develop fissures. Borehole peeping was performed one day after the completion of high-pressure mechanical fracturing at three metres away from the fracturing hole: the resulting fractured fissures are shown in Figure 16(b). Ten days after fracturing, the borehole was redrilled, and borehole peeping revealed

TABLE 2: Mass parameters of coal samples under dynamic load tests.

Specimen group	Number	Dry mass of raw coal sample (g)		Dry mass of immersed coal sample (g)		Mass change of coal sample (g)		Damage variable S (%)	
		Tested	Average	Tested	Average	Tested	Average	Tested	Average
Acidic solution	A4-3	228.6		223.5		5.1		2.23	
	A5-3	230.5	229.50	224.8	224.03	5.7	5.47	2.47	2.38
	A6-3	229.4		223.8		5.6		2.44	
NaCl solution	B4-7	230.6		226.8		3.8		1.65	
	B5-7	229.8	230.63	225.9	226.93	3.9	3.70	1.70	1.60
	B6-7	231.5		228.1		3.4		1.47	
Alkaline solution	C4-11	230.3		223.4		6.9		3.00	
	C5-11	231.4	230.50	224.2	223.37	7.2	7.13	3.11	3.09
	C6-11	229.8		222.5		7.3		3.18	
Distilled water	D4-7	231.3		228.6		2.7		1.17	
	D5-7	229.8	230.53	226.9	227.87	2.9	2.67	1.26	1.16
	D6-7	230.5		228.1		2.4		1.04

(a)

(b)

FIGURE 11: Relationship between damage variables and dynamic mechanical parameters for samples immersed in chemical solutions.

(a)

(b)

FIGURE 12: Continued.

FIGURE 12: Ratio of reflected energy, transmitted energy, and dissipated energy of samples immersed in different chemical solutions: (a) acidic solution ($S = 2.38\%$), (b) NaCl solution ($S = 1.60\%$), (c) alkaline solution ($S = 3.09\%$), (d) distilled water ($S = 1.16\%$), and (e) raw coal ($S = 0\%$).

FIGURE 13: Fractal dimension determined by particle size and mass for samples immersed in different solutions.

TABLE 3: Calculated fractal dimension of impact fragments.

Specimen group	Number	Dry mass of immersed coal sample (g)		0.5 mm		1 mm		10 mm		20 mm		b		30 mm		Fractal dimension D	Correlation coefficient R
				cumulative mass under sieve (g)		cumulative mass under sieve (g)		cumulative mass under sieve (g)		cumulative mass under sieve (g)		cumulative mass under sieve (g)		cumulative mass under sieve (g)			
				Tested	Average	Tested	Average	Tested	Average	Tested	Average	Tested	Average	Tested	Average	Tested	Average
Acidic solution	A4-3	223.5		0.4		0.7		10.2		21.1		32.2		1.09		1.91	0.998
	A5-3	224.8	224.03	0.2	0.30	0.8	0.67	9.4	9.37	20.4	19.67	31.6	30.63	1.19	1.14	1.81	0.989
	A6-3	223.8		0.3		0.5		8.5		17.5		28.1		1.14		1.86	0.996
NaCl solution	B4-7	226.8		0.1		0.3		5.1		11.8		19.3		1.27		1.73	0.998
	B5-7	225.9	226.93	0.1	0.10	0.2	0.23	4.3	4.70	11.2	11.27	20.1	19.37	1.31	1.29	1.69	0.975
	B6-7	228.1		0.1		0.2		4.7		10.8		18.7		1.30		1.7	0.998
Alkaline solution	C4-11	223.4		1.1		2.3		17.2		31.0		42.6		0.88		2.12	0.998
	C5-11	224.2	223.37	1.7	1.33	2.4	2.23	17.1	17.13	29.8	30.73	41.0	42.27	0.81	0.86	2.19	0.996
	C6-11	222.5		1.2		2.0		17.1		31.4		43.2		0.88		2.12	0.997
Distilled water	D4-7	228.6		0.1		0.2		3.9		9.7		16.7		1.29		1.71	0.998
	D5-7	226.9	227.87	0.1	0.10	0.2	0.17	3.8	3.77	10.1	10.00	17.8	17.77	1.31	1.36	1.69	0.998
	D6-7	228.1		0.1		0.1		3.6		10.2		18.8		1.47		1.53	0.975
Raw sample	E4-0	229.3		0.1		0.1		2.5		7.6		14.7		1.41		1.59	0.973
	E5-0	230.2	230.00	0.1	0.10	0.1	0.10	2.0	2.33	6.1	7.20	11.8	14.07	1.35	1.39	1.65	0.970
	E6-0	230.5		0.1		0.1		2.5		7.9		15.7		1.40		1.60	0.972

FIGURE 14: Relationship between damage variables and fractal dimension for samples immersed in different solutions.

FIGURE 15: Model of rock structure surrounding roadway, (a) rock structure surrounding excavated roadway, (b) rock structure surrounding fractured roadway, and (c) rock structure surrounding roadway formed after fracturing and chemical erosion.

FIGURE 16: Borehole peeping before and after fracturing: (a) before fracturing, (b) after fracturing, and (c) fracturing + chemical corrosion.

fragmented coal and crisscrossed fissures within six to twelve metres of the borehole, as shown in Figure 16(c). These findings indicate that the coal was eroded by the residual chemical solution, causing the primary and fractured fissures to connect into an effective anti-impact soft structure in the coal. In addition, no significant rockburst event occurred in the fracturing test section during the mining influence period, the roadway formation was of good quality, and the H_2S concentration in the return airway was below 6.6 ppm, indicating that the mining operation environment had improved.

5. Conclusion

In this study, static compression and dynamic impact tests were performed to investigate the static and dynamic mechanical properties of coal under chemical erosion. The AE patterns of the immersed coal samples, the energy dissipation, and the fractal characteristics of the fractured coal under dynamic loading were also analysed. In the field, high-pressure fracturing in conjunction with the injection of an alkaline solution was effectively used to construct an anti-impact soft structural coal layer, thereby maintaining the stability of the rock structure surrounding the roadway. The following conclusions were drawn from the experimental research and field test results.

- (1) The mechanical properties of the coal deteriorated after immersion in different types of chemical solutions. After chemical solution erosion, microjoint fissures in the coal propagated, and damage

occurred. The static and dynamic mechanical properties of the coal samples decreased according to an exponential power law in the damage variable. The chemical erosion lowered the strength and increased the ductility of the coal sample. The effects of the chemical solutions on weakening the mechanical properties of the coal sample decreased in the following order: alkaline solution > acidic solution > NaCl solution > distilled water.

- (2) Four stages were observed in the AE curve of the coal samples, namely, pore compaction-closure, a slowly rising linear elastic regime, prepeak steady-state crack propagation, and unsteady crack propagation at the peak strain. As the coal damage increased, the duration of the pore compaction-closure stage increased and that of the linear elastic stage decreased.
- (3) The larger the damage variable of the coal sample was, the lower the dissipated energy of the coal sample was, and the higher the fractal dimension was. These results were obtained because as the damage to the coal samples increased, internal joint fissures developed, and less energy was consumed by fissure propagation than by fissure initiation.
- (4) After high-pressure coal fracturing of the coal, the residual chemical solution in the closed fissures caused secondary weakening of the coal strength over time. Subsequent coal erosion produced a fissure network that served as an effective anti-impact soft structure.

Data Availability

The authors declare that all data supporting the findings of this study are available within the article, the reader can find and use them, and there are no unavailable data.

Conflicts of Interest

The authors declare that they have no known conflicts of financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the financial support provided by the National Natural Science Foundation of China (Project 51564044).

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