Research Article

Numerical Simulation Study of Variable-Mass Permeation of the Broken Rock Mass under Different Cementation Degrees

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In order to analyze variable-mass permeation characteristics of broken rock mass under different cementation conditions and reveal the water inrush mechanism of geological structures containing broken rock masses like karst collapse pillars (KCPs) in the coal mine, the EDEM-FLUENT coupling simulation system was used to implement a numerical simulation study of variable-mass permeation of broken rock mass under different cementation conditions and time-dependent change laws of parameters like porosity, permeability, and mass loss rate of broken rock specimens under the erosion effect were obtained. Study results show that (1) permeability change of broken rock specimens under the particle migration effect can be divided into three phases, namely, the slow-changing seepage phase, sudden-changing seepage phase, and steady seepage phase. (2) Specimen fillings continuously migrate and run off under the water erosion effect, porosity and permeability rapidly increase and then tend to be stable, and the mass loss rate firstly rapidly increases and then gradually decreases. (3) Cementation degree has an important effect on permeability of broken rock mass. As cementing force of the specimen is enhanced, its maximum mass loss rate, mass loss, porosity, and permeability all continuously decrease. The study approach and results not only help enhance coal mining operations safety by better understanding KCP water inrush risks. It can also be extended to other engineering applications such as backfill paste piping and tailing dam erosion.

1. Introduction

The karst collapse pillar (KCP) is a concealed vertical geological phenomenon widespread in Carboniferous Permian coalfields in north China, which is caused by the karst subsidence that occurs in Ordovician limestone aquifers [1]. The cave gradually collapses under the gravity and penetrates the coal seam, eventually forming a plug-shaped geological structure (Figure 1). The existence of the geological phenomenon reduces the recoverable coal reserves by damaging coal seams and influences full-mechanized coal mining. More importantly, the Ordovician limestone KCP usually functions as a channel for groundwater inrush, thus posing a great threat to safe production in the coal mines [2].

As shown in Figure 1, the KCP is a broken rock mass in essence [3]. Moreover, it consists of a solid skeleton and filling particles. Therefore, an experimental study of seepage

characteristics for broken rock mass is an important precondition to correctly reveal the water inrush mechanism of the KCP. The research team led by Xiexing Miao firstly used the MTS815 mechanical testing machine to conduct a systematic study of permeability of the rock mass and obtained permeability change laws of the broken rock mass under different lithological characteristics and different stress states [4–7]. Li et al. [8] established unsteady seepage dynamics models of non-Darcy seepage, gas seepage, and temperature-seepage coupling of the broken rock mass. Chen et al. [9] used the truncated spectral method to study the dynamic response of the broken rock mass seepage system under time-dependent change of permeability characteristics and boundary conditions.

Based on the experimental and theoretical study on broken rock mass, a number of investigations have been performed to explore the water inrush mechanism of KCPs

FIGURE 1: Schematic diagram of KCPs in the strata.

using single or combined methods of theoretical analysis, numerical simulation, and experimental studies. For instance, Bai et al. [10] established a mechanical model-plug model, which was used to describe the behavior of water seepage flow in the coal-seam floor containing KCPs. Furthermore, the variable-mass dynamics and nonlinear dynamics were introduced, and the seepage properties of KCPs associated with particles migration were investigated using numerical simulation [11]. Ma et al. [2] numerically studied the impacts of mining-induced damage on KCPs and the surrounding rocks and on the formation of the fracture zone and analyzed mining-induced KCP groundwater inrush risk. Wang and Kong [12] explored the time-varying and nonlinear characteristics of the dynamic seepage system of broken rocks and examined the varying behavior of the mass loss rate. Yao [13] experimentally studied the evolution of the crushed rock mass seepage properties under different particle sizes and stresses and analyzed the particle migration feature and the KCPs' water inrush mechanism. Moreover, there are also some studies focused on the permeability change of the KCPs to investigate the water inrush mechanisms [14–16].

The aforementioned research results have important reference significance and value for understanding permeability characteristics of broken rock mass [17–19] and revealing the water inrush mechanism of geological structures like KCPs. However, the present research results have scarcely considered influence of erosion on broken rock mass permeability characteristics. Even though some scholars have recognized that water inrush of KCPs is actually a sudden change process of permeability of a broken geologic structure due to internal filling particle loss under the erosion effect [20, 21], there is still a lack of effective experimental means of observing dynamic loss of variable-mass permeable filling particles in the broken rock mass under the erosion effect, and there is no systematic study of variable-mass permeability change characteristics under different cementation conditions of broken rock mass. Based on the above research results, the EDEM-FLUNENT coupling system considering the particle migration effect was used in this paper to simulate the dynamic development process of particle migration of broken rock mass under the erosion effect. Chang laws of parameters like mass loss rate,

porosity, and permeability of broken rock mass under different cementation conditions were studied, expecting to provide an experimental basis for guiding water inrush prevention and control of KCPs in the coal mine.

2. EDEM-FLUENT Coupling Theory

In the Eulerian model of EDEM, solid particles will generate an influence on fluid flow, so the volume fraction is added in the conservation equation to correct the continuity equation of the fluid phase:

$$\frac{\partial \varepsilon \rho}{\partial t} + \nabla \cdot \rho \varepsilon u = 0, \quad (1)$$

where ρ is the fluid density, t is the time, u is the fluid velocity, and ε is the volume fraction.

The momentum conservation equation of the fluid phase is expressed as follows:

$$\frac{\partial \varepsilon \rho u}{\partial t} + \nabla \cdot \rho \varepsilon u u = -\nabla p + \nabla (\mu \varepsilon \nabla u) + \rho \varepsilon g - S, \quad (2)$$

where g is the gravitational acceleration, μ is the viscosity, S is the momentum sink which is the resultant resistance F acting in grid cells. The resistance is generated by relative movement between the fluid and solid phases, and its computational formula is as follows:

$$S = \sum_{i=1}^n \frac{F_{D_i}}{V}, \quad (3)$$

where V is the volume of CFD grid cells and F_{D_i} is the drag force of the particle i .

The Ergun and Wen and Yu resistance model is adopted, and the computational formula of its resistance F_D is as follows:

$$F_D = \frac{\beta V_s |v| v}{1 - \alpha}, \quad (4)$$

where V_s is the particle volume, v is the relative velocity between particles and the fluid, α is the free volume of CFD grid cells, computational formula of β is as follows:

$$\beta = \begin{cases} \frac{150(1-e)^2 n}{ed^2} + \frac{1.75(1-e)\rho_s |v|}{d}, & \phi < 0.8, \\ \frac{3}{4} C_D \rho_s e^{-1.65} (1-e) |v|, & \phi \geq 0.8, \end{cases} \quad (5)$$

where d is the diameter of solid particles and C_D is the resistance coefficient and its computational formula is as follows:

$$C_D = \begin{cases} \frac{24}{Re}, & Re \leq 0.5, \\ 0.44, & Re > 1000, \\ \frac{24(1 + 0.25 Re^{0.687})}{Re}, & 0.5 < Re \leq 1000, \end{cases} \quad (6)$$

where Re is the Reynolds number. In the computational process of the EDEM-FLUENT coupling model, the

buoyancy force F_a of solid particles should be taken into consideration besides resistance, and its computational formula is as follows:

$$F_a = \rho g V_s. \quad (7)$$

3. Establishment of EDEM-FLUENT Coupling Numerical Simulation Model

The established circular straight-pipe model with diameter being 100 mm and height being 200 mm is shown in Figure 2. Face 1 is the pressure inlet boundary, and face 2 is the pressure outlet boundary. The established model is imported into grid generation software to obtain the model grid generation diagram as shown in Figure 3.

As shown in Fig. 4, after grid creation, two particle models with sizes of 0~10mm and 10~20mm are generated inside the circular pipe, in which the particles with larger particles become the skeleton of the broken rock mass, while particles with small size are used as fillings. The particle material is rock, and the circular pipe material is steel. Inlet pressure is set as water pressure 0.05 MPa, and the boundary condition of pressure outlet is the standard atmospheric pressure. The flow monitor is set as model outlet to monitor the change of outlet flow quantity. The model is initialized, the time step is set to be $2e-05$ s, and the number of iterative time steps is 40,000. Data are saved every other 0.02 s during the calculation process, and the model parameter setting is shown in Table 1.

4. Numerical Simulation Results and Analysis

4.1. Mass Loss. Table 2 and Figure 5 give data and curves related to the time-dependent change of model filling particle mass loss. It can be seen from Figure 5 that overall model mass loss presents a continuously increasing trend, and the greater the cohesive force of fillings, the less the mass loss. When the filling cohesive force is 15 J/m^2 and the total mass loss is 260.92 g which occupies about 20.91% of the total filling mass; when the filling cohesive force is 20 J/m^2 and 25 J/m^2 , respectively, the total mass loss will be 214.68 g and 173.351 g, respectively, occupying 17.89% and 14.45% of the total filling mass, respectively; when the filling cohesive force is 30 J/m^2 , the total mass loss is 125.16 g, which occupies about 10.43% of the total filling mass.

4.2. Mass Loss Rate. Table 3 and Figure 6 give data and curves related to the time-dependent change of model mass loss rates under different cementation degrees. It can be seen that the model mass loss rate presents firstly increasing and then decreasing change trends on the whole, and the greater the cohesive force, the smaller the maximum mass loss rate. The maximum mass loss rate is about 2,350 g/s when the cohesive force is 15 J/m^2 ; when the cohesive force is 20 J/m^2 and 25 J/m^2 , the maximum mass loss rate is 2,150 g/s and 1,750 g/s, respectively. The maximum mass loss rate is about 1,450 g/s when the cohesive force is 30 J/m^2 .

FIGURE 2: EDEM-FLUENT coupling numerical calculation model.

FIGURE 3: Model grid generation.

FIGURE 4: Particle model generated through EDEM.

4.3. Porosity and Permeability. Table 4 and Figure 7 give data and curves related to the time-dependent change of model porosity and Table 5 and Figure 8 give data and curves related to the time-dependent change of model permeability. It can be seen that their variation tendencies are similar to change laws of mass loss; namely, with migration and loss of model filling particles, initially

TABLE 1: Numerical simulation parameters.

Simulation parameter	Value
Water density	1,000 kg/m ³
Dynamic viscosity	1.01 × 10 ⁻³ Pa·s
Particle material density	2,400 kg/m ³
Circular pipe material density	7,850 kg/m ³
Large particle size	10~20 mm
Small particle size	0~10 mm
Total mass of generated particles	2,400 g
Filling height	180 mm
Inlet water pressure	0.05 MPa
Mass proportion of skeleton to filling substance	1 : 1

TABLE 2: Mass losses under different cohesive forces (g).

Time (s)	Cohesive force			
	15 J/m ²	20 J/m ²	25 J/m ²	30 J/m ²
0	0	0	0	0
0.02	2.915673	2.345672	1.0806894	0.5644316
0.04	10.03126	7.102347	4.5906528	2.6465132
0.06	23.63215	16.21364	11.857165	8.1136458
0.08	49.31643	33.43365	29.824248	23.6453347
0.1	89.12305	65.81369	59.029935	49.8764224
0.12	135.9103	108.4919	94.535887	79.1346576
0.14	165.3503	129.4325	120.68845	98.1346571
0.16	186.5103	140.3165	128.45919	102.346158
0.18	199.9216	148.347	133.89105	105.045673
0.2	208.3682	155.9135	140.9066	107.136543
0.22	215.1744	161.7844	145.09607	110.316414
0.24	221.9103	168.6543	149.53669	112.513643
0.26	225.1029	174.698	153.94155	114.143547
0.28	229.521	180.3546	158.06276	115.231615
0.3	235.1205	185.8135	161.2561	116.543167
0.32	238.5642	189.1365	162.56408	117.314658
0.34	240.3615	193.2136	164.73661	118.346577
0.36	242.1361	198.0781	165.18808	119.453146
0.38	244.0135	201.6021	167.02905	120.046579
0.4	245.2035	205.3025	167.973	120.864533
0.42	245.9123	208.6102	169.37403	121.765455
0.44	246.5232	210.1315	170.4286	122.611325
0.46	247.1935	212.4614	171.26218	123.013278
0.48	248.0123	213.3462	171.6217	123.546133
0.5	249.3025	214.0132	172.37396	123.846521
0.52	250.921	214.6806	173.35134	124.431645
0.54	250.921	214.6806	173.35134	124.846254
0.56	250.921	214.6806	173.35134	125.161336
0.58	250.921	214.6806	173.35134	125.161336
0.6	250.921	214.6806	173.35134	125.161336

porosity and permeability increase slowly, and then they rapidly increase and finally tend to be steady. The greater the cohesive force, the smaller the increase of amplitudes of model porosity and permeability. After the cohesive force increases from 15 J/m² to 30 J/m², final model porosity reduces from 0.3663 to 0.3292; permeability reduces from 32.33 μm^2 to 20.99 μm^2 .

4.4. Particles Erosion Process. Figure 9 gives the cloud chart of the internal filling particle loss process of the model with the cohesive force being 25 J/m² under the erosion effect. It

FIGURE 5: Time-dependent change curves of mass losses under different cohesive forces.

TABLE 3: Mass loss rates under different cohesive forces (g/s).

Time (s)	Cohesive force			
	15 J/m ²	20 J/m ²	25 J/m ²	30 J/m ²
0	0	0	0	0
0.02	145.7837	117.2836	54.03447	28.22158
0.04	355.7792	237.8337	175.4982	104.1041
0.06	680.0447	455.5648	363.3256	273.3566
0.08	1284.214	861.0002	898.3541	776.5844
0.1	1990.331	1619.002	1460.284	1311.554
0.12	2339.36	2133.91	1775.298	1462.912
0.14	1472.001	1047.031	1307.628	950
0.16	1058.003	544.1986	388.5371	210.575
0.18	670.565	401.5245	271.593	134.9758
0.2	422.3284	378.3245	350.7773	104.5435
0.22	340.3102	293.5446	209.4738	158.9935
0.24	336.7964	343.4966	222.031	109.8615
0.26	159.6263	302.1867	220.2428	81.49519
0.28	220.908	282.8294	206.0608	54.40341
0.3	279.9756	272.9424	159.6668	65.57761
0.32	172.1822	166.1544	65.39905	38.57454
0.34	89.86789	203.853	108.6264	51.59596
0.36	88.72557	243.2259	22.57376	55.32845
0.38	93.8745	176.2005	92.04816	29.67164
0.4	59.49542	185.0206	47.19755	40.89772
0.42	35.44457	165.3844	70.05147	45.0461
0.44	30.54103	76.06155	52.72885	42.29347
0.46	33.51493	116.4955	41.67863	20.09766
0.48	40.94394	44.242	17.9763	26.64279
0.5	64.50564	33.35155	37.61299	15.0194
0.52	80.92889	33.36984	48.86872	29.25619
0.54	0	0	0	20.73045
0.56	0	0	0	15.75408
0.58	0	0	0	0
0.6	0	0	0	0

can be clearly seen that particle loss is a dynamic process. There is no particle transport at $t = 0$ s, and few particles run off between $t = 0$ and $t = 0.2$ s, while more particles transport out between $t = 0.2$ s and $t = 0.4$ s, and the particle erosion effect decreases from $t = 0.4$ s to $t = 0.6$ s, which

FIGURE 6: Time-dependent change curves of mass loss rates under different cohesive forces.

TABLE 4: Porosity coefficients under different cohesive forces.

Time (s)	Cohesive force			
	15 J/m ²	20 J/m ²	25 J/m ²	30 J/m ²
0	0.292286	0.292286	0.292286	0.292286
0.02	0.293146	0.292978	0.292605	0.292452
0.04	0.295244	0.29438	0.29364	0.293066
0.06	0.299255	0.297067	0.295782	0.294678
0.08	0.306828	0.302145	0.301081	0.299258
0.1	0.318567	0.311693	0.309693	0.306994
0.12	0.332363	0.324278	0.320163	0.315621
0.14	0.341045	0.330453	0.327875	0.321224
0.16	0.347284	0.333663	0.330166	0.322466
0.18	0.351239	0.336031	0.331768	0.323262
0.2	0.35373	0.338262	0.333837	0.323878
0.22	0.355737	0.339993	0.335072	0.324816
0.24	0.357723	0.342019	0.336381	0.325464
0.26	0.358664	0.343801	0.33768	0.325945
0.28	0.359967	0.345469	0.338896	0.326266
0.3	0.361618	0.347079	0.339837	0.326652
0.32	0.362634	0.348059	0.340223	0.32688
0.34	0.363164	0.349261	0.340864	0.327184
0.36	0.363687	0.350695	0.340997	0.32751
0.38	0.364241	0.351735	0.34154	0.327685
0.4	0.364592	0.352826	0.341818	0.327927
0.42	0.364801	0.353801	0.342231	0.328192
0.44	0.364981	0.35425	0.342542	0.328442
0.46	0.365179	0.354937	0.342788	0.32856
0.48	0.36542	0.355198	0.342894	0.328717
0.5	0.3658	0.355394	0.343116	0.328806
0.52	0.366278	0.355591	0.343404	0.328978
0.54	0.366278	0.355591	0.343404	0.329101
0.56	0.366278	0.355591	0.343404	0.329194
0.58	0.366278	0.355591	0.343404	0.329194
0.6	0.366278	0.355591	0.343404	0.329194

indicate that particle transport is very slow at the beginning, and then it sharply increases and finally becomes steady. In addition, a run-through channel is gradually formed with particle loss.

FIGURE 7: Porosity coefficients under different cohesive forces.

TABLE 5: Permeability coefficients under different cohesive forces (μm^2).

Time (s)	Cohesive force			
	15 J/m ²	20 J/m ²	25 J/m ²	30 J/m ²
0	12.7343	12.7343	12.7343	12.7343
0.02	12.87826	12.85001	12.7875	12.76205
0.04	13.23524	13.08734	12.96158	12.86492
0.06	13.94018	13.55196	13.32814	13.13825
0.08	15.35577	14.46711	14.27119	13.94088
0.1	17.78363	16.32616	15.92116	15.38791
0.12	21.039	19.07583	18.13715	17.14637
0.14	23.33393	20.56052	19.92918	18.37542
0.16	25.11156	21.36981	20.48942	18.65758
0.18	26.29694	21.98401	20.88886	18.84034
0.2	27.06779	22.57632	21.41444	18.98292
0.22	27.70295	23.04515	21.7336	19.2015
0.24	28.3441	23.60423	22.07626	19.35376
0.26	28.6524	24.10555	22.42067	19.46736
0.28	29.08381	24.58293	22.74701	19.54351
0.3	29.63861	25.05123	23.00263	19.63563
0.32	29.98431	25.34002	23.10804	19.68999
0.34	30.16612	25.6982	23.28401	19.76289
0.36	30.34655	26.13122	23.32073	19.84132
0.38	30.53847	26.44879	23.47094	19.88349
0.4	30.66065	26.78581	23.54827	19.94173
0.42	30.73363	27.09016	23.66346	20.00605
0.44	30.79664	27.23113	23.75048	20.0666
0.46	30.86592	27.44825	23.81945	20.09543
0.48	30.95073	27.5311	23.84925	20.13369
0.5	31.08475	27.59369	23.91171	20.15529
0.52	31.25361	27.65644	23.99306	20.19742
0.54	31.25361	27.65644	23.99306	20.22732
0.56	31.25361	27.65644	23.99306	20.25006
0.58	31.25361	27.65644	23.99306	20.25006
0.6	31.25361	27.65644	23.99306	20.25006

5. Discussion

According to change curves of model permeability characteristics under the erosion effect, the seepage can be

FIGURE 8: Permeability coefficients under different cohesive forces.

FIGURE 9: Particles loss under water erosion. (a) $t = 0$ s. (b) $t = 0.2$ s. (c) $t = 0.4$ s. (d) $t = 0.6$ s.

divided into three phases: slow-changing seepage phase, sudden-changing seepage phase, and steady seepage phase. Filling loss is very slow in the slow-changing seepage phase, and porosity and permeability also increase slowly; fillings

abruptly run off and porosity and permeability sharply increase in the sudden-changing seepage phase, and porosity and permeability change of the particle model system mainly happens in this phase; filling loss phenomenon disappears and porosity and permeability remain steady in the steady seepage phase.

It can also be seen that a change trend of permeability characteristics of broken rock mass under the erosion effect is similar to dynamic change laws of water inrush of the KCP (Figure 10), indicating that the particle migration effect is a key factor causing water inrush of broken geologic structures like KCP in the coal mine. Its water inrush mechanism can be simplified as follows (Figure 11): broken geologic structures like water-inrush KCP in the coal mine can be regarded as consisting of three-type media—broken solid media (skeleton and fillings), liquid (fluid) media in holes and fractures, and fine filling particles in liquid media; under the water erosion effect, fine filling particles inside the KCP migrate and run off; and porosity of the KCP increases, so does its permeability; increasing permeability accelerates water flow and enhances water carrying capacity in turn, and consequently, more particles migrate and run off and permeability of the KCPs is further strengthened. In the meantime, the cementation degree of the KCPs decides mass of erodible particles, so it also has an important influence on variable-mass permeability characteristics of KCPs.

6. Conclusions

The EDEM-FLUENT coupling simulation system was utilized in this paper to study change laws of parameters like mass loss rate, porosity, and permeability of broken rock specimens under different cementation degrees, and the following conclusions were mainly drawn:

- (1) Permeability change of the broken rock mass under the erosion effect can be divided into three phases, namely, the slow-changing seepage phase, sudden-changing seepage phase, and steady seepage phase. Permeability of the broken rock mass slowly increases in the slow-changing seepage phase; it suddenly increases by several and even dozens of times in the sudden-changing seepage phase; after sudden seepage change, permeability basically remains unchanged in the steady seepage phase.
- (2) Cementation degree has an important influence on permeability characteristics of the broken rock mass. As the cohesive force of the specimen increases, the maximum mass loss rate, mass loss, porosity, and permeability all continuously decrease.
- (3) Filling particle loss in the KCP under the erosion effect is an important cause for its water inrush. When the KCP is exposed in coal mining, filling particles continuously run off under water erosion, accompanied by continuously enhanced permeability; the rising permeability accelerates water flow and reinforce water carrying capacity in turn, and as

FIGURE 10: Curve of the water flow volume for a KCP.

FIGURE 11: Schematic diagram of the seepage change process of broken rock mass seepage under the erosion effect.

a result more particles are brought out. This interaction process continuously enlarges permeability and water inflow of the KCP, and finally it will cause the water inrush accident of the KCP.

The study of variable-mass permeation of the broken rock mass under different cementation degrees not only helps enhance the safety of coal mining operations by better understanding KCP water inrush risks. It can also be extended to other engineering applications such as backfill paste piping and tailing dam erosion.

Data Availability

The complete (curve) data used to support the findings of this study are included within the supplementary information file (curve data).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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